



**HAL**  
open science

**Les foraminifères benthiques : bio-indicateurs  
l'eutrophisation naturelle et anthropique en milieu  
marin franc**

Meryem Mojtahid

► **To cite this version:**

Meryem Mojtahid. Les foraminifères benthiques : bio-indicateurs l'eutrophisation naturelle et anthropique en milieu marin franc. Planète et Univers [physics]. Université d'Angers, 2007. Français. NNT: . tel-00346409

**HAL Id: tel-00346409**

**<https://theses.hal.science/tel-00346409>**

Submitted on 11 Dec 2008

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**Les foraminifères benthiques : bio-indicateurs d'eutrophisation  
naturelle et anthropique en milieu marin franc**

THÈSE DE DOCTORAT

Spécialité : Environnements et paléo-environnements océaniques

ÉCOLE DOCTORALE D'ANGERS

présentée et soutenue publiquement

le 23 Novembre 2007

à Angers

par

**Meryem MOJTAHID**

**Devant le jury ci-dessous :**

M. Frans JORISSEN, Pr., Université d'Angers	Directeur de thèse
Mme. Elisabeth ALVE, Pr., Université d'Oslo	Rapporteur
M. Jean-Claude DAUVIN, Pr., Université de Lille 1	Examineur
M. Christophe FONTANIER, Mdc, Université d'Angers	Examineur
M. François GALGANI, Dr., Ifremer, Centre de Méditerranée	Rapporteur
M. Jack MIDDELBURG, Pr., Institut Néerlandais d'Écologie	Examineur
M. Thomas H. PEARSON, Dr., Oban, Écosse	Examineur



## REMERCIEMENTS

*Mes premiers remerciements s'adressent à Frans Jorissen qui a dirigé ce travail de thèse. Je souhaite lui exprimer ma profonde et sincère reconnaissance pour la confiance qu'il a su m'accorder tout au long de cette thèse mais aussi pour ses conseils avisés, réfléchis et clairvoyants, ses incontestables qualités pédagogiques et son soutien permanent. Outre ses compétences scientifiques, je tiens également à saluer ses grandes qualités humaines qui m'ont permis de mener ce travail dans d'excellentes conditions. En créant au quotidien une ambiance chaleureuse et conviviale, il m'a procuré une source de motivation supplémentaire et je l'en remercie sincèrement. Merci enfin pour les pauses café, les débats colorés des pauses déjeuners, les fêtes de laboratoire...Frans, j'espère que tu as eu autant de joie à encadrer cette thèse que j'en ai eu à travailler avec toi ! Au plaisir de poursuivre cette collaboration dans les années à venir.*

*Je souhaite remercier chaleureusement les différents membres de mon jury qui ont volontiers accepté de rapporter et examiner ce travail.*

*Comment continuer cet avant-propos sans remercier tous les membres de mon laboratoire qui se trouvent être des gens formidables et qui ont tout simplement fait de ces trois dernières années de vrais moments de plaisir. Grace à eux, la thèse a été une superbe aventure humaine. Christine, merci pour ton amitié, ta spontanéité et ton aide quand le moral n'était pas au rendez-vous. Merci aussi pour tes conseils avisés sur mon travail et autres sujets existentiels, j'ai aimé partager avec toi tous ces moments. Merci Clémentine pour toutes les pauses bonbons, les discussions chiffons, les fous rires, le mois de collocation, les petits cadeaux, les quelques réunions Green Peace, c'était superbe...Je t'adore ! Édouard, merci pour tous les moments de bonheur que tu nous as procurés, depuis que tu es arrivé dans nos vies, nous avons tous pris au moins 3 kilos chacun. Les pauses chocolat, c'est impitoyable !! Comment oublier Christophe, ce magnifique maître de conférence (et de jeu) qui me fait beaucoup rire et sans lequel le laboratoire ne serait pas aussi chaleureux. Merci pour toutes les soirées et pour toutes les quiches que tu nous as préparées, surtout les quiches aux courgettes (ou aux concombres ??) ! Eduardo, mi amigo basco, te agradezco por tu amistad y tu ayuda. Gracias para todos los debates que tuvimos juntos. Neven, my dear Croatian friend, thanks for your help, for your supporting, for your jokes, for restaurants, for*

walks around the « Étang St Nicholas », for your presents, you are a wonderful person and I like you so much! La petite Sophie, merci pour ton aide, pour tes douces intentions, merci pour les cailloux que tu as collectés exprès pour moi au Mont St Michel, ça m'a beaucoup touchée. La grande Sophie, merci pour ta bonne humeur, pour tes nombreux petits cadeaux et pour tous les papotages qu'on a pu avoir, c'est vrai que c'est un labo de filles finalement. Mélissa, merci pour avoir trié mes milliers d'échantillons, ton aide m'a été très précieuse. Sylvie, ton sourire et ta bonne humeur égaie le labo chaque jour. Oh Fabrice, superbe danseur de Salsa, et superbe géologue de l'Anjou, merci également pour ta bonne humeur communicative, ton enthousiasme débordant, tes irrésistibles blagues. Gégé, sans toi je n'aurais jamais connu le superbe chanteur « Didier Super », ça a été une révélation artistique pour moi. Manue, merci pour ton aide pour les enseignements, ce fut précieux. Erika, merci pour ta gentillesse. Hélène, merci pour tout ton soutien, ton fort caractère m'a toujours plu et ton grand cœur m'a toujours profondément touchée, tu as toujours été là pour nous tous dans ce laboratoire, aussi bien sur le plan professionnel que sur le plan humain, tu es une personne formidable. Frans, je tiens à te remercier encore une fois, tu as su supporter pendant ces trois années mon mauvais caractère. C'était un grand défi pour toi. Je te félicite et je te remercie de tout cœur. J'ai énormément pris plaisir à travailler avec toi et également à manger des « Fish and chips », ce fut un délice. Enfin, je tiens à remercier les patriarches du laboratoire, Messieurs Jean-Pierre André et Alain Baloge, pour leur bonne humeur, leur énorme savoir géologique et leur disponibilité.

En dehors du laboratoire, j'ai également la chance de connaître de formidables personnes qui ont toujours été là pour moi, des vrais amis (es) à toute épreuve qui ont de superbes qualités humaines. Merci Sophie pour tout, ta douceur et ta gentillesse m'ont toujours profondément touchée. Merci pour toutes les soirées Salsa qu'on a pu faire ensemble. De vrais moments de bonheur. Merci à Francy, superbe italienne, qui a su en quelques mois conquérir mon cœur, et sans qui je n'aurais jamais été au « souperou » ni aurais pu un jour acheter « un mouton noir ». Merci Francy, j'ai été beaucoup « émotionnée ». Moumoulie et Mikou, mes deux chers amis de Bordeaux. Merci pour toutes ces années de bonheur, j'ai été extrêmement heureuse en votre compagnie, je me suis énormément amusée, bref, c'était génial. Maryam et Maria, mes superbes meilleures amies de toujours, merci d'avoir été là pour moi, merci de m'avoir donnée autant d'amour. Notre amitié dure depuis près de 15 ans maintenant, et je suis sûre que vous allez devoir me supporter encore très longtemps. Merci à tous mes amis (es) du Mans (Sarrah, Anne,

*Mathilde, Anne-Laure, Fabrice, Ronan), des gens merveilleux avec lesquels j'ai partagé mon plus beau voyage, ce voyage qui s'est déroulé dans mon pays, ah, qu'il est beau mon pays ! Merci à tous mes amis du Maroc, je pense à Hatim, Ziko, Naoufal, Hicham, Mouad, Kaoutar, Tarik, Amine ; Vous êtes tous formidables.*

*Je finirai par les personnes qui comptent le plus à mes yeux ; Ma famille. Dans ce contexte, j'ai également la chance d'en avoir deux :*

*Je commencerai par ma famille française ; la famille Bellois. Cette famille si magnifique et si généreuse. Merci pour votre soutien indéfectible, quels que soient les événements. Je ne serai jamais assez reconnaissante. Merci Martine pour tous tes gâteaux au chocolat, pour ton soutien et ton amour dans les moments les plus difficiles. Merci Christian pour ta bonne humeur (surtout quand tu as posé le plancher de mon appartement). Merci pour m'avoir initiée à tous les chefs d'œuvres Français. Sans toi, je ne sais pas si j'aurais eu le privilège de connaître le célèbre chanteur « Riton la Manivelle ». Merci Morgane, Killian, Amélia, Charlotte, pour tous les bons moments qu'on a passés ensemble, à l'étang, à jouer aux cartes, à rigoler, à faire la fête, à discuter des soucis de chacun. Vous avez été une vraie famille pour moi. Merci Grégouné pour avoir été à mes côtés pendant toutes ces années, sans ton soutien, ton amour et ta grande générosité, je n'y serais jamais arrivée. Je ne pense pas qu'il y ait des mots pour décrire ce que je ressens en ce moment et toute la gratitude que j'ai à ton égard. Je dirai tout simplement Merci.*

*Pour finir, je souhaite exprimer mon immense gratitude et amour à mes parents. Merci pour m'avoir toujours laissée libre de mes choix. Je sais que vous êtes toujours là pour moi et c'est la preuve d'un amour immense et sans frontière qui me touche plus que tout. J'espère que vous êtes fiers de moi. Également, un immense merci à Simohamed, mon cher frère et à mes superbes sœurs Dounia et Sarrah, à Mourad et à mes petits neveux pour tout leur amour. Je vous aime.*

*Je ne sais comment exprimer ma sensibilité à tout l'amour qui m'entoure. Je vous dédie tout simplement cette thèse qui représente pour moi bien plus qu'une simple étude scientifique. Une expérience que je ne suis pas prête d'oublier !*



# TABLE DES MATIÈRES

<b>INTRODUCTION GÉNÉRALE</b> .....	<b>11</b>
<b>CHAPITRE 1. GÉNÉRALITÉS</b> .....	<b>17</b>
1.1 EUTROPHISATION DES ÉCOSYSTÈMES MARINS CÔTIERS .....	19
1.2 SÉDIMENTS MARINS PEU PROFONDS ET MINÉRALISATION DE LA MATIÈRE ORGANIQUE .....	21
1.3 OXYDATION DE LA MATIÈRE ORGANIQUE.....	23
1.4 PH, MARQUEUR DE LA MINÉRALISATION.....	25
1.5 L'OXYGÈNE : UN ÉLÉMENT IMPORTANT DANS L'ÉVOLUTION DE LA MATIÈRE ORGANIQUE .....	27
1.5.1 Cycle biogéochimique benthique de l'oxygène.....	27
1.5.2 Distribution spatiale et dynamique temporelle de l'oxygène.....	28
1.6 LES FORAMINIFÈRES BENTHIQUES : BIO-INDICATEURS D'EUTROPHISATION .....	31
1.6.1 Généralités .....	31
1.6.2 Biologie des foraminifères.....	32
1.6.3 Écologie des foraminifères benthiques.....	35
1.6.3.1 Distribution spatiale des foraminifères benthiques.....	35
1.6.3.2 Microhabitat .....	37
1.6.4 Les foraminifères benthiques en tant que bio-indicateurs.....	39
1.7 LA MACROFAUNE BENTHIQUE : BIO-INDICATEURS D'EUTROPHISATION .....	40
1.8 RÉFÉRENCES .....	42
<b>CHAPITRE 2. SPATIAL DISTRIBUTION OF BENTHIC FORAMINIFERA IN THE RHÔNE PRODELTA: FAUNAL RESPONSE TO ORGANIC MATTER FOCUSSING</b> .....	<b>55</b>
<b>RÉSUMÉ</b> .....	<b>57</b>
2.1 ABSTRACT .....	60
2.2 INTRODUCTION .....	60
2.3 REGIONAL SETTINGS.....	62
2.4 MATERIAL AND METHODS .....	63
2.5 RESULTS.....	68
2.5.1 C <sub>orgs</sub> , Total nitrogen, C/N atomic ratio and δ <sup>13</sup> C of organic matter.....	68
2.5.2 Oxygen analyses.....	70



2.5.3	pH.....	72
2.5.4	Foraminiferal analyses.....	73
2.5.4.1	Living foraminifera (> 150 µm fraction).....	73
2.5.4.2	Living foraminifera (> 63 µm fraction = 63-150 µm + > 150 µm.....	80
2.6	DISCUSSION.....	87
2.7	SYNTHESIS.....	101
2.8	CONCLUSIONS.....	104
2.9	REFERENCES.....	106
	APPENDICES.....	114
	PLATES.....	128

### **CHAPITRE 3. MICROHABITAT SELECTION OF BENTHIC FORAMINIFERA IN THE RHÔNE PRODELTA.....143**

	RÉSUMÉ.....	145
3.1	ABSTRACT.....	148
3.2	INTRODUCTION.....	148
3.3	ENVIRONMENTAL SETTINGS.....	151
3.4	MATERIAL AND METHODS.....	152
3.5	RESULTS.....	154
3.5.1	Living foraminiferal density and composition.....	154
3.5.2	Vertical distribution of living foraminifera.....	156
3.5.2.1	Overall vertical distribution of individual taxa.....	159
3.5.2.2	Vertical distribution of the main taxa at each station.....	163
3.6	DISCUSSION.....	169
3.7	CONCLUSIONS.....	175
3.8	REFERENCES.....	175

### **CHAPITRE 4. COMPARISON BETWEEN DEAD AND LIVING BENTHIC FORAMINIFERAL FAUNAS IN THE RHÔNE PRODELTA.....183**

	RÉSUMÉ.....	185
4.1	ABSTRACT.....	188
4.2	INTRODUCTION.....	188
4.3	MATERIAL AND METHODS.....	191
4.4	RESULTS.....	194
4.5	DISCUSSION.....	204
4.6	CONCLUSIONS.....	207
4.7	REFERENCES.....	208

APPENDICES.....	211
-----------------	-----

**CHAPITRE 5. COMPARISON OF BENTHIC FORAMINIFERAL AND  
MACROFAUNAL RESPONSES TO ORGANIC POLLUTION IN THE FIRTH OF  
CLYDE (SCOTLAND).....217**

RÉSUMÉ.....	219
5.1 ABSTRACT .....	222
5.2 INTRODUCTION .....	222
5.3 STUDY AREA .....	224
5.4 MATERIAL AND METHODS .....	226
5.5 RESULTS .....	228
5.5.1 Chemical properties of surficial sediments .....	228
5.5.2 Foraminiferal faunas.....	232
5.5.3 Macrofauna.....	239
5.6 DISCUSSION.....	246
5.7 CONCLUSIONS.....	260
5.8 REFERENCES .....	261
APPENDICES.....	273
PLATE.....	282

**CHAPITRE 6. BENTHIC FORAMINIFERA AS BIO-INDICATORS OF DRILL  
CUTTING DISPOSAL IN TROPICAL EAST ATLANTIC OUTER SHELF  
ENVIRONMENTS.....285**

RÉSUMÉ.....	287
6.1 ABSTRACT .....	290
6.2 INTRODUCTION .....	290
6.3 MATERIAL AND METHODS .....	294
6.4 RESULTS.....	296
6.4.1 Grain size analysis.....	296
6.4.2 Sediment organic matter and nutrients contents.....	296
6.4.3 Hydrocarbon and Barium contents .....	297
6.4.4 Redox potential.....	298
6.4.5 Leaching, microtoxicology tests, and biodegradability of organic matter.....	299
6.4.6 Foraminiferal analyses.....	300
6.4.6.1 Living fauna (> 150 µm fraction).....	300
6.4.6.2 Living fauna (63-150 µm fraction).....	303
6.4.6.3 Dead fauna.....	304

<b>6.5</b>	<b>DISCUSSION</b> .....	306
<b>6.6</b>	<b>CONCLUSIONS</b> .....	311
<b>6.7</b>	<b>ACKNOWLEDGMENTS</b> .....	312
<b>6.8</b>	<b>REFERENCES</b> .....	312
	<b>APPENDICES</b> .....	317
	<b>PLATES</b> .....	326

**CHAPITRE 7. AGED DRILLED CUTTINGS OFFSHORE GABON: NEW  
METHODOLOGY FOR ASSESSING THEIR IMPACT.....331**

	<b>RÉSUMÉ</b> .....	333
<b>7.1</b>	<b>ABSTRACT</b> .....	336
<b>7.2</b>	<b>INTRODUCTION</b> .....	336
<b>7.3</b>	<b>DESCRIPTION</b> .....	337
<b>7.4</b>	<b>MATERIAL AND METHODS</b> .....	338
<b>7.5</b>	<b>RESULTS</b> .....	341
	<b>7.5.1 Physico-chemical analyses</b> .....	341
	7.5.1.1 Particle size analysis.....	341
	7.5.1.2 Redox potential.....	342
	7.5.1.3 Organic matter.....	342
	7.5.1.4 Total hydrocarbon and Barium.....	343
	<b>7.5.2 Toxicity tests</b> .....	343
	<b>7.5.3 Macrobenthos analyses</b> .....	344
	7.5.3.1 General composition.....	344
	7.5.3.2 General structure .....	345
	<b>7.5.4 Benthic foraminiferal fauna</b> .....	346
<b>7.6</b>	<b>DISCUSSION</b> .....	349
<b>7.7</b>	<b>CONCLUSION</b> .....	352
<b>7.8</b>	<b>ACKNOWLEDGMENTS</b> .....	354
<b>7.9</b>	<b>REFERENCES</b> .....	354
	<b>APPENDICES</b> .....	356

**SYNTHÈSE ET PERSPECTIVES.....361**





## **INTRODUCTION GÉNÉRALE**



## INTRODUCTION GÉNÉRALE

À l'interface des domaines océaniques, terrestres et atmosphériques, les zones côtières offrent une richesse écologique unique et sont le support d'une activité économique importante. Cette activité a un impact significatif sur les écosystèmes qui sont extrêmement vulnérables. Les phénomènes d'eutrophisation dus à l'enrichissement du milieu aquatique en éléments nutritifs (nitrates, phosphates) ou à une introduction anthropique de polluants organiques sont en grande partie les causes d'une dégradation environnementale. À terme, ces phénomènes d'eutrophisation entraînent une intensification de la consommation en oxygène liée au recyclage de la matière organique apportée et produite dans la colonne d'eau. Dans des cas extrêmes, des conditions hypoxiques peuvent en être la conséquence.

Après une forte perturbation et dans les mécanismes accompagnant l'évolution d'un écosystème d'un état instable, vers un état d'équilibre (succession écologique), la richesse spécifique tend à s'accroître et les liens trophiques deviennent plus complexes (parasitisme, symbiose). Les interactions entre les populations augmentent, renforçant la stabilité du milieu. Ainsi, les biocénoses présentes dans des environnements stables ont généralement une diversité spécifique supérieure à celles exposées à des perturbations d'origine anthropique. En réponse à une forte eutrophisation qui déséquilibre l'écosystème, on observera une régression des espèces typiques des environnements stables qui sont remplacées progressivement par des espèces opportunistes en milieu fortement enrichi. En effet, la fragilité du milieu marin est liée au fait qu'il soit soumis à différents facteurs d'origine naturelle ou anthropique qui peuvent le modifier considérablement. Ces facteurs ont pour conséquence directe la variation de la densité, de la composition et de la biodiversité des faunes benthiques, à telle enseigne que ces paramètres sont retenus comme notion intégrative de la qualité des communautés vivantes permettant de faire le diagnostic de l'état de l'environnement dans un milieu donné.

Les phénomènes de pollution en milieu marin/océanique ouvert se multiplient (boues de forages pétroliers, rejets de dragage portuaire, rejets des stations d'épuration, etc...), et par conséquent, une forte demande sociétale de suivi des sites impactés est aujourd'hui présente. Traditionnellement, la macrofaune (bivalves, vers polychètes...) est utilisée à ces fins ; une méthode laborieuse et donc onéreuse. Dans cette optique, les foraminifères benthiques ne sont que rarement utilisés. Ils représentent néanmoins d'excellents bio-indicateurs d'eutrophisation, qu'elle soit d'origine, naturelle ou anthropique. Omniprésents dans les



milieux marins, ils occupent de très nombreuses niches écologiques (des marais maritimes aux plaines abyssales). Du fait de leur cycle de vie court (1 à 3 mois en moyenne, 1 an maximum), les foraminifères réagissent rapidement aux changements de leur environnement. Leurs populations peuvent croître ou diminuer, leur composition se transformer et leur morphologie se modifier. La pollution et les changements environnementaux peuvent conduire à une transformation radicale des populations de foraminifères. Ainsi, leur cycle de vie court et leur ubiquité dans le milieu marin, associés à une grande richesse à l'interface eau-sédiment ainsi que dans le sédiment (analyses statistiques robustes) et une trace dans le fossile (grâce à la préservation des tests calcaires) font des foraminifères, en particulier benthiques, de très bons bio-indicateurs de la qualité de l'environnement marin.

Depuis quelques décennies, de nombreux chercheurs s'intéressent à l'étude des effets de la pollution sur les assemblages de foraminifères benthiques et la possibilité de leur utilisation en tant que bio-indicateurs de la pollution en milieu marin. Dans le contexte des travaux antérieurs liés aux problématiques qu'engendre une eutrophisation de l'écosystème benthique, mais également dans un contexte plus général de compréhension de la réponse faunistique aux perturbations environnementales, l'étude des foraminifères benthiques semble primordiale. En effet, ces micro-organismes jouent un rôle prépondérant, au même titre que les bactéries hétérotrophes, dans la consommation et la minéralisation de la matière organique. Du fait de leur importante contribution dans le devenir et le recyclage de la matière organique, l'étude des foraminifères benthiques est fondamentale afin de mieux comprendre l'impact d'un enrichissement organique sur un écosystème benthique. Également, l'étude des facteurs abiotiques qui conditionnent la réponse faunistique, à savoir l'oxygène, la quantité et la qualité de la matière organique, le pH, l'hydrodynamisme du milieu, la température, la salinité, la turbidité, permet de mieux évaluer l'étendue de la perturbation environnementale et se prononcer ainsi sur l'état de santé du milieu.

L'intérêt général de cette thèse concerne l'utilisation des foraminifères benthiques comme bio-indicateurs d'eutrophisation provenant d'une source anthropique ou naturelle et l'identification des paramètres physicochimiques responsables de cette réponse.

Ainsi, une première phase du travail a consisté à étudier la répartition spatiale des foraminifères benthiques dans des zones affectées par une eutrophisation naturelle, plus particulièrement dans une zone de plateau continentale sous l'influence d'une décharge fluviale importante (le Rhône). La réponse de la faune des foraminifères benthiques vivants à un gradient croissant d'enrichissement organique a été également étudiée dans le prodelta du Rhône (Chapitre 2). Dans ce contexte d'eutrophisation naturelle, le microhabitat des

foraminifères benthiques (Chapitre 3) ainsi que l'analyse des thanatocénoses de foraminifères (Chapitre 4) ont également été explorés afin d'extraire des renseignements écologiques, qui permettront d'affiner notre compréhension de la réponse de la faune aux phénomènes d'eutrophisation.

Dans un second temps, la réponse faunistique à l'eutrophisation naturelle a été comparée à la répartition spatiale des peuplements de foraminifères benthiques dans des régions affectées par une pollution organique de source anthropique (rejets de boues d'épuration ; chapitre 5 ; rejets de boues de forages pétroliers ; chapitres 6 et 7). Pareillement, la réponse des foraminifères à un gradient croissant d'enrichissement organique accompagné d'un appauvrissement en oxygène de l'écosystème benthique a été étudiée.

Dans un troisième temps, nous avons essayé d'introduire dans 2 études (chapitres 5 et 7) la macrofaune benthique dans le but de comparer sa réponse à la perturbation environnementale à celle des foraminifères benthiques. Ceci nous a permis de mieux estimer l'impact de l'eutrophisation et surtout de mieux déterminer le potentiel des foraminifères en tant que bio-indicateurs de ce genre de perturbation.

Enfin, nous avons exploré la possibilité de développer un indice biotique basé sur les foraminifères benthiques dans le but de donner une description quantitative de l'impact environnemental. Celui-ci a été mis en place grâce à la détermination de groupes écologiques présentant une succession faunistique du site le moins impacté vers le site le plus dégradé. Ainsi, nous avons pu déduire de manière plus exacte l'étendue de la perturbation.

Dans la présentation de ce manuscrit, et après un premier chapitre consacré à une synthèse bibliographique (chapitre 1), nous commencerons par décrire l'impact de l'eutrophisation naturelle dans le prodelta du Rhône comprenant la succession spatiale des faunes (chapitre 2), leur microhabitat (chapitre 3) et la comparaison entre les faunes mortes et vivantes (chapitre 4). Nous décrirons ensuite les sites impactés par une source anthropique, ceux-ci étant classés de la zone la plus impactée vers la zone la moins impactée. Nous étudierons ainsi le Firth of Clyde en Écosse (impacté par le rejet des boues d'épuration ; chapitre 5), puis le site N'Kossa au large du Congo (chapitre 6) et enfin le site AGM6 au large du Gabon (chapitre 7). Ces deux derniers sites étant impactés par les rejets des boues et déblais de forages pétroliers. Dans un dernier chapitre, nous présenterons une synthèse des données, et indiquerons des perspectives pour des futures recherches.



## CHAPITRE 1. GÉNÉRALITÉS

<b>1.1</b>	<b>EUTROPHISATION DES ÉCOSYSTÈMES MARINS CÔTIERS ..</b>	<b>19</b>
<b>1.2</b>	<b>SÉDIMENTS MARINS PEU PROFONDS ET MINÉRALISATION DE LA MATIÈRE ORGANIQUE.....</b>	<b>21</b>
<b>1.3</b>	<b>OXYDATION DE LA MATIÈRE ORGANIQUE.....</b>	<b>23</b>
<b>1.4</b>	<b>PH, MARQUEUR DE LA MINÉRALISATION .....</b>	<b>25</b>
<b>1.5</b>	<b>L'OXYGÈNE : UN ÉLÉMENT IMPORTANT DANS L'ÉVOLUTION DE LA MATIÈRE ORGANIQUE .....</b>	<b>27</b>
<b>1.5.1</b>	<b>Cycle biogéochimique benthique de l'oxygène.....</b>	<b>27</b>
<b>1.5.2</b>	<b>Distribution spatiale et dynamique temporelle de l'oxygène ....</b>	<b>28</b>
<b>1.6</b>	<b>LES FORAMINIFÈRES BENTHIQUES : BIO-INDICATEURS D'EUTROPHISATION.....</b>	<b>31</b>
<b>1.6.1</b>	<b>Généralités.....</b>	<b>31</b>
<b>1.6.2</b>	<b>Biologie des foraminifères.....</b>	<b>32</b>
<b>1.6.3</b>	<b>Écologie des foraminifères benthiques .....</b>	<b>35</b>
<b>1.6.3.1</b>	<b>Distribution spatiale des foraminifères benthiques.....</b>	<b>35</b>
<b>1.6.3.2</b>	<b>Microhabitat.....</b>	<b>37</b>
<b>1.6.4</b>	<b>Les foraminifères benthiques en tant que bio-indicateurs.....</b>	<b>39</b>
<b>1.7</b>	<b>LA MACROFAUNE BENTHIQUE : BIO-INDICATEURS D'EUTROPHISATION.....</b>	<b>40</b>
<b>1.8</b>	<b>RÉFÉRENCES.....</b>	<b>42</b>



## CHAPITRE 1. GÉNÉRALITÉS

### 1.1 EUTROPHISATION DES ÉCOSYSTÈMES MARINS CÔTIERS

L'eutrophisation des zones côtières<sup>1</sup> fait partie des sujets les plus étudiés dans la communauté scientifique. Le terme « eutrophisation » vient du grec *eu* : « bien, vrai » et *trophein* : « nourrir », et désigne usuellement le déséquilibre qui résulte d'un apport excessif de nutriments (principalement d'azote et de phosphore). Néanmoins, *Nixon (1995)* a suggéré que les nutriments ne sont pas les seuls éléments qui déterminent l'état trophique de la colonne d'eau mais que l'eutrophisation pourrait être définie également par l'augmentation du taux d'introduction du carbone organique dans un écosystème donné. Le processus d'eutrophisation peut résulter des épandages agricoles (engrais riches en azote et phosphore), de l'accroissement des rejets industriels, urbains ou agricoles excessivement riches en nutriments et en matière organique. S'appuyant sur les équations chimiques moyennes de la synthèse, puis de la dégradation de la matière organique en mer, cette définition opérationnelle privilégie donc les conséquences néfastes de l'enrichissement, c'est-à-dire la production d'une biomasse algale excessive, voire déséquilibrée au point de vue biodiversité, ainsi que l'hypoxie<sup>2</sup> plus ou moins sévère qui résulte de la dégradation de cet excès de matière organique. Dans l'acceptation courante, l'eutrophisation est donc souvent synonyme de pollution, bien que celle-ci puisse revêtir bien d'autres aspects : contamination biologique (bactéries, parasites...), chimique (pesticides, métaux, solvants...) ou physique (chaleur...).

Le carbone organique arrivant sur le fond océanique provient aussi bien de la production primaire<sup>3</sup> (carbone autochtone) que de source externe (carbone allochtone). Il existe peu de mesures viables de la quantité de carbone organique allochtone introduit dans le système marin contrairement à la production primaire qui, dans beaucoup d'environnements marins, est bien mesurée. Ainsi, *Nixon (1995)* a proposé un schéma de classification décrivant

---

<sup>1</sup> Zones côtières : dans les zones côtières sont comprises les zones ouvertes (plateau continental, estuaire) et semi fermées comme les lagunes (selon le LOICZ ; Land-Ocean Interaction in the Coastal Zone).

<sup>2</sup> Hypoxie : dans les écosystèmes aquatiques, la concentration en oxygène dissous est inférieure à 2 mg/l (*Rabalais et al., 1999*).

<sup>3</sup> Production primaire : la production primaire est la transformation des éléments minéraux présents dans l'eau (gaz carbonique, azote, phosphore) en molécules organiques vivantes. Dans les océans, cette production est constituée par des algues et des cyanobactéries, planctoniques ou vivantes sur le fond.

les états trophiques du milieu océanique basé sur les taux de production primaire phytoplanctonique mesurés en  $\text{gC.m}^{-2}.\text{an}^{-1}$  (oligotrophique,  $<100$  ; mésotrophique, 100-300 ; eutrophique, 301-500 et hypertrophique,  $>500$ ) pour les systèmes marins côtiers et pour les écosystèmes estuariens.

Les mécanismes conduisant à l'eutrophisation dans les environnements côtiers sont (*IFREMER, 2001*):

- Un confinement de la masse d'eau ; en lagunes, c'est le pourtour terrestre qui fournit un confinement statique, alors qu'en mer ouverte, ce sont des phénomènes hydrodynamiques qui créent un confinement dynamique. Ainsi, le piégeage horizontal des masses d'eau dans les zones de courant résiduel très faible accueillant des effluents trop riches en nutriments, issus par exemple, d'exploitations agricoles, humaines ou industrielles, conduit à une prolifération excessive de la biomasse algale. En effet, l'hydrodynamisme se charge du transport et de la dilution des nutriments dissous, de l'évacuation des algues en suspension ainsi que de la ventilation des eaux permettant la dégradation de l'excès d'algues.

- Un bon éclairage de la suspension algale, expliquant la localisation des marées vertes à ulves aux lagunes et eaux littorales peu profondes. Dans les panaches de dilution des fleuves, le confinement en surface d'une couche dessalée et riche en nutriments par un front de densité contribue à assurer au phytoplancton de surface un éclairage moyen plus élevé qu'en zone non stratifiée.

- Des apports en nutriments en excès par rapport à la capacité d'évacuation ou de dilution du site. Le contrôle de la prolifération phytoplanctonique en zone côtière est toutefois variable dans l'espace et dans le temps : dans le panache de la Seine ou en baie de Vilaine par exemple, l'élément limitant au printemps et près de l'embouchure est actuellement le phosphore, tandis que plus au large, l'azote devient limitant, surtout en été.

- Des apports importants en matière organique via les rivières, accentuant ainsi les phénomènes de minéralisation et donc de consommation d'oxygène dans les écosystèmes benthiques.

Les manifestations de l'eutrophisation en réponse à l'augmentation de la biomasse algale sont multiples. En effet, cette prolifération végétale excessive conduit à une réduction de la pénétration de la lumière dans la colonne d'eau (réduisant rétroactivement le développement

du phytobenthos). Celle-ci peut être accompagnée d'une apparition de blooms<sup>4</sup> d'espèces phytoplanctoniques toxiques ou néfastes pour l'homme comme le *Dinophysis* ou l'*Alexandrium minutum*. Néanmoins, la plus sérieuse des manifestations et certainement la plus discutée est l'apparition des phénomènes d'hypoxie. Ces phénomènes apparaissent lorsque le dépôt de la matière organique sur le fond sédimentaire, lié à une augmentation de la biomasse végétale dans la colonne d'eau et à une importante introduction de matière organique continentale, entraîne une forte demande benthique en oxygène (Fig. 1-1). En effet, lors de la mort, puis de la dégradation bactérienne de cette biomasse phytoplanctonique, la consommation en oxygène dissous peut dépasser les apports en oxygène dans le milieu qui ont lieu généralement par le biais de la photosynthèse, de la réaération à partir de l'atmosphère, ou encore à travers le renouvellement des masses d'eau par les courants marins. Pour *Diaz et al. (1995)*, l'oxygène est la variable environnementale qui a le plus évolué au cours des dernières décennies. Dans des cas extrêmes, cette hypoxie étant de plus en plus sévère, un phénomène d'anoxie<sup>5</sup> apparaît dans les eaux de fond. Associés à une production benthique de sulfure d'hydrogène, sous l'action de bactéries sulfato-réductrices, les phénomènes d'anoxie deviennent nuisibles pour les espèces benthiques et pélagiques. L'oxygène apparaît donc comme un élément clé dans les processus de dégradation du matériel organique et dans la conservation de la qualité des eaux. Dans les sédiments, la consommation d'oxygène est gérée par un ensemble de réactions physiques, chimiques et/ou biologiques participant à la minéralisation de la matière organique que l'on qualifie de « diagenèse précoce » (*Berner, 1980*).

## 1.2 SÉDIMENTS MARINS PEU PROFONDS ET MINÉRALISATION DE LA MATIÈRE ORGANIQUE

Les zones côtières reçoivent d'importantes quantités de carbone organique et inorganique particulaire ou dissous ( $\sim 1 \text{ GTC an}^{-1}$ ), mais peu d'informations sont disponibles quand au devenir de ce matériel (*Wollast, 2002*). En comparaison avec l'océan ouvert, les

---

<sup>4</sup> Bloom phytoplanctonique : efflorescence algale. Dans le milieu aquatique, on parle de floraison d'une espèce phytoplanctonique qui survient principalement au printemps grâce aux conditions propices en température, luminosité et nutriments.

<sup>5</sup> Anoxie : absence totale d'oxygène (0 mg/l). Dans un milieu anoxique, le maintien de la respiration aérobie étant impossible, la vie se limite à la présence d'organismes dont le métabolisme est assuré par des mécanismes anaérobies (fermentation, respiration anaérobie comme la sulfato-réduction, la photosynthèse bactérienne, etc).



zones côtières sont caractérisées par une forte productivité biologique due aux importants apports en nutriments non seulement des rivières mais également par le transfert des eaux profondes océaniques riches en nutriments à travers la bordure continentale (*Wollast, 1991*). Une partie de la matière organique en résultant peut être déposée et enfouie dans les sédiments de la plate-forme et de la pente continentale ou exportée vers l'océan profond, contribuant ainsi à la pompe biologique du carbone. Parmi le stock de matière organique produit par la production primaire, une partie est minéralisée dans la colonne d'eau, principalement grâce à la boucle microbienne contribuant à la production régénérée<sup>6</sup> (*Azam et al., 1983*). La fraction de matière organique non minéralisée à la surface de la colonne d'eau est exportée à la surface des sédiments (Fig.1-1).

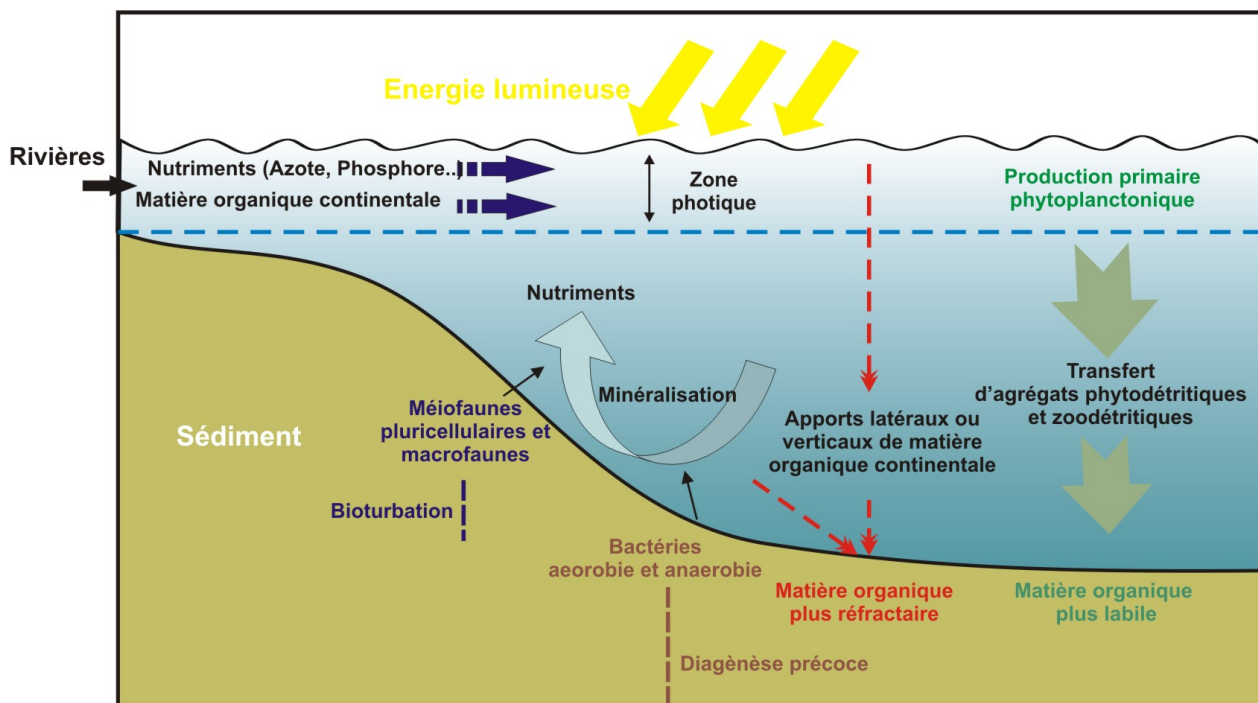


Figure 1-1. Schéma explicatif de l'origine du carbone organique et de son devenir dans la colonne d'eau et dans le sédiment marin (schéma inspiré de Fontanier, 2003)

Dans les zones côtières peu profondes, comme les lagunes, la faible hauteur d'eau permet à une grande quantité de matière organique de se déposer à l'interface eau-sédiment. Par conséquent, les sédiments des zones côtières, qui ne représentent que 10 % de la surface océanique globale, enfouissent 80% de la matière organique marine (*Wollast, 1991*) et

<sup>6</sup> Production régénérée : la matière organique reminéralisée en surface alimente un circuit « fermé » appelé la production régénérée.

accumulent 90 % des particules provenant des systèmes fluviaux (*Gibbs, 1981*). Les sédiments des zones côtières participent donc largement au devenir du matériel organique.

### 1.3 OXYDATION DE LA MATIÈRE ORGANIQUE

De structure complexe, la matière organique particulaire possède un comportement, une stabilité et un devenir variant selon son origine (continentale ou marine) et selon les conditions environnementales où elle évolue. Elle comprend de nombreux constituants : protéines, phospholipides, polysaccharides, etc., et voit sa « réactivité » diminuer au cours de sa minéralisation dans la colonne sédimentaire (*Berner, 1980 ; Middelburg, 1989*). Pour simplifier, la matière organique particulaire d'origine phytoplanctonique est représentée suivant la stœchiométrie proposée par *Redfield et al. (1963)* :  $(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}(\text{H}_3\text{PO}_4)_1$ .

Dans un système aquatique et, en particulier, dans un milieu confiné (sédiments par exemple), une succession d'agents oxydants (accepteurs d'électrons) peut être décrite lors de la dégradation (oxydation bactérienne) de la matière organique. *Froelich et al. (1979)* ont été les premiers à proposer un modèle conceptuel à l'état stationnaire représentant la séquence verticale des réactions redox liées à la dégradation de la matière organique dans la colonne sédimentaire (Fig. 1-2) : la matière organique est en premier lieu oxydée par l'oxygène présent. A l'interface eau-sédiment, l'oxygène est transporté des eaux de fond vers les sédiments par diffusion moléculaire ou par bio-irrigation sous l'action des organismes benthiques. Dans cette zone superficielle ou « zone oxique », variant de quelques millimètres à plusieurs dizaines de centimètres selon l'intensité de la dégradation, l'oxygène est le premier oxydant à être utilisé. En effet, les microorganismes utilisent préférentiellement les oxydants qui produisent la plus grande quantité d'énergie libre<sup>7</sup> indispensable à leur développement physiologique (croissance, reproduction, etc.). En milieu confiné, la quantité d'oxygène est rapidement consommée avant que la totalité du carbone organique n'ait été oxydée. La réaction de dégradation se poursuit alors par la consommation d'autres accepteurs

---

<sup>7</sup> Le terme d'énergie libre a été proposé par un savant américain du nom de Josiah Willard Gibbs (1839-1903). Il a défini une quantité appelée énergie libre (ou enthalpie libre) qui indique si la réaction aura lieu ou non. Elle est symbolisée par  $\Delta G$  en l'honneur de son nom. Cette énergie libre est généralement exprimée en kilojoules (kJ) par mole de réactif. Si, par rapport à un état initial, il y a une diminution de l'énergie libre ( $\Delta G < 0$ ) alors la réaction peut se produire spontanément. On parle de processus exothermique qui augmente l'ordre (diminue le désordre) à l'intérieur d'un système. Si, au contraire  $\Delta G > 0$ , la réaction est dite endothermique (augmente l'état de désordre d'un système) et nécessite un apport d'énergie supplémentaire (solaire, chimique, etc.).

d'électrons comme les nitrates, les oxydes métalliques (de fer et de manganèse) et les sulfates, en l'absence de perturbations extérieures (remaniement du sédiment par exemple). Dans cette succession de réactions d'oxydoréductions, l'étape de la réduction des oxydes métalliques (Fe et Mn) est intéressante. En effet, dans le cas (le plus fréquent) où la réaction n'est pas limitée par la quantité de matière organique, l'oxydation de cette dernière par l'oxygène, puis par les nitrates, impose un potentiel où les oxydes métalliques se réduisent à leur tour (les métaux passent en solution au degré +2 :  $\text{Fe}^{2+}$  et  $\text{Mn}^{2+}$ ). À ce stade, les métaux entraînés (métaux associés : Cd, Cu, Pb, Hg, etc.) lors de la formation de ces oxydes métalliques dans la colonne d'eau se trouvent libérés et deviennent éventuellement biodisponibles. Quand les potentiels décroissent et atteignent les valeurs où les sulfates à leur tour interviennent, il y a formation de  $\text{HS}^-$  et  $\text{S}^{2-}$  qui donne lieu à la précipitation de sulfures insolubles (FeS et sulfures de métaux associés) qui peuvent rester piégés dans le sédiment ou être réoxydés s'il n'y a pas de remaniement du sédiment. Les métaux associés participent ainsi à un cycle dans lequel le fer joue un rôle central.

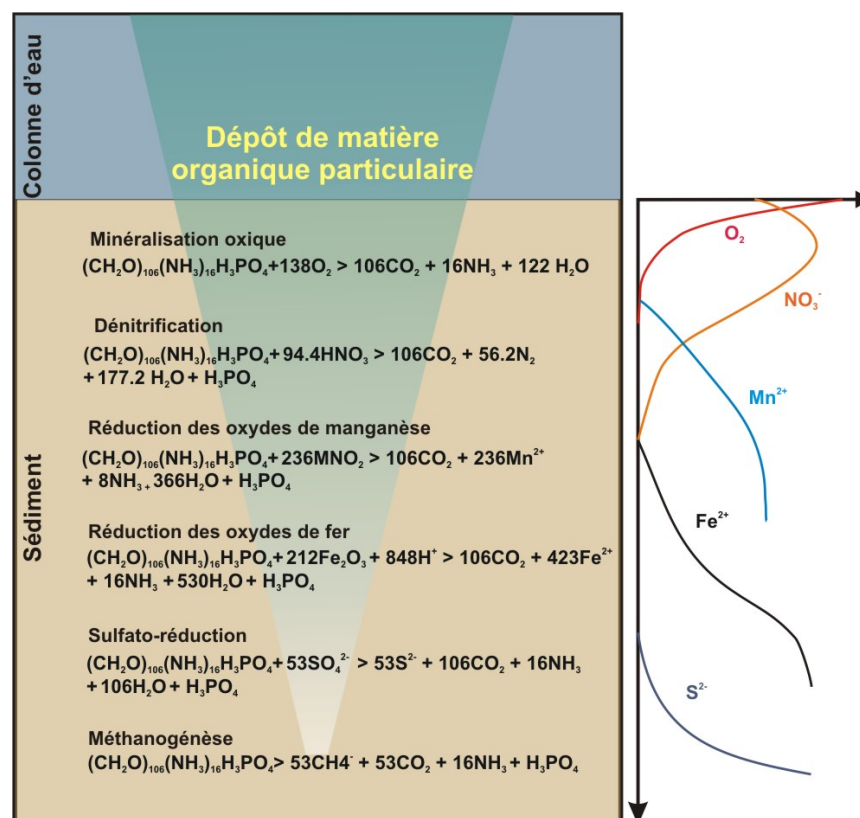


Figure 1-2. A gauche, les principales voies de minéralisation de la matière organique dans les sédiments marins (Froelich et al., 1979), en assumant les rapports stœchiométriques de Redfield (Redfield et al., 1963). A droite, une représentation schématique de la distribution des composés dissous majeurs dans les sédiments marins. La profondeur et la concentration sont arbitraires. Cette distribution verticale montre l'utilisation préférentielle de l'oxygène en tant qu'agent oxydant, suivi des nitrates, puis des oxydes métalliques et enfin des sulfates.

Dans un milieu naturel, ce modèle conceptuel décrivant un état stationnaire n'est pas toujours réaliste. Celui-ci peut subir des modifications dû à de nombreux facteurs environnementaux. En effet, de nombreuses études ont montré que les variations des apports en carbone organique, des taux de sédimentation, de la composition chimique de l'eau surnageante, de l'activité biologique, etc. induisent un état non stationnaire de la composition sédimentaire s'opérant sur de longues échelles de temps : géologiques (*Colley et al., 1984 ; de Lange, 1986 ; Buckley et Cranston, 1988 ; Wilson et Thomson, 1998*), mais aussi sur des échelles de temps plus courtes : annuelles et saisonnières (*Gobeil et al., 1997 ; Luther et al., 1997 ; Anschutz et al., 2000*). *Luther et al. (1997), Hulth et al. (1999), Anschutz et al. (2000)* et *Hyacinthe et al. (2001)* ont récemment mis en évidence des nouvelles voies d'oxydo-réduction, comme la nitrification anaérobie par les oxydes de manganèse.

#### **1.4 pH, MARQUEUR DE LA MINÉRALISATION**

Les sédiments marins constituent le piège ultime des particules (ex : matière organique) qui transitent dans la colonne d'eau. La respiration microbienne, intervenant dans la dégradation de la matière organique, met en œuvre des réactions d'oxydo-réduction entre accepteurs d'électrons inorganiques (oxygène dissous, nitrate, oxydes métalliques, sulfate) et donneurs d'électrons (matière organique). Ces réactions redox engendrent aussi la formation de produits acido-basiques qui vont créer les conditions pH des eaux interstitielles. Les sédiments jouent ainsi le rôle d'un réacteur biogéochimique dans lequel intervient une grande variété de mécanismes diagénétiques (la diagenèse précoce) contrôlant les cycles biogéochimiques du Carbone et de nombreux autres éléments (ex. N, S, métaux). Si les mesures de pH dans les solutions aqueuses diluées sont bien maîtrisées et faciles à réaliser aujourd'hui, celles dans l'eau de mer fortement ionisée restent plus complexes, particulièrement à cause des solutions standard difficiles à réaliser dans une matrice eau de mer.

D'après la séquence diagénétique, une diminution du pH directement sous l'interface eau-sédiment correspond à la minéralisation de la matière organique en présence d'O<sub>2</sub> comme accepteur d'électrons (Tableau 1-1). Cette diminution de pH induit la dissociation des acides carboniques et la diminution du taux de saturation des carbonates. En dessous de la zone oxygène, la dénitrification entraîne également une diminution du pH. Plus en profondeur, les réactions de minéralisation de la matière organique par les oxydes métalliques augmentent le

pH alors que la sulfato-réduction est une réaction légèrement acidifiante pour le milieu. D'autres réactions peuvent également participer à l'acidification des eaux interstitielles, comme l'oxydation de la pyrite et des produits réduits ( $\text{Mn}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{HS}^-$ ).

Processus	pH
<p><b>1. Photosynthèse et Respiration</b>  <math>(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 138\text{O}_2 &gt; 106\text{HCO}_3^- + 16\text{NO}_3^- + \text{HPO}_4^{2-} + 124\text{H}^+</math></p>	Diminue
<p><b>2. Dénitrification</b>  <math>(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 94.4\text{NO}_3^- &gt; 106\text{HCO}_3^- + 55.2\text{N}_2 + 71.2\text{H}_2\text{O} + \text{HPO}_4^{2-} + 13.6\text{H}^+</math></p>	Diminue
<p><b>3. Réduction des oxydes métalliques</b>  <math>(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 236\text{MnO}_2 + 364\text{H}^+ &gt; 106\text{HCO}_3^- + 236\text{Mn}^{2+} + 8\text{N}_2 + 260\text{H}_2\text{O} + \text{HPO}_4^{2-}</math>  <math>(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 424\text{FeOOH} + 756\text{H}^+ &gt; 106\text{HCO}_3^- + 424\text{Fe}^{2+} + 16\text{NH}_4^+ + 636\text{H}_2\text{O} + \text{HPO}_4^{2-}</math></p>	Augmente
<p><b>4. Sulfato-réduction</b>  <math>(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 53\text{SO}_4^{2-} &gt; 53\text{HS}^- + 106\text{CO}_2 + 16\text{NH}_4^+ + 106\text{H}_2\text{O} + \text{HPO}_4^{2-} + 39\text{H}^+</math></p>	Diminue
<p><b>5. Nitrification</b>  <math>\text{NH}_4^+ + 2\text{O}_2 &gt; \text{NO}_3^- + \text{H}_2\text{O} + 2\text{H}^+</math></p>	Diminue
<p><b>6. Oxydation de <math>\text{Mn}^{2+}</math> et <math>\text{Fe}^{2+}</math></b>  <math>2\text{Mn}^{2+} + \text{O}_2 + 2\text{H}_2\text{O} &gt; 2\text{MnO}_2 + 4\text{H}^+</math> / <math>4\text{Mn}^{2+} + \text{O}_2 + 6\text{H}_2\text{O} &gt; 4\text{MnOOH} + 8\text{H}^+</math>  <math>4\text{Fe}^{2+} + 3\text{O}_2 + 2\text{H}_2\text{O} &gt; 4\text{FeOOH} + 4\text{H}^+</math> / <math>4\text{Fe}^{2+} + \text{O}_2 + 10\text{H}_2\text{O} &gt; 4\text{Fe}(\text{OH})_3 + 8\text{H}^+</math>  <math>4\text{Fe}^{2+} + \text{O}_2 + 4\text{H}_2\text{O} &gt; 4\text{Fe}_2\text{O}_3 + 8\text{H}^+</math></p>	Diminue
<p><b>7. Oxydation de HS et de la pyrite</b>  <math>\text{HS}^- + 2\text{O}_2 &gt; \text{SO}_4^{2-} + \text{H}^+</math>  <math>\text{FeS}_2(\text{s}) + 15/4\text{O}_2 + 3/2\text{H}_2\text{O} &gt; \text{Fe}(\text{OH})_3(\text{s}) + 4\text{H}^+ + 2\text{SO}_4^{2-}</math></p>	Diminue
<p><b>8. Formation de FeS et <math>\text{Fe}_2\text{S}</math></b>  <math>\text{Fe}^{2+} + \text{H}_2\text{S} &gt; \text{FeS} + 2\text{H}^+</math> / <math>\text{Fe}^{2+} + \text{HS}^- &gt; \text{FeS} + \text{H}^+</math>  <math>\text{Fe}^{2+} + 2\text{H}_2\text{S} &gt; \text{FeS}_2 + \text{H}_2 + 2\text{H}^+</math> / <math>\text{Fe}^{2+} + 2\text{HS}^- &gt; \text{FeS}_2 + 2\text{H}^+</math></p>	Diminue

Tableau 1-1. Séquence diagénétique et variation de pH (Froelich et al., 1979 ; De Lange, 1986). Seules les réactions de minéralisation de la matière organique par les oxydes métalliques augmentent le pH, toutes les autres ont un effet acidifiant.

L'importance relative de chaque processus est donc mise en évidence par les profils de pH associés aux profils des éléments participant aux variations acido-basiques du milieu. Par exemple, Luther III et al. (1999) ont démontré, en effectuant simultanément des profils *in-situ* d' $\text{O}_2$ ,  $\text{Mn}^{2+}$ ,  $\text{Fe}^{2+}$  et pH, que l'augmentation brutale du pH dans la zone anoxique des sédiments correspondait à la réduction des  $\text{MnO}_2$  (augmentation des  $\text{Mn}^{2+}$ ) et que la diminution du pH sous cette zone est partiellement due à la précipitation des phases carbonatées pouvant incorporer du Mn et générer du  $\text{CO}_2$  et de l' $\text{H}_2\text{O}$  (Boudreau et al., 1998).

Dans une autre étude menée par *Van Cappellen et Wang (1996)*, les variations de pH, obtenues par des simulations de modèles diagénétiques, apparaissent fortement liées au cycle du fer, et dans une moindre mesure au cycle du manganèse. Ces exemples mettent donc en évidence l'intérêt de mesurer les variations de pH dans les sédiments marins même si, en l'état actuel de la recherche, ces variations ne pourvoient pas d'informations quantitatives sur l'importance relative des réactions.

## **1.5 L'OXYGÈNE : UN ÉLÉMENT IMPORTANT DANS L'ÉVOLUTION DE LA MATIÈRE ORGANIQUE**

### **1.5.1 Cycle biogéochimique benthique de l'oxygène**

L'oxygène est l'accepteur d'électron qui est énergétiquement le plus favorable dans les réactions de minéralisation de la matière organique dans les sédiments marins (*Froelich et al., 1979*). De ce fait, il joue un rôle primordial dans sa transformation et son devenir. Lorsque les apports de matière organique vers le sédiment sont élevés (ex. en période d'efflorescence printanière), la minéralisation du carbone organique peut être dominée par des processus anaérobies. Dans ce cas, l'oxygène permet la réoxydation des produits réduits, tel que le sulfure, issus de la minéralisation anoxique qui diffusent vers la zone oxiq, selon les réactions figurant dans le tableau 1-1. L'importance relative des processus aérobie et anaérobies contrôle la dynamique de l'oxygène dans le sédiment. C'est pourquoi la demande sédimentaire en oxygène est utilisée pour évaluer la « respiration benthique », autrement dit la minéralisation benthique de la matière organique (*Jahnke, 1996*). Cependant, la fixation des espèces réduites (représentant autant de produits réduits non réoxydés par l'oxygène) ou leur libération vers la colonne d'eau peuvent changer les termes du bilan et par conséquent l'estimation de la respiration benthique totale. D'autre part, le remaniement sédimentaire induit par des phénomènes de mélange (bioturbation, décharge sédimentaire, érosion) est susceptible de perturber la distribution verticale des composés oxydés et réduits, et ainsi modifier la séquence diagénétique verticale.

L'importance relative des diverses voies aérobie et anaérobie de dégradation de la matière organique varie généralement en fonction de la température, de l'oxygénation des eaux de fond, de l'intensité des apports qualitatifs et quantitatifs de matière organique et de la production primaire benthique. En zone côtière notamment, ces facteurs présentent une forte variabilité saisonnière. De ce fait, il n'est pas toujours simple d'identifier la principale cause de la dynamique du cycle benthique de l'oxygène. Cependant, de forts apports de matière organique, caractérisant souvent ces environnements côtiers, augmentent la demande benthique en oxygène, et par conséquent diminuent la pénétration de l'oxygène dans les sédiments (de quelques centimètres à quelques millimètres). En effet, dans ces sédiments riches en matière organique, les processus anaérobies prédominent, alors que les sédiments « pauvres » en matière organique sont plutôt un lieu de minéralisation oxydante (*Canfield et al., 1993*).

### 1.5.2 Distribution spatiale et dynamique temporelle de l'oxygène

La demande benthique en oxygène, pour minéraliser le matériel organique et les produits réduits issus de cette dégradation, dépend de nombreux facteurs tels que:

- L'oxygénation de l'eau de fond : les variations des concentrations des eaux interstitielles dans les sédiments de surface sont attribuées aux variations du degré d'oxygénation de la colonne d'eau, celui-ci étant contrôlé par la stratification des eaux, les fluctuations des apports fluviaux et la productivité primaire (*Paropkari et al., 1992 ; Pedersen et al., 1992 ; Canfield, 1994 ; Cai et Reimers, 1995*).

- Le flux et la qualité de matière organique à la surface du sédiment : dans les sédiments côtiers, la matière organique provient aussi bien de la production primaire des eaux de surface (matière organique généralement labile<sup>8</sup>), étant plus accrue dans ces environnements où les apports en nutriments sont importants (*Nixon, 1981 ; Bay, 1984 ; Barranguet et al., 1994, 1996 ; Olesen et Lundsgaard, 1995 ; Pasqualini et al., 1998 ; Fenchel et Glud, 2000*), que du

---

<sup>8</sup> Matière organique labile : le caractère labile de la matière organique est déterminé par la fraction hydrolysable du carbone organique (acides aminés, sucres, sucres aminés et ammonium) qui est très facilement assimilable par les organismes benthiques. La matière organique d'origine marine contient une importante fraction hydrolysable (*Etcheber et al., 1999*).

continent par le biais des rivières (matière organique généralement réfractaire<sup>9</sup>). La dégradation de ces importantes quantités de matière organique arrivant au fond mène à une consommation benthique importante de l'oxygène (*Jørgensen, 1977 ; Froelich et al., 1979 ; Graf, 1987 ; Archer et Devol, 1992 ; Canfield et al., 1994*).

- La bioturbation : le micro-environnement chimique peut varier en fonction des activités métaboliques à la surface et dans le sédiment. On regroupe sous le terme bioturbation l'ensemble des perturbations induites par l'activité des organismes benthiques (invertébrés, vertébrés, bactéries, champignons...) liées à leur déplacement, leur mode alimentaire, leurs besoins respiratoires (creusement de galeries et de terriers), la production de fèces, la circulation d'eau dans les galeries... Toutes ces activités engendrent d'importantes modifications physico-chimiques, minéralogiques et biologiques dans le sédiment et conduisent notamment au développement de micro-environnements aérobies dans la zone globalement anaérobie du sédiment (*Jørgensen et Revsbech, 1985 ; Archer et al., 1989 ; Gundersen et Jørgensen, 1990 ; Jørgensen et Des Marais, 1990 ; Archer et Devol, 1992 ; Rasmussen et Jørgensen, 1992 ; Glud et al., 1993, 2003 ; Aller, 1998 ; Kristensen, 2000 ; Wenzhöfer et Glud, 2004*).

- La température : les variations de concentrations temporelles dans les eaux interstitielles sont principalement dues à la différence de température entre les eaux de fond et le sédiment de surface. Cette différence de température peut se traduire par un changement dans le taux de dégradabilité de la matière organique, dans l'activité métabolique, dans la diffusion des éléments et dans l'activité biologique (bioturbation). Dans les sédiments de surface, les gradients sont généralement plus marqués en été qu'en hiver. L'effet de la température sur l'intensité des processus biogéochimiques a été démontré dans les environnements côtiers, les marais salants et les lacs (*Thamdrup et al., 1998*).

- La dynamique de la DBL (Diffusive Boundary Layer) : la DBL constitue la fine couche d'eau au-dessus de l'interface eau-sédiment, généralement inférieure au millimètre, où le

---

<sup>9</sup> Matière organique réfractaire : le caractère réfractaire de la matière organique est déterminé par une forte fraction non hydrolysable. En effet la matière organique de provenance terrestre est essentiellement constituée de bipolymères difficilement dégradables (lignine, cutine, subérine et sporopollénine) provenant des tissus vasculaires des plantes, des boutures des feuilles, des racines ou encore des grains de pollen (*Bruland et al., 1989*). De plus, la partie bioassimilable par les organismes est progressivement dégradée au cours du transport vers l'océan.



transport diffusif<sup>10</sup> domine. L'épaisseur de la DBL est souvent associée à la microtopographie du sédiment (*Archer et al., 1989 ; Rasmussen et Jørgensen, 1992 ; Jørgensen et Boudreau, 2001 ; Røy et al., 2002 ; Oldham et al., 2004*).

Ces paramètres étant susceptibles de varier à l'échelle du jour à la saison, la dynamique du cycle benthique de l'oxygène s'exprime également à ces échelles de temps : l'oxygénation de l'eau de fond dans des régions peu profonde est en relation en partie avec la stratification des masses d'eau, elles mêmes liées à la température et donc à l'ensoleillement ; le dépôt de matériel organique dépend de l'intensité des blooms phytoplanctoniques printaniers et automnales. Enfin, l'activité benthique biologique (largement dépendante des apports de surface) dépend elle aussi des flux saisonniers et annuels, etc.

La distribution spatiale de l'oxygène, représentée par sa pénétration verticale dans les sédiments et l'hétérogénéité latérale entre les profils, est aussi directement ou indirectement liée aux variations spatiales des paramètres précédemment cités (Figure 1-3). Ainsi, des dépôts localisés de matière organique dans les sédiments peuvent engendrer une augmentation significative de la consommation en oxygène dissous et entraîner une diminution de la pénétration de l'oxygène. Une augmentation de l'épaisseur de la DBL crée une diminution de la pénétration de l'oxygène dans le sédiment (*Jørgensen et Revsbech, 1985*) et, par conséquent, peut avoir un impact sur la demande benthique en O<sub>2</sub>. Les diffusions latérales d'oxygène au travers de structures biologiques pourront également participer à cette hétérogénéité spatiale, ainsi que la quantité de produits réduits qui migrent vers la zone oxique. Cette hétérogénéité spatiale peut s'étendre sur une gamme très large d'échelles, variant du kilomètre (entre deux stations par exemple) au centimètre (entre deux profils lors d'un même déploiement).

---

<sup>10</sup> D'après *Crank, J. (1975)*: « Diffusion of solutes [...] is the process by which matter is transported from one point of the system to another as a result of random molecular motions ». Le transport diffusif d'un soluté est souvent défini comme étant un mouvement moléculaire ou ionique de la zone la plus concentrée vers la moins concentrée.

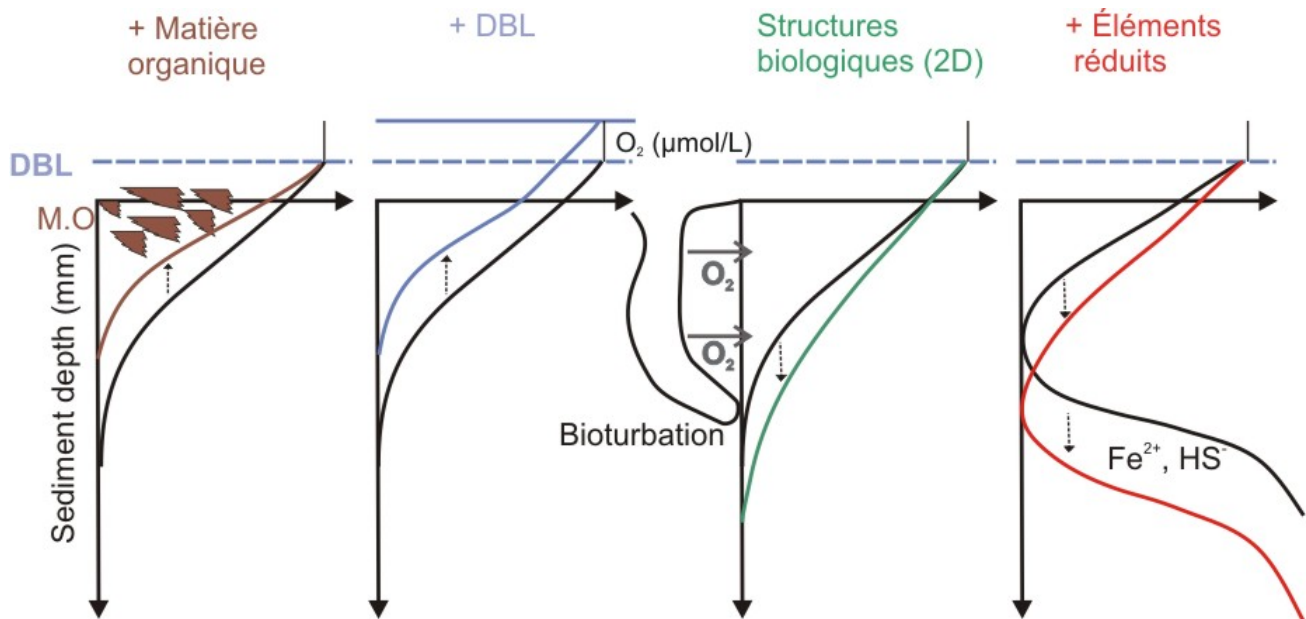


Figure 1-3. Variation de la distribution spatiale de l'oxygène dans les eaux interstitielles des sédiments, représentée par sa pénétration verticale et son hétérogénéité latérale, fonction de plusieurs facteurs : apport supplémentaire de matériel organique, augmentation de l'épaisseur de la DBL, présence de structure biologique, augmentation de l'apport de produits réduits vers la zone oxygène (Rabouille et al., 2003).

## 1.6 LES FORAMINIFÈRES BENTHIQUES : BIO-INDICATEURS D'EUTROPHISATION

### 1.6.1 Généralités

Les foraminifères benthiques sont des protozoaires rhizopodes de la classe des « Foraminifera », du règne des « Protoctista » et de l'embranchement des « Granuloreticulosa » étant apparus au Cambrien (Sen Gupta, 1999). Près de 2455 genres et 30000 espèces de foraminifères vivants et fossiles sont répertoriés actuellement. Le test (parfois baptisé coquille), comprenant une ou plusieurs chambres (ou loculis ou loges), est muni d'un ou plusieurs foramens (orifices). Leur taille varie généralement de 38  $\mu\text{m}$  à 1 mm. Leur régime alimentaire est constitué de bactéries, d'algues, de larves de mollusques, de crustacés et de déchets variés. Les tests des foraminifères benthiques peuvent être de nature organique, agglutinée (agglutinats de particules terrigènes ou biogènes), carbonatée (biocristaux de calcite ou d'aragonite biominéralisés par l'organisme) et même, mais très rarement, de nature siliceuse. Ces organismes possèdent un fort potentiel de fossilisation

dépendant principalement de leur nature propre ainsi que des conditions physico-chimiques du milieu sédimentaire dans lequel ils se sont enfouis. Les tests des foraminifères retrouvés dans les archives sédimentaires constituent ainsi un outil micropaléontologique majeur dans les reconstitutions paléoenvironnementales ainsi que dans l'établissement des échelles biostratigraphiques.

La morphologie du test constitue le principal critère de classification actuelle des foraminifères (*Loeblich et Tappan, 1988 ; Sen Gupta, 1999*). La composition et les microstructures du test sont de première importance pour classer les foraminifères en divers ordres. La composition chimique et les arrangements granulaires des biocristaux sont utilisés comme critères discriminants secondaires afin de définir et de distinguer les sous-ordres et les super-familles. Le mode d'addition des chambres d'habitation, la nature des cloisons et les ouvertures sont également pris en compte. Finalement, la forme et l'arrangement des chambres ainsi que la nature sessile ou vagile des organismes sont considérés (*Sen Gupta, 1999*). Dans la mesure où cette classification ne tient pas compte des analyses génétiques indispensables aujourd'hui pour classer les organismes vivants en espèces dites biologiques, les espèces de foraminifères actuellement répertoriées sont des espèces dites morphologiques, hiérarchisées dans une classification purement phénétique<sup>11</sup>. L'établissement d'une classification phylogénétique<sup>12</sup> des foraminifères (basée sur la reconnaissance de séquences de gènes) est en cours depuis quelques années (e.g. *Pawłowski, 2000 ; Pawłowski et al., 2002*) et tend à démontrer une diversité spécifique beaucoup plus grande que le laisse supposer la classification morphologique actuellement en vigueur, plus particulièrement pour les foraminifères planctoniques.

## 1.6.2 Biologie des foraminifères

Depuis une vingtaine d'années, la biologie des foraminifères est de plus en plus décrite. Les foraminifères présentent un corps constitué d'un cytoplasme<sup>13</sup> se différenciant en (1) un ectoplasme<sup>14</sup> concentré près des orifices qui parsèment le test; ce test étant considéré comme un squelette intra-cytoplasmique ; cet ectoplasme se ramifie en

---

<sup>11</sup> La phénétique repose sur le postulat de base que le degré de ressemblance est corrélé au degré de parenté. Elle suppose donc de quantifier la ressemblance entre les êtres vivants à classer.

<sup>12</sup> La phylogénie est l'étude de la formation et de l'évolution des organismes vivants en vue d'établir leur parenté.

<sup>13</sup> Le cytoplasme constitue la matière vivante à l'intérieur d'une cellule, à l'exclusion du noyau.

<sup>14</sup> L'ectoplasme est la zone externe du cytoplasme d'une cellule.

pseudopodes (0,5 mm de diamètre et parfois plus d'un centimètre de long ; *Murray, 2002*) et (2) un endoplasme, correspondant à la plus grande partie de la masse cytoplasmique à l'intérieur du test. Les foraminifères possèdent deux modes de croissance : une croissance continue aboutissant à des tests uniloculaires (monothalame) et une croissance discontinue aboutissant à des tests pluriloculaires (polythalame). La construction de nouvelles loges se fait à l'abri d'un kyste constitué de matériel exogène par l'animal (*Debenay et al., 2000*). Les foraminifères se nourrissent grâce à leurs pseudopodes (voir *Debenay et al., 1996 ; Goldstein, 1999*) ; les formes benthiques se nourrissent d'algues et de flagellés sur les fonds vaseux et boueux. Les formes planctoniques se nourrissent de larves de métazoaires et de copépodes préalablement transformés par des ferments. Certaines espèces de foraminifères benthiques présentent des relations endosymbiotiques<sup>15</sup> afin de s'affranchir des apports en carbone organique. Ces endosymbioses sont de plusieurs types, soit avec des algues (e.g. *Lee et al., 1995*), soit avec des bactéries (e.g. *Bernhard, 1996, 2003*). Toutefois, la grande majorité des foraminifères est hétérotrophe<sup>16</sup> et trouve essentiellement sa source de carbone dans la matière organique, suivant plusieurs modes, dont ceux qui suivent : herbivore, détritivore, carnivore, cannibalisme, parasitisme, assimilation de la matière dissoute et omnivore (*Debenay et al., 1996*). Grâce à leurs pseudopodes, les foraminifères se déplacent lentement de 0,01 à 0,5 mm par minute (*Kitazato, 1988 ; Wetmore, 1988*).

Le cycle de vie des foraminifères benthiques a été étudié pour 30 espèces environ (*Lee et al., 1991 ; Goldstein, 1999*). Le schéma basique de reproduction consiste en une alternance entre phases sexuée et asexuée pour donner naissance à des individus qui sont libérés par l'abandon ou la dissolution des tests maternels (*Murray et al., 2006*). Dans le cas des espèces chez lesquelles l'alternation des générations est obligatoire (ex : *Elphidium crispum*), la reproduction dans l'agamonte<sup>17</sup> se fait par une méiose<sup>18</sup> donnant lieu à des individus mononucléaires<sup>19</sup> haploïdes<sup>20</sup>. Les gamontes<sup>21</sup> produisent des gamètes qui forment des

---

<sup>15</sup> Les relations endosymbiotiques sont les relations définissant une espèce vivant à l'intérieur d'une espèce hôte et tirant sa substance de son association avec l'hôte.

<sup>16</sup> Un organisme hétérotrophe est un organisme qui est incapable de produire ses propres molécules organiques et doit donc les puiser chez les êtres autotrophes.

<sup>17</sup> Agamonte : individu asexué chez les foraminifères

<sup>18</sup> Méiose : processus de division cellulaire en deux étapes qui, d'une cellule diploïde (à 46 chromosomes), aboutit à la formation de deux cellules haploïdes (à 23 chromosomes).

<sup>19</sup> Mononucléaire : adjectif désignant une cellule qui ne possède qu'un seul noyau.

<sup>20</sup> Haploïde : qualifie tout organisme (individu ou cellule) comportant un seul génome, un seul ensemble de chromosomes, symbolisé par la lettre n

<sup>21</sup> Gamonte : nom donné aux cellules spéciales sexuées.

zygotes<sup>22</sup> et croissent dans des agamontes (Fig. 1-4, flèches pleines). Dans certains cas, où le cycle de vie consiste en une alternance facultative de générations, des successions de cycles asexués ont lieu (reproduction par de multiples fissions comme chez *Ammonia tepida*). L'agamonte commence en étant un zygote diploïde. Celui-ci peut subir une méiose et une fission multiples pour former des juvéniles haploïdes qui vont croître dans des gamontes mononucléaires ; ou peut subir une multiple fission pour produire plusieurs générations asexuées successives (Fig. 1-4, flèches en tireté). Une autre stratégie consiste à sauter une génération (apogamie). La taille du proloculus<sup>23</sup> varie entre les générations. Dans la reproduction sexuée, il y a juste une fusion entre deux gamètes (proloculus microsphérique) tandis que dans la reproduction asexuée, les juvéniles héritent d'un noyau ainsi que d'une partie du cytoplasme parental (proloculus mégalosphérique) (*Murray et al., 2006*). Le foraminifère meurt en se reproduisant.

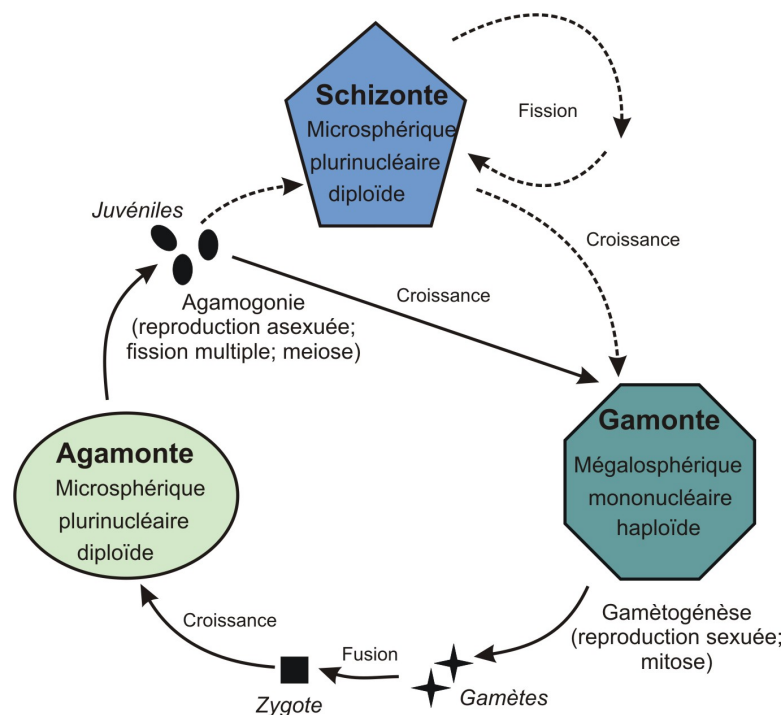


Figure 1-4. Représentation schématisée du cycle de vie classique (alternance de générations) des foraminifères benthiques (dans Murray, 2006 ; basé sur Lee et al., 1991 et Goldstein, 1999). Les flèches pleines : cycle basique ; flèches en tireté : fission multiple alternative.

<sup>22</sup> Zygote : cellule formée par la fusion sexuelle de deux gamètes.

<sup>23</sup> Proloculus : nom donné à la Loge initiale chez les foraminifères.

### 1.6.3 Écologie des foraminifères benthiques

#### 1.6.3.1 Distribution spatiale des foraminifères benthiques

La grande majorité des foraminifères possède une vie marine ; 95% de ces organismes ont une vie benthique. Les premières études écologiques ont porté l'accent sur une répartition bathymétrique des faunes de foraminifères benthiques (e.g. *Williamson, 1858 ; Brady, 1884*). Toutefois, lorsque ce paramètre est devenu insuffisant pour expliquer les répartitions faunistiques, les facteurs physico-chimiques sont apparus plus révélateurs des variations spatiales (e.g. *Pujos, 1972, 1976 ; Streeter, 1973 ; Schnitker, 1974, 1980 ; Blanc-Vernet, 1988*). Plus récemment, il apparaît que l'abondance et la distribution des foraminifères benthiques, en milieu marin profond, sont en majorité contrôlées par deux paramètres intimement liés :

- L'oxygène : l'oxygène est un élément essentiel contrôlant la vie ainsi que la biodiversité des foraminifères benthiques. En général, dans les bassins fermés tels que les étangs, les lagunes ou les marais salants, la richesse spécifique diminue et seulement certaines espèces résistantes à ce stress environnemental peuvent subsister temporairement. Toutefois, il semble que l'oxygénation des eaux de fond ne deviendrait un facteur limitant qu'à des valeurs inférieures à 1 ml.l<sup>-1</sup> (e.g. *Sen Gupta et Machain-Castillo, 1993 ; Gooday, 1994 ; Jorissen et al., 1995 ; Gooday et al., 2000*).

- La matière organique : les foraminifères benthiques semblent constituer un maillon important des chaînes trophiques des écosystèmes benthiques en participant amplement à la fixation et au recyclage du carbone, de l'azote ou du phosphore issus de la matière organique détritique (e.g. *Altenbach et Sarnthein, 1989 ; Gooday et al., 1992 ; Moodley et al., 2000, 2002*). À ce titre, il est généralement suggéré que la composition, la densité et les microhabitats des communautés de foraminifères benthiques sont influencés par la qualité de la matière organique exportée au sédiment (e.g. *Altenbach et Sarnthein, 1989 ; Corliss et Emerson, 1990 ; Corliss, 1991 ; Herguera and Berger, 1991 ; Rathburn and Corliss, 1994 ; Jorissen et al., 1995, Jorissen et al., 1998, De Rijk et al., 2000 ; Licari et al., 2003*).

D'autres facteurs physico-chimiques participent à la distribution spatiale des foraminifères benthiques, particulièrement en milieu côtier :

- Le pH : ce paramètre intervient dans la constitution des tests et donc dans la distribution des formes agglutinées ou calcitiques ; les tests agglutinés étant plus résistants aux pH acides (e.g *Murray, 1989*). *Boltovskoy and Wright (1976)* ont observé que la dissolution des tests calcaires commençait à partir d'un pH de 7,8. Toutefois, ces auteurs n'ont ni spécifié quelles espèces ont été les plus affectées ni s'il s'agissait de faunes mortes ou vivantes. Il est probable qu'en fonction des espèces, la limite critique du pH change et que les espèces vivantes sont moins facilement attaquées dû à la présence d'un cytoplasme. Par exemple, *Shafer (1970)* a observé des espèces d'*Elphidium* vivant à un pH de 6,7.

- La teneur en  $\text{CaCO}_3$  : de cette teneur va dépendre évidemment la constitution des tests calcitiques ou aragonitiques.

- La salinité : les foraminifères benthiques sont retrouvés dans des eaux saumâtres à hyposalines (0-33), euhalines ou marines normales (33-37) ou dans des eaux hypersalines (> 37). Les organismes qui sont confinés dans des eaux de salinité normale sont dits sténohalins. Ceux qui sont tolérants aux eaux saumâtres ou hypersalines sont dits euryhalins. Le rayon de salinité toléré par les foraminifères est large allant des eaux douces aux eaux fortement hypersalines (0 à ~ 70) (*Murray, 2006*). La salinité influence les organismes principalement à travers l'osmose<sup>24</sup> cellulaire. Néanmoins, une réponse à un changement de salinité peut dépendre de la température puisque l'osmorégulation<sup>25</sup>, la viscosité de l'eau et la dissolution de l'oxygène sont influencés par ces deux facteurs. En dessous d'une salinité de 10-12, une cellule peut s'arrêter de fonctionner sauf si l'organisme maintient une importante composition ionique interne à travers l'osmorégulation (*McLusky et Elliott, 2004*). C'est pourquoi, la majorité des espèces ainsi que les plus fortes biodiversités sont rencontrées dans les eaux de salinité normale (33-37). Vers les salinités extrêmes, la diversité et le nombre d'espèces diminuent progressivement (*Murray, 2006*).

---

<sup>24</sup> L'osmose désigne le phénomène de diffusion des molécules d'un solvant (l'eau de façon générale) à travers une membrane semi-perméable qui sépare deux liquides de concentrations en soluté différentes.

<sup>25</sup> L'osmorégulation est la régulation de la concentration en sels dissouts dans les fluides internes d'un être vivant aquatique.

- La température : les foraminifères benthiques sont retrouvés dans les eaux polaires, tempérées, tropicales ou chaudes. Les organismes qui sont confinés dans des eaux à température restreinte sont dits sténothermes. Ceux qui sont tolérants à un large éventail de températures sont dits eurythermes. La température limite supérieure de tolérance des foraminifères benthiques marins est autour de 45 °C (*Murray, 2006*).

- L'hydrodynamisme : les marées introduisent une énergie physique dans l'environnement marin. En effet, les conditions mesotidales<sup>26</sup> et macrotidales<sup>27</sup> créent des forts courants de marée. Dans les environnements marins côtiers, il existe fréquemment des grandes variations de marées diurnes induisant des modifications de salinités. Toutefois, les variations de température sont minimales. Ceci est dû au fait que les masses d'eaux sont constamment en mouvement. *Haynesina germanica*, à titre d'exemple, est une espèce qui tolère ces conditions. Les courants génèrent des déplacements horizontaux qui sont de grande importance pour l'oxygénation de l'eau de fond ainsi que pour le transfert de la matière organique. Une forte courantologie crée une perturbation physique dans le milieu en balayant le sédiment. Ce phénomène est dépendant de la taille des grains. Dans ces environnements à forte courantologie, vit généralement une épifaune<sup>28</sup> attachée au substrat (*Murray, 2006*).

### 1.6.3.2 Microhabitat

Le microhabitat désigne la répartition dans le sédiment des foraminifères benthiques. Il est généralement étudié jusqu'à dix centimètres de profondeur. Cette répartition est directement liée aux conditions physico-chimiques du sédiment (e.g. *Corliss, 1985*) et à l'activité biologique. Deux types d'espèces sont rencontrées ; les formes épipéliques vivant sur la surface du sédiment et les formes endopéliques vivant dans le sédiment. Cette répartition est directement liée au flux de matière organique et à l'oxygénation (e.g. *Shirayama, 1984 ; Corliss et Emerson, 1990*), bien que d'autres facteurs comme la compétition interspécifique, peuvent également intervenir dans cette répartition (*Goody, 1986*). Un modèle, nommé TROX (TRophic et OXYgen), explique cette distribution en fonction de ces paramètres (Figure 1-5 ; *Jorissen, et al., 1995*). Ainsi, selon ce modèle

---

<sup>26</sup> Mesotidale : se dit des marées dont l'amplitude est de 1 à 5 m.

<sup>27</sup> Macrotidale : se dit des grosses marées dont l'amplitude est supérieure à 5 m.

<sup>28</sup> Epifaune : faune vivant à la surface du sédiment.



conceptuel, la profondeur de pénétration de l'oxygène contrôle la profondeur de vie des organismes, et en présence d'oxygène en profondeur, la distribution des organismes est déterminée par la disponibilité en nourriture. C'est-à-dire qu'en milieu oligotrophe<sup>29</sup>, la matière organique labile est rapidement métabolisée en surface et le sédiment est bien oxygéné en profondeur. Ces milieux limités en nourriture sont caractérisés par des espèces épipéliques et endopéliques superficielles alors que les espèces endopéliques plus profondes sont rares. En milieu eutrophe<sup>30</sup>, le flux de matière organique et la consommation d'oxygène sont importants. Ainsi la déplétion d'oxygène se fait directement sous l'interface eau-sédiment, et les faunes sont dominées en surface par des espèces endopéliques (intermédiaires et profondes) tolérantes à de très faibles teneurs en oxygène. Les conditions mésotrophes sont situées entre les conditions oligotrophes et eutrophes, ce qui correspond à une profondeur maximale de vie des foraminifères dans le sédiment.

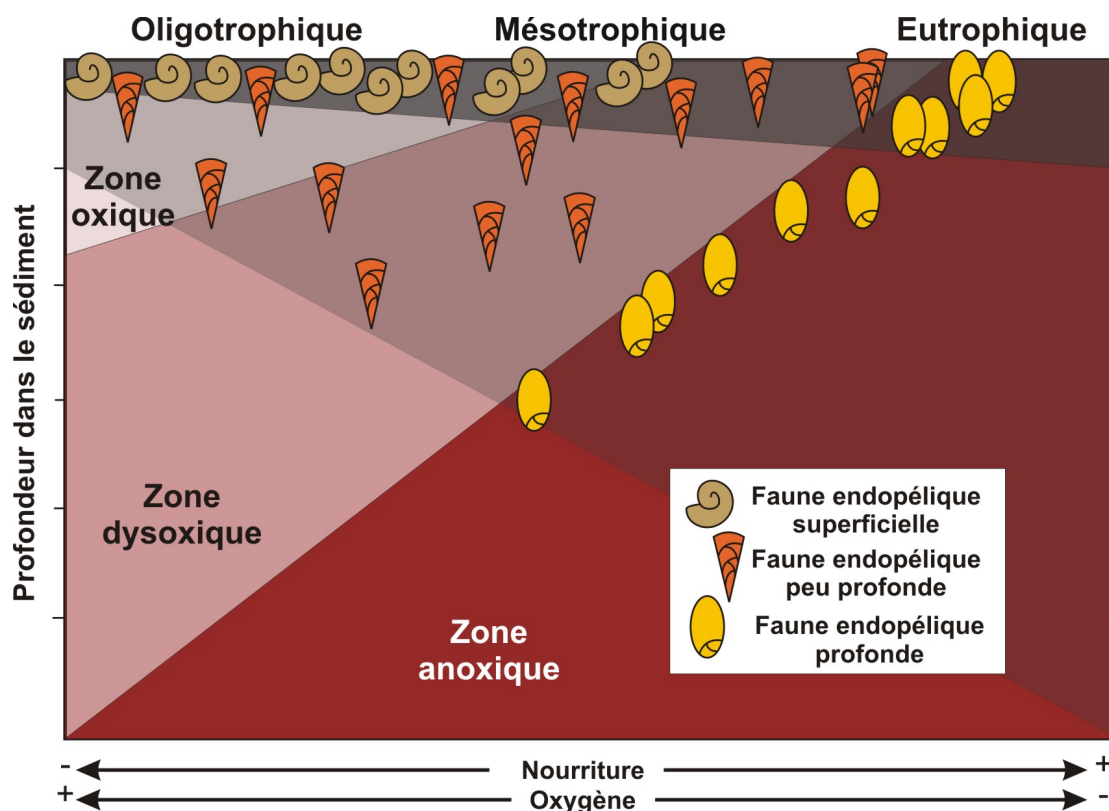


Figure 1-5. Modèle de microhabitat en fonction de la profondeur de la zone oxique et de l'abondance de la matière organique (Jorissen et al., 1995 ; De Stigter, 1996).

<sup>29</sup> Oligotrophe : qualificatif se rapportant à une masse d'eau pauvre en matières nutritives.

<sup>30</sup> Eutrophe : se dit des eaux riches en matières nutritives mais également des eaux soumises à d'importants apports en matière organique continentale

#### 1.6.4 Les foraminifères benthiques en tant que bio-indicateurs

Les foraminifères font partie des protistes les plus abondants dans les environnements marins benthiques (Murray, 1991). Omniprésents dans le milieu marin, les foraminifères benthiques occupent de très nombreuses niches écologiques aussi variées que les plaines abyssales oligotrophes, les zones de résurgence hydrothermales et les zones lagunaires hypersalines (Murray, 1970 ; Coull et al., 1977 ; Steineck et Bergstein, 1979 ; Debenay, 1990 ; Sen Gupta et Aharon, 1994), et ont également colonisés certains environnements d'eaux saumâtres et d'eaux douces (Pawlowski, 2000). Du fait de leur court cycle de vie (1 à 3 mois en moyenne, 1 an maximum, Murray, 1991), de leur forte biodiversité et des demandes écologiques spécifiques à chaque espèce, les foraminifères réagissent rapidement au stress environnemental et peuvent être utilisés efficacement comme bio-indicateurs de changement de leur environnement, comme celui provoqué par une pollution anthropique (comme défini par Kramer et Botterweg, 1991). Les assemblages de foraminifères sont faciles à collecter ; les foraminifères sont abondants dans les sédiments marins, permettant d'obtenir des analyses statistiques solides à partir d'un petit volume de sédiment. De plus, beaucoup de taxons secrètent une coquille calcaire laissant ainsi un excellent enregistrement fossile qui permet de revenir aux conditions antérieures à la modification du milieu (Alve, 1995). Ces caractéristiques font des foraminifères, en particulier benthiques, d'excellents bio-indicateurs de la qualité de l'environnement ou proxies des changements environnementaux.

Les études concernant les effets de la pollution sur les assemblages des foraminifères benthiques et leur utilisation possible en tant qu'indicateurs de pollution, ont été initiées dans les années 60 par Resig (1960) et Watkins (1961). Durant la dernière décennie, les foraminifères ont été utilisés, de manière plus importante, pour des suivis de pollution dans divers environnements marins, comme au niveau des estuaires affectés par une pollution organique (Alve, 1995), des vasières intertidales affectées par les marées noires (e.g. Morvan et al., 2004, 2006), les eaux portuaires affectées par une forte pollution en métaux lourds (Armynot Du Châtelet et al., 2004), les plateaux continentaux externes dans l'Atlantique Est impactés par les dépôts des débris de forages pétroliers (Durrieu et al., 2006 ; Mojtahid et al., 2006) ou encore au niveau des plateaux continentaux eutrophiés (Sharifi et al., 1991 ; Yanko and Flexer, 1991 ; Platon et al., 2005).

Alve (1995) a proposé un modèle simplifié des changements faunistiques des foraminifères benthiques après la mise en place d'une pollution organique (Fig. 1-6). Ce modèle propose une division des faunes en trois groupes : faune de pré-pollution (espèces

« naturelles ») ; faune transitoire et faune opportuniste. La faune « naturelle » a une faible tolérance à la pollution et meurt aussitôt que la pollution croît. La faune transitoire peut montrer une augmentation temporaire en réponse à un degré intermédiaire de pollution organique. Les espèces opportunistes sont capables de répondre rapidement aux conditions d'enrichissement organique qui sont beaucoup moins tolérées par les autres groupes faunistiques. Quand la pollution montre un degré maximale, la faune disparaît complètement. La biodiversité décroît également avec un gradient croissant de pollution.

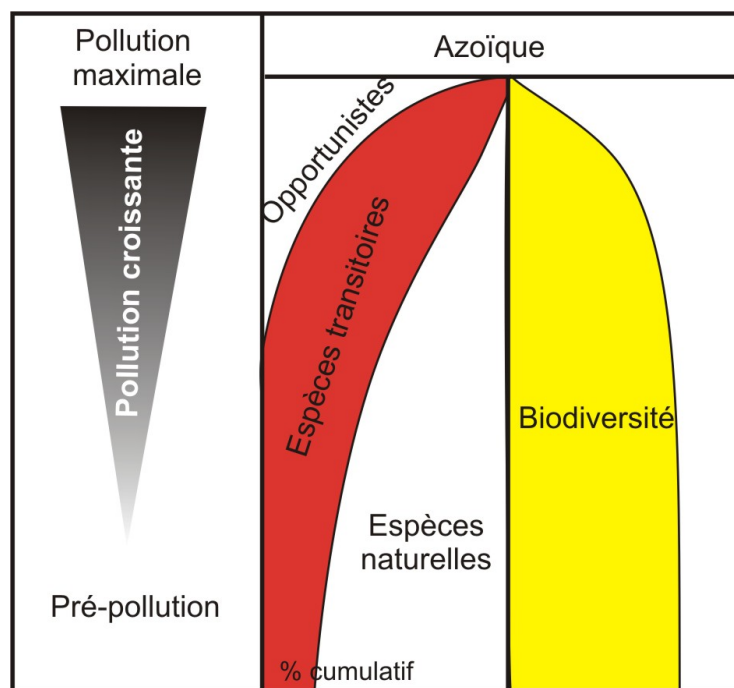


Figure 1-6. Modèle de réponse des foraminifères benthiques à l'augmentation d'une pollution organique (d'après Alve, 1995).

## 1.7 LA MACROFAUNE BENTHIQUE : BIO-INDICATEURS D'EUTROPHISATION

Une perturbation d'origine anthropique des écosystèmes marins peut être évaluée directement par des paramètres physiques et chimiques (*Daskalakis et O' Connor, 1995*), ou indirectement en utilisant la faune benthique qui reflète la qualité écologique de son habitat. Dans le paragraphe précédent, nous avons vu l'utilisation des foraminifères benthiques en tant que bio-indicateurs d'une perturbation environnementale. Dans le même registre, la

macrofaune benthique a été largement utilisée (*Pearson et Rosenberg, 1978 ; Lindegarth et Hoskin, 2001 ; Cruz-Motta et Collins, 2004 ; Currie et Isaacs, 2005*). Les espèces macrobenthiques présentent un intérêt particulier dans ce contexte du fait que : (1) la majorité de la macrofaune benthique est sessile ou a une mobilité limitée (*Olsgard et Gray, 1995 ; Rosenberg, 2001*) ; elle est ainsi directement liée aux conditions environnementales, et (2) la macrofaune montre des réponses marquées aux changements environnementaux selon leurs niveaux de sensibilité et de tolérance spécifiques à chaque espèce (*Ferraro et Cole, 1995 ; Paiva, 2001 ; Mendez, 2002 ; Lancellotti et Stotz, 2004*). Tout ceci a fait que l'analyse de la composition et de la structure des peuplements de la macrofaune fait partie des normes internationales pour l'évaluation de la santé d'un écosystème marin, tel que « European Union Water Framework Directive » (*Borja et al., 2003 ; Rosenberg et al., 2004*).

Les changements spatio-temporels des communautés macrobenthiques le long d'un gradient d'enrichissement organique sont inscrits dans un modèle typique de succession des cortèges faunistiques initialement décrit par *Pearson et Rosenberg (1978)* et adopté par la suite par de nombreux auteurs (e.g, *Zmarzly et al., 1994 ; Trueblood et al., 1994 ; Glémarec et Hily, 1981 ; Nilsson et Rosenberg, 2000 ; Rosenberg, 2001 ; Bolam et al., 2004*). Selon ce modèle, la richesse et la densité d'espèces macrobenthiques diminuent progressivement avec l'augmentation de l'enrichissement organique. Néanmoins, certaines espèces du macrobenthos peuvent également montrer, dans les premières étapes de la succession faunistique, des pics d'abondance dus à la prolifération d'espèces opportunistes. D'un point de vue qualitatif, toute la séquence de la succession est caractérisée par le passage de la dominance d'une faune sensible à une faune tolérante (*Pearson et Rosenberg, 1978 ; Grall et Glémarec, 1997 ; Karlson et al., 2002*). Les groupes taxonomiques étant plus ou moins sensibles à la pollution organique, il est possible d'établir un classement des espèces en groupes écologiques<sup>31</sup> suivant leur sensibilité à la teneur en matière organique (Fig. 1-7). Par exemple, les amphipodes<sup>32</sup> et les cumacés<sup>33</sup> sont connus dans la littérature pour être des organismes sensibles à l'enrichissement du sédiment en matière organique (*Geisteira et Dauvin, 2000 ;*

---

<sup>31</sup> *Glémarec et Hily (1981)* ont caractérisé, selon leur degré de résistance aux pollutions organiques, 5 groupes écologiques (I : espèces sensibles ; II : indifférentes ; III : tolérantes ; IV : opportunistes et V : indicatrices de pollution)

<sup>32</sup> Amphipodes : petits crustacés (taille adulte maximum 1 cm), au corps aplati latéralement et allongé.

<sup>33</sup> Cumacés : petits crustacés ayant l'avant du corps renflé, l'abdomen long, grêle et mobile, vivant enfoui au fond des mers à toutes les profondeurs, rarement en eau douce

Grall et Glémarec, 2003 ; Dauvin et Ruellet, 2007) contrairement aux annélides polychètes<sup>34</sup> comme les *Cirratulidea*, les *Capitellidae* et les *Spionidae* qui sont des organismes très résistants à la pollution organique et peuvent montrer un comportement opportuniste en réponse à cet important enrichissement du milieu en matière organique (Pearson et Rosenberg, 1978 ; Hily et al., 1986 ; Rosenberg, 2001).

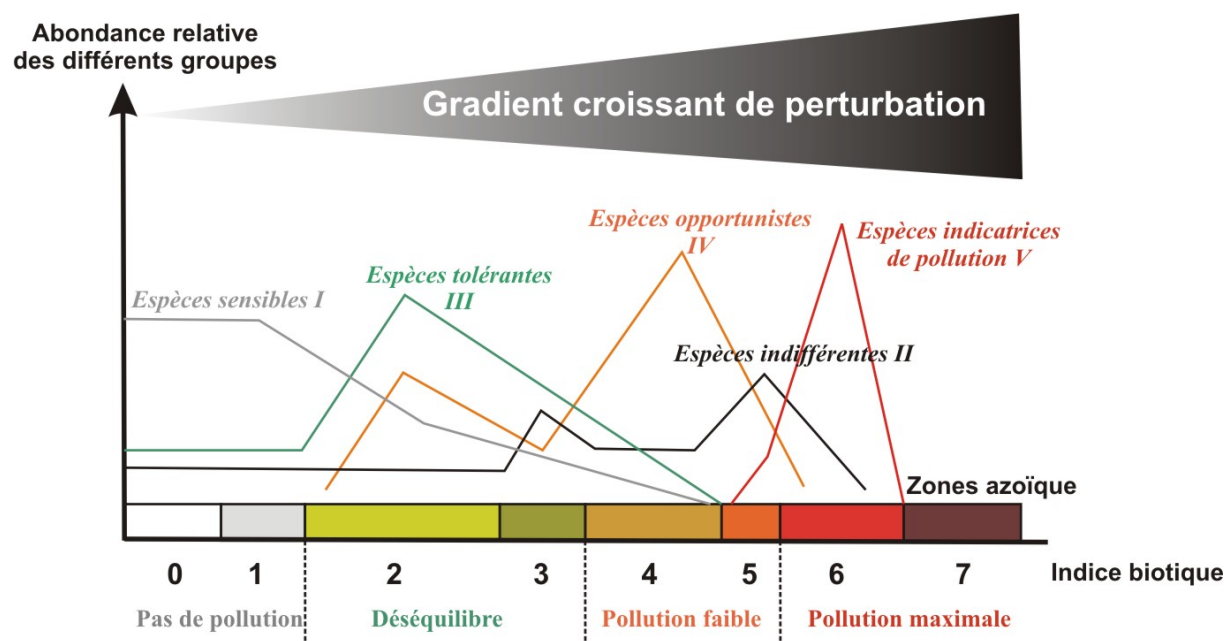


Figure 1-7. Modèle de succession faunistique du macrobenthos avec les indices biotiques le long d'un gradient d'enrichissement organique (d'après Glémarec et Hily, 1981).

## 1.8 RÉFÉRENCES

Aller, R.C., 1998. Benthic fauna and biogeochemical processes in marine sediments: The role of burrow structures. In: T.H. Blackburn and J. Sørensen (Ed.), Nitrogen cycling in coastal marine environments. Wiley, pp. 301-338.

Altenbach, A.V. et Sarntheim, M., 1989. Productivity record in benthic foraminifera. In: Berger, W.H., Smetacek, V.S. and Wefer, G. (Editors), Productivity of the ocean: present and past. John Wiley, Chichester, pp. 255-269.

<sup>34</sup> Annélides polychètes : Les annélides sont des animaux segmentés (possédant des métamères quelquefois très nombreux) et en forme de « ver ». Les polychètes sont des annélides dont les segments portent des expansions latérales (parapodes) sur lesquelles sont insérées des soies chitineuses plus ou moins nombreuses et complexes.

- Alve, E., 1991. Benthic foraminifera in sediment cores reflecting heavy metal pollution in Sørø jord, western Norway. *Journal of Foraminiferal Research*, 21, 1-19.
- Alve, E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. *Journal of Foraminiferal Research*, 25, 190-203.
- Anschutz, P., Sundby, B., Lefrançois, L., Luther III, G.W. et Mucci, A., 2000. Interactions between metal oxides and species of nitrogen and iodine in bioturbated marine sediments. *Geochimica et Cosmochimica Acta*, 64, 2751-2763.
- Archer, D. et Devol, A., 1992. Benthic oxygen fluxes on the Washington shelf and slope: a comparison of in situ microelectrode and chamber flux measurements. *Limnology and Oceanography*, 37, 614-629.
- Archer, D., Emerson, S. et Smith, C.R., 1989. Direct measurement of the diffusive sublayer at the deep sea floor using oxygen microelectrodes. *Nature*, 340, 623-626.
- Armynot du Châtelet, E., Debenay, J.P. et Soulard, R., 2004. Foraminiferal proxies for pollution monitoring in moderately polluted harbours. *Environmental Pollution*, 127, 27-40.
- Azam, F., Fenchel, T., Field, J.G., Gray, J.S., Meyer-Reil, L.-A. et Thingstad, F., 1983. The ecological role of water-column microbes in the sea. *Marine Ecology Progress Series*, 10, 257-263.
- Barranguet, C., Alliot, E. et Plante-Cuny, M.-R., 1994. Benthic microphytic activity at two Mediterranean shellfish cultivation sites with reference to benthic fluxes. *Oceanologica Acta*, 17, 211-221.
- Barranguet, C., Plante-Cuny, M.R. et Alivon, E., 1996. Microphytobenthos production in the Gulf of Fos, French Mediterranean coast. *Hydrobiologia*, 333, 181-193.
- Bay, D., 1984. A field study of the growth dynamics and productivity of *Posidonia oceanica* (L.) delile in Calvi Bay, Corsica. *Aquatic Botany*, 20, 43-64.
- Berner, R.A., 1980. *Early Diagenesis : A theoretical Approach*. Princeton University Press, 241 pp.
- Bernhard, J.M., 1996. Microaerophilic and facultative anaerobic benthic foraminifera: A review of experimental and ultrastructural evidence. *Revue de Paléobiologie*, 15, 261-275.
- Bernhard, J.M., 2003. Potential symbionts in bathyal foraminifera. *Science*, 299, 861.
- Blanc-Vernet, L., 1988. Répartition bathymétrique des foraminifères benthiques sur la plate-forme continentale. *Géologie Méditerranéenne*, 15, 5-12.
- Bolam, S.G., Whomersley, P. et Schratzberger, M., 2004. Macrofaunal recolonization on intertidal mudflats: effect of sediment organic and sand content. *Journal of Experimental Marine Biology and Ecology*, 306, 157-180.
- Boltowskoy, E. et Wright, R., 1976. *Recent foraminifera: Dr. W. Junk b.v., The Hague*, 515 pp.
- Borja, A., Muxika, I. et Franco, J., 2003. The application of a Marine Biotic Index to different impact sources affecting soft-bottom benthic communities along European coasts. *Marine Pollution Bulletin*, 46, 835-845.

Boudreau, B.P., Mucci, A., Sundby, B., Luther III, G.W. et Silverberg, N., 1998. Comparative diagenesis at three sites on the Canadian continental margin. *Journal of Marine Research*, 56, 1259-1284.

Bourdillon, C., 1995. Les foraminifères benthiques (protozoaires) comme bioindicateurs de pollution en milieu littoral : le point des connaissances actuelles, ANPP - Colloque International - Marqueurs Biologiques de Pollution, Chinon, France, pp. 1-9.

Brady, H.B., 1884. Report on the foraminifer dredged by H.M.S. Challenger during the years 1873-1876. Report of the scientific results of the voyage of H.M.S. Challenger, 1873-1876, *Zoology*, 9, London, England, 814 pp.

Bruland, K.W., Beinfang, P.K., Bishop, J.K., Eglinton, G., Ittekkot, V.A.W., Lampitt, R., Sarnthein, M., Theide, J., Walsh, J.J et Wefer, G., 1989. Flux to the sea floor. In Berger, W. H. et al. (editors), *Productivity of the Oceans: Present and Past*. Wiley, New York, 193-215.

Buckley, D.E. et Cranston, R.E., 1988. Early diagenesis in deep sea turbidites: The imprint of paleo-oxidation zones. *Geochimica and Cosmochimica Acta*, 52, 2925-2939.

Cai, W.-J. et Reimers, C.E., 1995. Benthic oxygen flux, bottom water oxygen concentration and core top organic carbon content in the deep northeast Pacific Ocean. *Deep Sea Research Part I: Oceanographic Research Papers*, 42, 1681-1699.

Canfield, D.E., 1994. Factors influencing organic carbon preservation in marine sediments. *Chemical Geology*, 114, 315-329.

Canfield, D.E., Jørgensen, B.B., Fossing, H., Glud, R.N., Gundersen, J.K., Ramsing, N.B., Thamdrup, B., Hansen, J.W., Nielsen, L.P. et Hall, P.O.J., 1993. Pathways of organic carbon oxidation in three continental margin sediments. *Marine Geology*, 113, 27-40.

Colley, S., Thomson, J., Wilson, T.R.S. et Higgs, N.C., 1984. Post-depositionnal migration of elements during diagenesis in brown clay and turbidite sequences in the North East Atlantic. *Geochimica and Cosmochimica Acta*, 48, 1287-1296.

Corliss, B.H., 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*, 314, 435-438.

Corliss, B.H., 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. *Marine Micropaleontology*, 17, 195-236.

Corliss, B.H. et Emerson, S., 1990. Distribution of Rose Bengal stained deep-sea benthic foraminifera from the Nova Scotia continental margin and Gulf of Maine. *Deep-Sea Research*, 37, 381-400.

Coull, B.C., Ellison, R.L., Fleeger, J.W., Higgins, R.P., Hope, W.D., Hummon, W.D., Rieger, R.M., Sterrer, W.E., Thiel, H. et Tietjen, J.H., 1977. Quantitative estimates of the meiofauna from the deep sea off North Carolina, USA. *Marine Biology*, 39, 233-240.

Cruz-Motta, J.J. et Collins, J., 2004. Impacts of dredged material disposal on a tropical soft-bottom benthic assemblage. *Marine Pollution Bulletin*, 48, 270-280.

Currie, D.R. et Isaacs, L.R., 2005. Impact of exploratory offshore drilling on benthic communities in the Minerva gas field, Port Campbell, Australia. *Marine Environmental Research*, 59, 217-233.

Daskalakis, K.D. et O'Connor, T.P., 1995. Normalisation and elemental sediment contamination in the coastal United States. *Environmental Sciences and Technology*, 29, 470-477.

Dauvin, J.-C. et Ruellet, T., 2007. Polychaete/amphipod ratio revisited. *Marine pollution bulletin*, 55, 215-224.

De Lange, G.J., 1986. Early diagenetic reactions in interbedded pelagic and turbiditic sediments in the Nares Abyssal Plain (western North Atlantic): Consequences for the composition of sediment and interstitial water. *Geochimica and Cosmochimica Acta*, 50, 2543-2561.

De Rijk, S., Jorissen, F.J., Rohling, E.J. et Troelstra, S.R., 2000. Organic flux control on bathymetric zonation of Mediterranean benthic foraminifera. *Marine Micropaleontology*, 40, 151-166.

De Stigter, H.C., 1996. Recent and fossil foraminifera in the Adriatic Sea: distribution patterns in relation to organic carbon flux and oxygen concentration at the seabed, *Geologica Ultraiectina*, 254 pp.

Debenay, J.P., 1990. Recent foraminiferal assemblages and their distribution relative to environmental stress in the paralic environments of west Africa (Cape Timiris to Ebrie Lagoon). *Journal of Foraminiferal Research*, 20, 267-282.

Debenay, J.P., Pawlowski, J. et Decrouez, D., 1996. *Les foraminifères actuels*. Masson, Paris, 329 pp.

Debenay, J.P., Guillou, J.J., Geslin, E. et Lesouard, M., 2000. Crystallization of calcite in foraminiferal tests. *Micropaleontology*, 46, 87-94.

Diaz R. J., Rosenberg R., Ansell A. D., Gibson R. N. et Barnes M. 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology Annual Review*, 33, 245-303.

Durrieu, J., Mojtahid, M., Cazes, L., Galgani, F., Jorissen, F. et Camps, R., 2006. Aged Drilled Cuttings Offshore Gabon, New methodology for assessing their impact. Vol. 98414. Society of Petroleum Engineers Inc. SPE, Abu Dhabi. 8 pp.

Etcheber, H., Relexans, J.C., Beliard, M., Weber, O., Buscail, R. et Heussner, S., 1999. Distribution and quality of sedimentary organic matter on the Aquitanian margin (Bay of Biscay). *Deep-Sea Research II*, 46, 2249-2288.

Fenchel, T. et Glud, R.N., 2000. Benthic primary production and O<sub>2</sub>-CO<sub>2</sub> dynamics in a shallow-water sediment: spatial and temporal heterogeneity. *Ophelia*, 53, 159-171.

Ferraro, S.P. et Cole, F.A., 1995. Taxonomic level sufficient for assessing pollution impacts on the Southern California bight macrobenthos—revisited. *Environmental Toxicology and Chemistry*, 14, 1031-1040.

Fontanier, C., 2003. *Ecologie des foraminifères benthiques du Golfe de Gascogne : Etudes de la variabilité spatiale et temporelle des faunes de foraminifères benthiques et de la composition isotopique ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) de leurs tests*. Thèse de doctorat obtenue à l'université de Bordeaux I en 2003, 471 pp.



Froelich, P.N., Klinkhammer, G.P., Bender, M.L., Luedtke, N.A., Heath, G.R., Cullen, D., Dauphin, P., Hammond, D., Hartman, B. and Maynard, V., 1979. Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: Suboxic diagenesis. *Geochimica et Cosmochimica Acta*, 43, 1075-1090.

Geisteira, J.L.G. et Dauvin, J.-C., 2000. Amphipods are good bioindicators of the impact of oil spills on soft-bottom macrobenthic communities. *Marine Pollution Journal*, 40, 1017-1027.

Gibbs, R.J., 1981. Sites of river derived sedimentation in the ocean. *Geology*, 9, 77-80.

Glémarec, M. et Hily, C., 1981. Perturbations apportées à la macrofaune benthique de la Baie de Concarneau par les affluents urbains et portuaires. *Acta Oecologica, Oecologica Applicata*, 2, 139-150.

Glud, R.N., Gundersen, J.K., Revsbech, N.P. and Jørgensen, B.B., 1993. In situ measurements of total and diffusive oxygen uptake of sediments. In: R. Guerrero and C. Pedros-Alio (Ed.), *Trends in Microbial Ecology*. pp. 427-430.

Glud, R.N., Gundersen, J.K., Røy, H. and Jørgensen, B.B., 2003. Seasonal dynamics of benthic O<sub>2</sub> uptake in a semienclosed bay: Importance of diffusion and faunal activity. *Limnology and Oceanography*, 48, 1265-1276.

Gobeil, C., Macdonald, R.W. and Sundby, B., 1997. Diagenetic separation of cadmium and manganese in suboxic continental margin sediments. *Geochimica et Cosmochimica Acta*, 61, 4647-4654.

Goldstein, S.T., 1999. Foraminifera: A biological Overview. In: B.K. Sen Gupta (Editor), *Modern Foraminifera*. Kluwer Academic Publisher, pp. 37-55.

Gooday, A.J., 1986. Meiofaunal foraminiferans from the bathyal Porcupine Seabight (northeast Atlantic): size structure, standing stock, taxonomy composition, species diversity and vertical distribution in the sediment. *Deep Sea Research*, 33, 1345-1373.

Gooday, A.J., 1994. The biology of deep-sea foraminifera: a review of some advantages and their applications in paleoceanography. *Palaios*, 9, 14-31.

Gooday, A., Levin, L.A., Linke, P. and Heeger, T., 1992. The role of benthic foraminifera in deep-sea food webs and carbon cycling. In: Rowe, G.T. and Patente, V. (Editors). *Deep-sea food chains and the Global Carbon cycle*. Kluwer Academic Publishers, The Netherlands, 63-91.

Gooday, A.J., Bernhard, J.M., Levin, L.A. and Suhr, S.B., 2000. Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings: taxonomic composition, diversity, and relation to metazoan faunas. *Deep Sea Research Part II: Topical Studies in Oceanography*, 47, 25-54.

Graf, G., 1987. Benthic response to the annual sedimentation pattern. In: J. Rumohr, E. Walger and B. Zeitzschel (Ed.), *Lecture notes on coastal and estuarine studies, Seawater-sediment interactions in coastal waters: an interdisciplinary approach*. Springer, Berlin, pp. 84-92.

Grall, J., Glémarec, M., 1997. Using biotic indices to estimate macrobenthic community perturbations in the Bay of Brest. *Estuarine Coast Shelf Science*, 44, 43-53.

Grall, J., Glémarec, M., 2003. Chapitre III., L'indice d'évaluation de l'endofaune côtière. In : Alzieu, C. (Editeur), *Bioévaluation de la qualité environnementale des sédiments portuaires et des zones d'immersion*. Ed. Ifremer, pp. 51-84.

Gundersen, J.K. et Jørgensen, B.B., 1990. Microstructure of diffusive boundary layers and the oxygen uptake of the sea floor. *Nature*, 345, 604-607.

Herguera, J.C. et Berger, W.H., 1991. Paleoproductivity from benthic foraminifera abundance; glacial and postglacial change in the west-equatorial Pacific. Abstracts with Program Geological Society of America, 23, 107.

Hily, C., le Bris, H. et Glémarec, M., 1986. Impacts biologiques des émissaires urbains sur les écosystèmes benthiques. *Oceanis*, 12, 419-426.

Hulth, S., Aller, R.C. et Gilbert, F., 1999. Coupled anoxic nitrification/manganese reduction in marine sediments. *Geochimica et Cosmochimica Acta*, 63, 49-66.

Hyacinthe, C., Anschutz, P., Carbonel, P., Jouanneau, J.-M. et Jorissen, F.J., 2001. Early diagenetic processes in the muddy sediments of the Bay of Biscay. *Marine Geology*, 177, 111-128.

IFREMER, 2001. L'eutrophisation des eaux marines et saumâtres en Europe, en particulier en France. Rapport IFREMER pour la Commission Européenne DG.ENV.B1 (<http://www.ifremer.fr/envlit/documentation/documents.htm>).

Jahnke, R.A., 1996. The global ocean flux of particulate organic carbon: Area distribution and magnitude. *Global Biogeochemical Cycles*, 10, 71-88.

Jorissen, F.J., de Stigter, H.C. et Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology*, 22, 3-15.

Jorissen, F.J., Wittling, L., Peypouquet, J.P., Rabouille, C. et Relexans, J.C., 1998. Live benthic foraminiferal faunas off Cap Blanc, NW Africa: community structure and microhabitats. *Deep-Sea Research I*, 45, 2157-2188.

Jørgensen, B.B., 1977. The sulfur cycle of a coastal marine sediment (Limfjorden, Denmark). *Limnology and Oceanography*, 22, 814-832.

Jørgensen, B.B. et Boudreau, B.P., 2001. Diagenesis and sediment-water exchange. In: B.P. Boudreau and B.B. Jørgensen (Ed.), *The Benthic Boundary Layer : transport processes and biogeochemistry*. Oxford University Press, pp. 221-244.

Jørgensen, B.B. et Revsbech, N.P., 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. *Limnology and Oceanography*, 30, 111-122.

Jørgensen, B.B. et Des Marais, D.J., 1990. The diffusive boundary layer of sediments: oxygen microgradients over a microbial mat. *Limnology and Oceanography*, 35, 1343-1355.

Karlson, K., Rosenberg, R. et Bonsdorff, E., 2002. Temporal and spatial large-scale effects of eutrophication and oxygen deficiency on benthic fauna in Scandinavian and Baltic waters: a review. *Oceanography and Marine Biology*, 40, 427-489.

Kitazato, H., 1988. Locomotion of some benthic foraminifera in and on sediments. *Journal of Foraminiferal Research*, 18, 344-349.

Kramer, K.L.M. and Botterweg, J., 1991. Aquatic biological early warning systems, an overview. In: Jeffrey, D.W., Madden B. (eds) Bioindicators and environmental management. Academic press, London, 95-126.

Kristensen, E., 2000. Organic matter diagenesis at the oxic/anoxic interface in coastal marine sediments, with emphasis on the role of burrowing animals. *Hydrobiologia*, 426, 1-24.

Lancellotti, D.A. et Stotz, W.B., 2004. Effects of shoreline discharge of iron mine tailings on a marine soft-bottom community in northern Chile. *Marine Pollution Bulletin*, 48, 303-312.

Lee, J.J., Faber, W.W., Anderson, O.R. et Pawlowski, J., 1991. Life cycles of foraminifera. In: Lee, J.J., Anderson, J. (Eds.), *Biology of Foraminifera*. Academic Press, London, pp. 285-334.

Lee, J.J., Morales, J., Symons, A. et Hallock, P., 1995. Diatom symbionts in large foraminifera from Caribbean hosts. *Marine Micropaleontology*, 26(1-4), 99-105.

Licari, L.N., Schumacher, S., Wenzhöfer, F., Zabel, M. et Mackensen, A., 2003. Communities and microhabitats of living benthic foraminifera from the tropical east Atlantic: impact of different productivity regimes. *Journal of Foraminiferal Research*, 33, 10-31.

Lindgarth, M. et Hoskin, M., 2001. Patterns of distribution of macrofauna in different types of estuarine, soft sediment habitats adjacent to urban and non-urban areas. *Estuarine Coastal and Shelf Science* 52, 237-247.

Loeblich, A.R. et Tappan, H., 1988. *Foraminifera genera and their classification*, Van Nostrand Reinhold, New York, 970 pp.

Luther, I., George W., Sundby, B., Lewis, B.L., Brendel, P.J. et Silverberg, N., 1997. Interactions of manganese with the nitrogen cycle: Alternative pathways to dinitrogen. *Geochimica et Cosmochimica Acta*, 61, 4043-4052.

Luther III, G.W., Reimers, C., Nuzzio, D.B. et Lovalvo, D., 1999. In Situ Deployment of Voltametric, Potentiometric, and Amperometric Microelectrodes from a ROV to determine Dissolved O<sub>2</sub>, Mn, Fe, S(-2), and pH in Porewaters. *Environmental Science and Technology*, 33, 4352-4356.

McLusky, D.S. et Elliott, M., 2004. *The Estuarine Ecosystem; Ecology, Threats and Management* (3rd edn.), Oxford University Press, Oxford, 216 pp.

Mendez, N., 2002. Annelid assemblages in soft bottoms subjected to human impact in the Uri'as estuary (Sinaloa, Mexico). *Oceanologica Acta* , 25, 139-147.

Middelburg, J.J., 1989. A simple rate model for organic matter decomposition in marine sediments. *Geochimica and Cosmochimica Acta*, 53, 1577-1581.

Mojtahid, M., Jorissen, F., Durrieu, J., Galgani, F., Howa, H., Redois, F. et Camps, R. 2006. Benthic foraminifera as bio-indicators of drill cutting disposal in tropical east Atlantic outer shelf environments. *Marine Micropaleontology*, 61, 58-75.

Moodley, L., Boschker, H.T.S., Middelburg, J.J., Pel, R., Herman, P.M.J., de Deckere, E. et Heip, C.H.R., 2000. Ecological significance of benthic foraminifera: <sup>13</sup>C labelling experiments. *Marine Ecology Progress Series*, 202, 289-295.

Moodley, L., Middelburg, J.J., Boschker, H.T.S., Duineveld, G.C.A, Poel, R., Herman, P.M.J et Heip, C.H.R., 2002. Bacteria and foraminifera: key players in a short-term deep-sea benthic response to phytodetritus. *Marine Ecology Progress Series*, 236, 23-29.

Morvan, J., Le Cadre, V., Jorissen, F. et Debenay, J.P., 2004. Foraminifera as potential bio-indicators of the « Erika » oil spill in the Bay of Bourneuf, Field and experimental studies. *Aquatic Living Research* 17, 317-322.

Morvan, J., Debenay, J.P., Jorissen, F., Redois, F., Bénéteau, E., Delplancke, M. et Ama, A-S., 2006. Patchiness and life cycle of intertidal foraminifera, Implication for environmental and paleoenvironmental interpretation. *Marine Micropaleontology* 61, 131-154.

Murray, J.W., 1970. The foraminifera of the hypersaline Abu Dhabi Lagoon, Persian Gulf. *Lethaia*, 3, 51-68.

Murray, J.W., 1989. Syndepositional dissolution of calcareous foraminifera in modern shallow water sediments. *Marine micropaleontology*, 15, 117-121.

Murray, J.W., 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman Scientific & Technical, Harlow, 397 pp.

Murray, J.W., 2002. Introduction to benthic foraminifera. In: S.K. Haslett (Editor), *Quaternary Environmental Micropaleontology*. Arnold, London, pp. 5-13.

Murray, J.W., 2006. *Ecology and applications of benthic foraminifera*. Cambridge: Cambridge University Press, 426 pp.

Nilsson, H.C., Rosenberg, R., 2000. Succession in marine benthic habitats and fauna in response to oxygen deficiency: analysed by sediment profile-imaging and by grab samples. *Marine Ecology Progress Series*, 197, 139-149.

Nixon, S.W., 1981. Remineralization and nutrient cycling in marine coastal ecosystems. In: B.J. Neilson and L.E. Cronon (Ed.), *Estuaries and nutrients*. Humana Press, Clifton, NJ, pp. 111-138.

Nixon, S., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. *Ophelia*, 41, 199-220.

Oldham, C.E., Ivey, G.N. et Pullin, C., 2004. Estimation of a characteristic friction velocity in stirred benthic chambers. *Marine Ecology Progress Series*, 279, 291-295.

Olesen, M. et Lundsgaard, C., 1995. Seasonal sedimentation of autochthonous material from the euphotic zone of a coastal system. *Estuarine, Coastal and Shelf Science*, 41, 475-490.

Olsgard, F. et Gray, J.S., 1995. A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. *Marine Ecology Progress Series*, 122, 277-306.

Paiva, P.C., 2001. Spatial and temporal variation of a nearshore benthic community in Southern Brazil: implications for the design of monitoring programs. *Estuarine Coastal and Shelf Science*, 52, 423-433.

Paropkari, A.L., Prakash Babu, C. et Mascarenhas, A., 1992. A critical evaluation of depositional parameters controlling the variability of organic carbon in Arabian Sea sediments. *Marine Geology*, 107, 213-226.

Pasqualini, V., Pergent-Martini, C., Clabaut, P. et Pergent, G., 1998. Mapping of *Posidonia oceanica* using Aerial Photographs and Side Scan Sonar: Application off the Island of Corsica (France). *Estuarine, Coastal and Shelf Science*, 47, 359-367.

Pawlowski, J., 2000. Introduction to the molecular systematics of foraminifera. *Micropaleontology*, 46, 1-12.

Pawlowski, J., Fahrni, J.F., Brykczynska, U., Habura, A. et Bowser, S.S., 2002. Molecular data reveal high taxonomic diversity of allogromiid Foraminifera in Explorers Cove (McMurdo Sound, Antarctica). *Polar Biology*, 25, 96-105.

Pearson, T.H. et Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology, an Annual Review*, 16, 229-311.

Pedersen, T.F., Shimmield, G.B. et N.B. Price, 1992. Lack of enhanced preservation of organic matter in sediments under the oxygen minimum on the Oman Margin. *Geochimica et Cosmochimica Acta*, 56, 545-551.

Platon, E., Sen Gupta, B.K., Rabalais, N.N. et Turner, R.E., 2005. Effect of seasonal hypoxia on the benthic foraminiferal community of the Louisiana inner continental shelf, the 20th century record. *Marine Micropaleontology*, 54, 263-283.

Pujos, M., 1972. Répartition des biocénoses de foraminifères benthiques sur le plateau continental du Golfe de Gascogne à l'ouest de l'embouchure de la Gironde. *Revista Española de Micropaleontología*, 4, 141-156.

Pujos, M., 1976. Ecologie des foraminifères benthiques et des thécamoebiens de la Gironde et du plateau continental Sud-Gascogne. Thèse d'Etat, Université de Bordeaux I, 318 pp.

Rabalais, N. N., Turner, R. E., Justić, D., Dortch, Q. et Wiseman, W.J., 1999. Characterization of Hypoxia: Topic 1 Report for the Integrated Assessment of Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 15. NOAA Coastal Ocean Program, Silver Spring, MD, 167 pp.

Rabouille, C., Denis, L., Dedieu, K., Stora, G., Lansard, B. et Grenz, C., 2003. Oxygen demand in coastal marine sediments: comparing in situ microelectrodes and laboratory core incubations. *Journal of Experimental Marine Biology and Ecology*, 285-286, 49-69.

Rasmussen, H. et Jørgensen, B.B., 1992. Microelectrode studies of seasonal oxygen uptake in a coastal sediment: role of molecular diffusion. *Marine Ecology Progress Series*, 81, 289-303.

Rathburn, A.E. et Corliss, B.H., 1994. The ecology of living (stained) deep-sea benthic foraminifera from the Sulu Sea. *Paleoceanography*, 9, 87-150.

Redfield, A.C., Ketchum, B.H. et Richard, F.A., 1963. The influence of organisms on the composition of seawater. In: M.N. Hill (Ed.), *The Sea*. Wiley-Interscience, New York, pp. 26-77.

Resig, J.M., 1960. Foraminiferal ecology around ocean outfalls off southern California. In: E. Person (Editor), *Disposal in the marine environment*. Pergamon Press, London, pp. 104-121.

Rosenberg, R., 2001. Marine benthic faunal successional stages and related sedimentary activity. *Scientia Marina* 62, 107–119.

Rosenberg, R., Blomqvist, M., Nilsson, H.C., Cederwall, H. et Dimming, A., 2004. Marine quality assessment by use of benthic species-abundance distributions: a proposed new protocol within the European Union Water Framework Directive. *Marine Pollution Bulletin*, 49, 728–739.

Røy, H., Hüttel, M. et Jørgensen, B.B., 2002. The role of small-scale sediment topography for oxygen flux across the diffusive boundary layer. *Limnology and Oceanography*, 47, 837-847.

Schnitker, D., 1974. West Atlantic abyssal circulation during the past 120,000 years. *Nature*, 248, 385-387.

Schnitker, D., 1980. Quaternary deep-sea benthic foraminifers and bottom water masses. *Annual Review of Earth and Planetary Science*, 8, 343-370.

Sen Gupta B.K., 1999. Systematics of modern foraminifera. In: Sen Gupta B.K. (Editor). *Modern foraminifera*. Kluwer Academic Publishers, pp. 7-36.

Sen Gupta, B.K. et Machain-Castillo, M.L., 1993. Benthic foraminifera in oxygen-poor habitats. *Marine Micropaleontology*, 20, 183-201.

Sen Gupta B.K. et Aharon, P., 1994. Benthic foraminifera of bathyal hydrocarbon vents of the Gulf of Mexico: Initial report on communities and stable isotopes. *Geo-marine Letters*, 14, 88-96.

Shafer, C.T., 1970. Studies of benthonic foraminifera in the Restigouche estuary: Faunal distributional patterns near pollution sources. *Maritime sediments*, 6, 121-134.

Sharifi, A.R., Croudace, I.W. et Austin, R.L., 1991. Benthic foraminiferids as pollution indicators in Southampton Water, southern England, UK. *Journal of micropaleontology* 10 (1), 109-113.

Shirayama, Y., 1984. The abundance of deep sea meiobenthos in the Western Pacific in relation to environmental factors. *Oceanologica Acta*, 7, 113-121.

Steineck, P.L. et Bergstein, J., 1979. Foraminifera from Hommocks salt-marsh, Larchmont Harbor, NY. *Journal of Foraminifera Research*, 9, 147-158.

Streeter, S.S., 1973. Bottom water and benthonic foraminifera in the North Atlantic - glacial-interglacial contrasts. *Quaternary Research*, 3, 131-141.

Thamdrup, B., Hansen, J.W. et Jørgensen, B.B., 1998. Temperature dependence of aerobic respiration in a coastal sediment. *FEMS Microbiology Ecology*, 25, 189-200.

Trueblood, D.D., Gallagher, E.D. et Gould, D.M., 1994. 3 stages of seasonal succession on the Savin Hill Cove Mudflat, Boston Harbor. *Limnology and Oceanography*, 39, 1440-1454.

Van Cappellen, P. et Wang, Y., 1996. Cycling of iron and manganese in surface sediments: a general theory for the coupled transport and reaction of carbon, oxygen, nitrogen, sulfur, iron and manganese. *American Journal of Science*, 296, 197-243.

Van der Zwaan, G.J., Duijnste, I.A.P., den Dulk, M., Ernst, S.R., Jannink, N.T., et Kouwenhoven, T.J., 1999. Benthic foraminifers: proxies or problems? a review of paleocological concepts. *Earth-Science Reviews*, 46, 213-236.

Watkins, J.G., 1961. Foraminiferal ecology around the Orange County, California, ocean sewer outfall. *Micropaleontology* 7(2), 199-206.

Wenzhöfer, F. et Glud, R.N., 2004. Small-scale spatial and temporal variability in coastal benthic O<sub>2</sub> dynamics: Effects of fauna activity. *Limnology and Oceanography*, 49, 1471-1481.

Wetmore, K.L., 1988. Burrowing and sediment movement by benthic foraminifera, as shown by time-lapse cinematography. *Revue de Paléobiologie*, Vol. Spec. n°, 2, 921-927.

Williamson, W.C., 1858. On the recent foraminifera of Great Britain. Royal Society of London, 107 pp.

Wilson, T.R.S. et Thomson, J., 1998. Calcite dissolution accompanying early diagenesis in turbidite deep ocean sediments. *Geochimica and Cosmochimica Acta*, 62, 2087-2096.

Wollast, R., 1991. The coastal organic carbon cycle: fluxes, sources, and sinks. In: R.F.C. Mantoura, J.M. Martin and R. Wollast (Ed.), *Ocean Margin Processes in Global Change*. John Wiley & Sons, pp. 469.

Wollast, R., 2002. Continental margins – Review of geochemical settings. From Wefer, G., Billet, D., Hebbeln, D., Jorgensen, B.B., Schlüter, M., Van Weering, T. (eds). *Ocean Margin Systems*. Springer-Verlag Berlin Heidelberg, pp 15-31.

Yanko, V. et Flexer, A., 1991. Foraminiferal benthonic assemblages as indicators of pollution (an example of north- western shelf of the Black Sea). Third Annual Symp. on the Mediterranean Margin of Israel. Haifa-Israel, 5pp.

Zmarzly, D.L., Stebbins, T.D., Pasko, D., Duggan, R.M., Barwick, K.L., 1994. Spatial patterns and temporal succession in soft-bottom macroinvertebrate assemblages surrounding an ocean outfall on the Southern San Diego shelf—relation to anthropogenic and natural events. *Marine Biology*, 118, 293-307.







# **CHAPITRE 2. SPATIAL DISTRIBUTION OF BENTHIC FORAMINIFERA IN THE RHÔNE PRODELTA: FAUNAL RESPONSE TO ORGANIC MATTER FOCUSING**

<b>RÉSUMÉ</b> .....	57
<b>2.1 ABSTRACT</b> .....	60
<b>2.2 INTRODUCTION</b> .....	60
<b>2.3 REGIONAL SETTINGS</b> .....	62
<b>2.4 MATERIAL AND METHODS</b> .....	63
<b>2.5 RESULTS</b> .....	68
<b>2.5.1 C<sub>org</sub>, Total nitrogen, C/N atomic ratio and δ<sup>13</sup>C of organic matter</b> .....	68
<b>2.5.2 Oxygen analyses</b> .....	70
<b>2.5.3 pH</b> .....	72
<b>2.5.4 Foraminiferal analyses</b> .....	73
2.5.4.1 Living foraminifera (> 150 μm fraction).....	73
2.5.4.2 Living foraminifera (> 63 μm fraction = 63-150 μm + > 150 μm)	80
.....	
<b>2.6 DISCUSSION</b> .....	87
<b>2.7 SYNTHESIS</b> .....	101
<b>2.8 CONCLUSIONS</b> .....	104
<b>2.9 REFERENCES</b> .....	106
<b>APPENDICES</b> .....	114
<b>PLATES</b> .....	128



## RÉSUMÉ

Dans les zones du plateau continental, la combinaison des apports de matière organique continentale et de la forte productivité primaire des eaux de surface, couplés à la faible profondeur d'eau conduit à un dépôt important de matière organique sur le fond marin. Dans le Golfe du Lion, le fleuve du Rhône est une source importante de nutriments et de matière organique. Cet apport important peut créer une eutrophisation et une forte demande en oxygène de l'écosystème benthique. Dans notre étude, nous montrons l'existence de quatre biofaciès de faunes de foraminifères vivants. Ces quatre biofaciès sont répartis en fonction de la qualité de la matière organique, du gradient d'enrichissement organique et de la pénétration de l'oxygène dans le sédiment. Le premier biofaciès est situé à proximité immédiate de l'embouchure ; la faune des foraminifères vivants y est caractérisée par de faibles densités et biodiversité; elle est dominée par *Fursenkoina fusiformis*, *Bulimina aculeata*, *Reophax scottii* et *Adelosina longirostra*. Cet assemblage répond à une forte teneur en matière organique d'origine continentale et à une très faible pénétration de l'oxygène dans le sédiment. Un deuxième biofaciès situé dans la partie intermédiaire de la zone d'enrichissement organique au niveau du panache du fleuve est caractérisé par des densités maximales et une faible biodiversité; en effet, au niveau du panache, la faune est dominée par les espèces opportunistes *Nonionella turgida* et *Nonion scaphum* accompagnées par l'espèce *Rectuvigerina phlegeri*. Un troisième biofaciès présent au niveau des stations les plus profondes et les moins affectées par les apports du fleuve est caractérisé par une densité et une biodiversité élevée; les assemblages sont dominés par l'espèce *Cassidulina carinata* accompagnée dans des proportions inférieures de *Epistominella vitrea*, *Valvulineria bradyana* et *Nonionella iridea/bradyi*. Enfin, un quatrième biofaciès se situe dans la partie orientale du prodelta, plutôt à l'abri de l'influence du fleuve du Rhône ; les faunes y sont dominées par les espèces *Bolivina dilatata/spathulata* et *Textularia porrecta*.

**Mots clés:** Foraminifères benthiques ; eutrophisation ; panache du fleuve ; oxygène ; carbone organique ; Golfe du Lion ; le fleuve du Rhône.



## CHAPITRE 2. SPATIAL DISTRIBUTION OF BENTHIC FORAMINIFERA IN THE RHÔNE PRODELTA: FAUNAL RESPONSE TO ORGANIC MATTER FOCUSING

M. Mojtahid <sup>(1)</sup>, F. Jorissen <sup>(1)</sup>, B. Lansard <sup>(2)</sup>, C. Fontanier <sup>(1)</sup>,  
B. Bombled <sup>(2)</sup> and C. Rabouille <sup>(2)</sup>.

(1) Laboratoire des Bio-Indicateurs Actuels et Fossiles (BIAF) UPRES EA 2644, Université d'Angers. 2, Boulevard Lavoisier, 49045 Angers Cedex, France, and Laboratoire d'Étude des Bio-Indicateurs Marins (LEBIM). Ker Chalon, 85350 Ile D'Yeu, France.

(2) Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS 1572 and IPSL, Avenue de la terrasse, F-91198, Gif sur Yvette, France.

Ce chapitre correspond à un article en cours de soumission pour la revue *Estuarine, Coastal and Shelf Science*.

**Keywords:** Benthic foraminifera; eutrophication; river plume; oxygen; organic carbon; Coastal ocean; Gulf of Lions; Rhône river.

## 2.1 ABSTRACT

On many continental shelf areas, the combination of continental detritus supply, high surface water productivity and limited water depth leads to important organic matter deposits on the sea floor. This situation may create important eutrophication phenomena in the benthic environment. In the Gulf of Lions, the Rhône River is a major source of nutrients and organic matter. In the Rhône prodelta, four benthic foraminiferal biofacies occur in relation to the quality of the organic matter, the organic enrichment gradient and the oxygen penetration into the sediment. A first biofacies is situated in the immediate vicinity of the river mouth; the faunas are characterized by a low density and biodiversity; they are dominated by *Fursenkoina fusiformis*, *Bulimina aculeata*, *Reophax scottii*, and *Adelosina longirostra*. This assemblage reflects a high input of continental organic matter, a high concentration of organic carbon and nitrogen and a minimum oxygen penetration into the sediment. A second biofacies, influenced by the river plume, is situated in the intermediate part of the organic enrichment zone and is characterized by maximum densities and very low biodiversity; faunas are dominated by the opportunistic species *Nonionella turgida* and *Nonion scaphum* accompanied in lower proportions by the species *Rectuvigerina phlegeri*. A third biofacies is situated in the outer part of the organic-rich area. The faunas are characterized by high densities and a high biodiversity; they are dominated by *Cassidulina carinata* accompanied in lower proportions by the species *Epistominella vitrea*, *Valvulineria bradyana* and *Nonionella iridea/bradyi*. A fourth biofacies, typical of the eastern part of the prodelta, which is less influenced by the river input, is dominated by the species *Bolivina spathulata*, *Bolivina dilatata* and *Textularia porrecta*.

## 2.2 INTRODUCTION

On continental margins, important supplies of continental detritus and a high primary production due to the river-induced nutrient input, in combination with a limited water depth, lead to important organic matter deposits on the sea floor. Consequently, the sediments in the coastal zones, that represent only 10 % of the total ocean surface, contain about 80 % of all marine organic matter (*Wollast, 1991*) and accumulate about 90 % of fluvial particles (*Gibbs, 1981*). The deposited organic matter is subject to a multitude of biochemical reactions that

ultimately lead to its mineralisation; only a small percentage (0.1 to 0.5 %) is definitively buried in the sediment.

Eutrophication of the marine environment is usually defined as a complex series of phenomena, initially triggered by the increase of limiting nutrients, especially nitrogen and phosphorus due to supply from terrestrial sources. In short, an increase in limiting nutrients leads to increased primary production and subsequently large amounts of organic material can be deposited on the sea floor. This may eventually lead to increase in biomass and densities of benthic organisms but also to hypoxic/anoxic conditions at the sediment-water interface and/or in the superficial sediment, that can result in massive reduction or mortality of benthic faunas (e.g. *Kemp and Boynton, 1992; Heip, 1995*). Moreover, the degradation of the deposited organic matter results in the regeneration of nutrients, such as nitrogen and/or phosphorous, that may be used by phytoplankton to sustain high primary production rates. This phenomenon is even more important when the water depth is limited. The intensity of this primary production is then directly related to the supply of nutrients and organic matter from natural or anthropogenic sources. These important supplies may have a negative effect on the marine food chain in places where important eutrophication and hypoxia occur at the sea floor. Hypoxia are defined as values inferior to the threshold below which significant impacts on the biota can be observed; it is generally considered that this is the case when dissolved oxygen concentrations fall below  $62.5 \mu\text{mol/l}$  or  $2 \text{ mg/l}$  (*Diaz and Rosenberg, 1995; Rabalais et al., 2001*).

The relationship between the composition of benthic foraminiferal faunas and the amount of organic carbon in the sediment has been the subject of a number of studies (e.g. *Miller and Lohmann, 1982; Corliss, 1985; Jorissen, 1987; Van der Zwaan and Jorissen, 1991*). In general, it has been noticed that especially in very productive areas, highly characteristic associations occur (e.g. *Seiglie, 1968; Phleger and Soutar, 1973; Van der Zwaan, 1982; Bernhard, 1986; Altenbach and Sarntheirn, 1989; Gooday and Turley, 1990*). However, it is not yet fully understood whether these characteristic faunas are resulting from the raised food availability, from the lowered oxygen availability, or from a combination of both. In most cases, the influence of these two parameters can not be separated. The percentage of organic carbon in the sediment is basically controlled by the organic flux from the surface layer, its decay during downward transport and the subsequent preservation history. With increased quantities of organic detritus reaching the sea-bottom, increased amounts of refractory organic matter tend to be preserved in the sediment. Since high input of



organic matter demands considerable amounts of oxygen for the consumption of its labile part, a high organic flux often results in dysoxic conditions in sea bottom environments.

Early studies about the distribution and the ecology of death assemblages of benthic foraminifera were performed in the Northwestern Mediterranean Sea by *Kruit (1955)*, *Blanc-Vernet (1969)* and *Bizon and Bizon (1985)*. *Kruit (1955)* was especially interested by the Rhône delta itself where brackish waters are dominant. Sediments in this study were subject to detailed research; on the contrary, the study of benthic foraminifera was somehow succinct. However, *Blanc-Vernet (1969)* and *Bizon and Bizon (1985)* brought precise informations on foraminifera in the Mediterranean Sea which were used as a support in our study.

In this paper we will discuss the relationship between the input of organic matter and the distribution of living benthic foraminifera in the Rhône prodelta (France), which is a naturally eutrophicated area due to the supply of important amounts of continental organic carbon and nutrients by the Rhône River.

## 2.3 REGIONAL SETTINGS

In the Mediterranean Sea, the Gulf of Lions is one of the largest ocean margin systems (*Riomar, McKee et al., 2004*). The area is strongly influenced by the input of the Rhône River which is the most important source of fresh water, nutrients and continental organic matter for the western Mediterranean Sea. The Gulf of Lions is a region where several intense and highly variable physical processes interact. These processes include the action of a powerful circulation along the continental slope, the formation of deep water, both on the continental shelf and offshore, and a seasonal stratification with aperiodic mixing events associated with strong winds (*Millot, 1990*). Stratification of the surface layer persists from approximately April to October. On the shelf, the seasonal thermocline forms a 10 to 20 m thick layer. The water temperature below the thermocline remains fairly constant at 13.5°C, whereas the water temperature above the thermocline is characteristically in the range of 20 to 25°C. The depth of the thermocline deepens from 20 to 40 m towards the open sea. In winter, the water column becomes homogeneous throughout the region (*Sempéré et al., 2000*). During our sampling in June 2005, the bottom water temperatures in the Rhône prodelta varied from 13 °C at the deepest stations (80 m) to 18 °C at the shallowest stations (20 m) whereas the surface water temperatures were in the range of 16 to 19 °C. The surface salinity was minimal in the area subjected to the river plume (33 ‰) and maximal far from this area (38 ‰). The mean flux of

total suspended matter supplied by the Rhône River has been estimated at  $9.9 \pm 6.4 \text{ Mt y}^{-1}$  (Sempéré *et al.*, 2000). On a longer time-scale, the Rhône River discharge has led to the formation of a prodeltaic sedimentary structure characterized by fine-grained deposits in the proximal shelf area (Roussiez *et al.*, 2005). The Rhône River discharges into the Gulf of Lions forms a visible plume of turbid water, 1 to 2 m thick, that extends several kilometres seaward. The Rhône River plume varies in thickness, size and extension depending on:

- The geostrophic circulation (Liguro-Provençal current), the flow of which is 500 times more important than the Rhône mean flow (Béthoux *et al.*, 1988). It spreads south-westwards along the shelf break (Millot, 1990; Marsaleix, 1993).
- The Rhône River discharge which varies from  $5 \cdot 10^2$  to  $10^4 \text{ m}^3 \cdot \text{s}^{-1}$ , with an annual mean flow  $1715 \text{ m}^3 \cdot \text{s}^{-1}$  (Millot, 1990; Marsaleix, 1993).
- The tidal amplitude, which is only a few centimetres in the Gulf of Lions. Consequently, the associated tidal currents are too weak to be measured over the shelf (Lamy *et al.*, 1981), and this parameter can be neglected when compared to the others.
- The different wind regimes determine the surface water transport and the distribution of suspended sediments on the shelf. Northerly (Mistral) and northwesterly (Tramontane) winds, and S–SE winds (Marin) are predominant in the Gulf of Lions. The Mistral and Tramontane are more frequent in winter and spring and induce distinctive and opposite circulation cells on the shelf, favouring the intrusion of slope waters in the eastern and central parts of the shelf and export of shelf water at its southwestern end (Estournel *et al.*, 2003; Petrenko *et al.*, 2005). Furthermore, these cold, dry winds are responsible for the strong cooling and homogenization of the shelf water column in winter, which facilitates dense water formation. Due to the short fetch, they generate only small waves (significant wave height  $< 2 \text{ m}$ , peak period  $> 6 \text{ s}$ ) on the inner shelf. Southeastern and eastern Marin wind events, are associated with a large swell (significant wave height up to  $10 \text{ m}$ , peak period up to  $12 \text{ s}$ ) and a significant rise in sea level along the coast. These episodes are often simultaneous with river floods, since the transport of humid marine air over the coastal relief promotes heavy precipitation in the catchment basin.

## 2.4 MATERIAL AND METHODS

Twenty three stations were sampled from 10 to 17 June 2005 in front of the Rhône River during cruise Minercot 2, with the *R.V. Tethys II* (Fig. 2-1). Sediments were collected

between 20 and 98 m water depth using a Bowers and Connelly Mark VI multicorer. This corer contains 4 Plexiglas tubes of 50 cm length and 15 cm internal diameter. Cores were extruded on-board and sliced for organic carbon, nitrogen,  $\delta^{13}\text{C}$  measurements and foraminiferal analyses.

For  $C_{\text{org}}$ , N and  $\delta^{13}\text{C}$  analyses, cores were sliced onboard into 1 cm layers down to 5 cm sediment depth. Each subsample was conserved in a hermetic bag and frozen. In the laboratory, the sediments were dried at 50°C; cracked using an agate mortar. The samples were treated with diluted hydrochloric to remove carbonates.  $C_{\text{org}}$  and N were measured using a CHN elementary analyser and  $\delta^{13}\text{C}$  was measured using a GC-IRMS mass spectrometer.

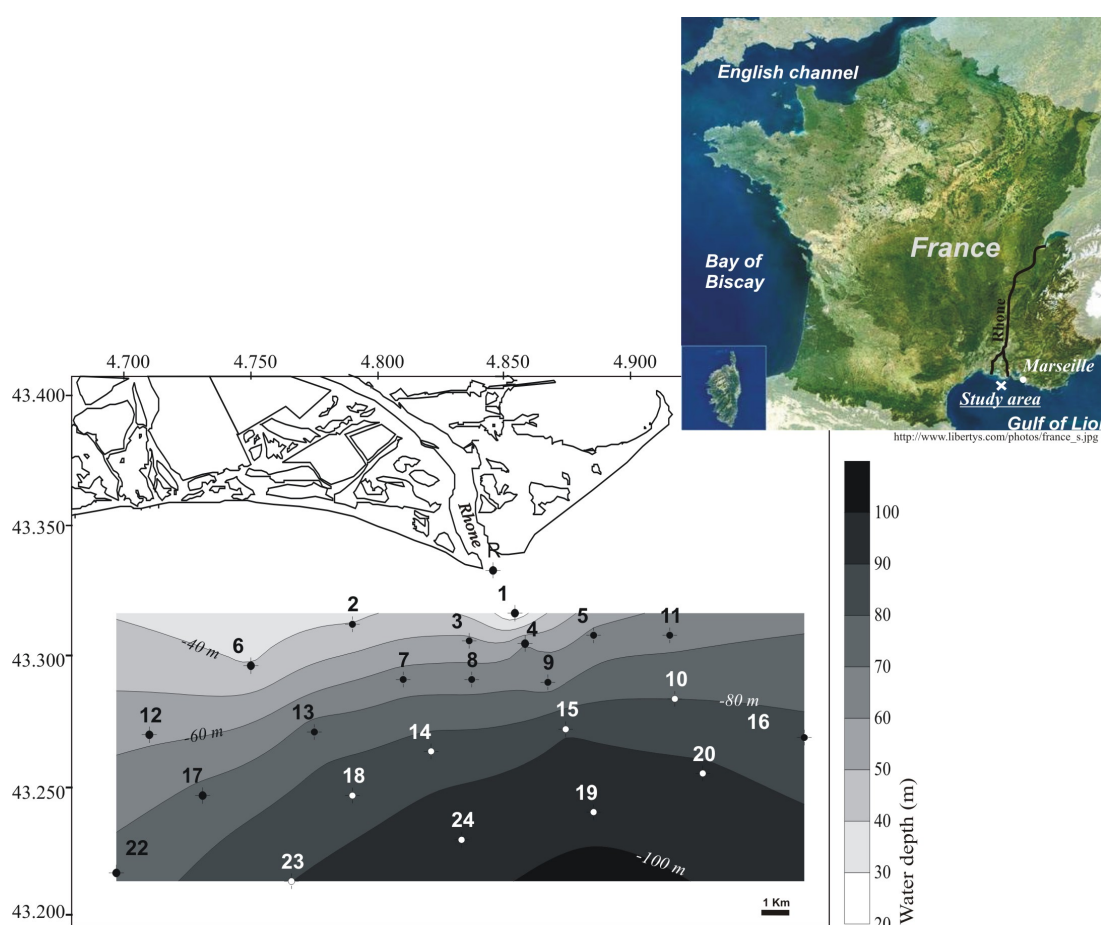


Figure 2-1. Study area in front of the Rhône delta, bathymetry and sampling location.

For the analysis of their foraminiferal content, the sampled cores were sliced onboard until 5 centimetres sediment depth (Table 1). For stations 1, 3, 4, 7, 9, 13, 14, 15, 17, 19 and 22, the cores were sliced into 0.5 cm levels down to 2 cm depth and then in 1 cm levels down to 5 cm depth. For the other stations, the cores were sliced in four intervals (0-0.5, 0.5-1, 1-2

and 2-5 cm). All samples were preserved in 95 % ethanol with 1 g/l Rose Bengal. In the laboratory, the collected samples were sieved over sieves with 63 and 150 µm meshes. For the fraction larger than 150 µm, living foraminifera from all levels (until 5 cm depth) were hand-sorted under a binocular microscope under wet conditions (in about 50 % ethanol). If necessary, samples were split with an Ottomicrosplitter, and a minimum of 200 to 300 specimens were collected (see Appendix 2-1). For the samples of the granulometric fraction 63-150 µm, living foraminifera from the first centimetre of the sediment (0-0.5 cm and 0.5-1 cm) were concentrated by density separation with trichloroethylene (D=1.46). Living as well as unaltered dead foraminifera should be present exclusively in the floated part. A check of the deposited sediment revealed the absence of living individuals, showing the efficiency of this method. Next, the floated part was dried, and because of the very rich fauna found in this fraction, samples were split with an Ottomicrosplitter and foraminifera from complete splits were hand-picked wet (in about 50% ethanol) until a minimum of 200 individuals was obtained. All foraminifera selected were determined using commonly used taxonomic reference works (*e.g. Parker, 1964; Loeblich and Tappan, 1964; Jones, 1994, etc.*) and taxonomic studies with emphasis on eutrophicated continental shelf environments (*e.g. Jorissen, 1988; Barmawidjaja, 1991; Schiebel, 1992*).

At 10 of the 23 sampled stations (1, 3, 4, 5, 6, 13, 14, 16, 17 and 22), in-situ measurements of oxygen, pH, resistivity were performed using microelectrodes (*e.g., Lansard et al., 2003; Rabouille et al., 2003*) fixed on an autonomous Lander profiler with a vertical resolution of 100 µm (*Unisense®*, Science Park Aarhus, Gustav Wieds Vej 10, DK-8000 Aarhus C, Denmark ; [www.unisense.com](http://www.unisense.com)) (Table 2-1). In-situ oxygen measurements were calibrated using an optode that measures the dissolved oxygen in the water above the sediment surface. This optode is also fixed on the in-situ profiler near the microelectrodes.

Sub-cores were sampled from the 23 cores to calculate the porosity. These sub-cores were sliced into 2 mm levels until 1 cm depth and then into 5 mm levels until 6 cm depth. The wet collected sediments were weighed and then dried in the laboratory under a temperature of 45 °C until the total evaporation of the interstitial waters. The dried sediments were weighed again and the difference between the dry and the wet weight gives the water component and thus the porosity.

The diffusive flux of oxygen at the water-sediment interface was calculated according to first Fick's Law at the 10 stations visited by the Lander profiler

$$\mathbf{J} = -\phi \times \mathbf{D}_S \times (d\mathbf{O}_2 / dz)_{z=0}$$

in which  $J$  is the flux expressed in moles per surface and time unity,  $\phi$  the porosity,  $D_s$  the coefficient of diffusion and  $dO_2/D_z$  is the gradient of concentration. The coefficient of diffusion  $D_s$  in the sediment corresponds to the coefficient of diffusion of this solute in the water at  $D_0$  the in-situ temperature, corrected for the sediment porosity  $\phi$  and the formation factor  $F$

$$D_s = D_0 / (\phi \times F)$$

in which the inverse of this factor  $F$  ( $F^{-1}$ ) is obtained by the measurement of the resistivity of the sediment according to the equation

$$F^{-1}(z) = R_{bw} / R(z)$$

If we consider that the diffusive transport of dissolved oxygen in the sediment is the dominant transport and that the system is stationary then we can consider that the entered net flux from the water column into the sediment corresponds to the sedimentary demand (consumption-production) in oxygen.

In order to better show spatial patterns of faunal variability, we applied a Principal Component Analysis (*StatSoft, Inc. (2004). STATISTICA (data analysis software system), version 7. www.statsoft.com.*) to the foraminiferal (> 150  $\mu\text{m}$  fraction and 63-150  $\mu\text{m}$  and > 150  $\mu\text{m}$  fraction summed together) percentage data. Cluster analyses were performed on the basis of non-standardized percentage data (*Davis, 1986*). Only taxa occurring with more than 5 % in at least one sample were retained in these PCA and Cluster analyses. For each station, the Shannon Wiener index ( $H$ ) was calculated according to

$$H = -\sum_{i=1}^s p_i \ln p_i$$

in which “ $s$ ” is the number of species and “ $p$ ” is the relative frequency of the “ $i$ th” species. Fisher alpha ( $\alpha$ ) indices were computed using

$$\alpha = n_1/x$$

where “ $x$ ” is a constant having a value inferior to 1 and “ $n_1$ ” can be calculated from  $N(1-x)$ ,  $N$  being the number of individuals (*Murray, 1991*). Species Evenness ( $E$ ) index that separates the effect of different population sizes (numbers of individuals within species) from simple species diversity (number of species) was computed using

$$E = e^D/s$$

where “e” is a constant having a value of 2.7, “D” is the value of the Shannon-Wiener Information Function and “s” is the number of species.

In order to enhance data visualization, geo-referenced contour maps of spatial distribution using a grid based contour program, Surfer for Windows (*Golden Software; version 6.02*), were performed.

Stations	Lat. (deg)	Long. (deg)	Prof. (m)	Distance in Km from the river mouth (43.33N; 4.845E)	% C <sub>org</sub>	%N tot	C/N	$\delta^{13}\text{C}$	Other analyses
1*	43.314	4.854	20	1.92	1.81	0.23	9.33	-26.83	F, Oxd, OxPr, pHPr, R
2	43.310	4.790	40	4.97	1.12	0.17	7.94	-25.75	F
3*	43.304	4.836	53	2.98	1.68	0.20	9.98	-26.71	F, Oxd, OxPr, pHPr, R
4*	43.303	4.858	60	3.18	1.18	0.18	7.87	-26.22	F, Oxd, OxPr, pHPr, R
5*	43.306	4.885	63	4.19	1.15	0.17	7.75	-25.91	F, Oxd, OxPr, pHPr, R
6*	43.295	4.750	40	8.62	0.97	0.15	7.71	-25.20	F, Oxd, OxPr, pHPr, R
7	43.290	4.810	65	5.27	1.26	0.18	8.33	-25.99	F
8	43.290	4.837	65	4.50	1.09	0.16	7.97	-25.82	F
9	43.289	4.867	65	4.89	1.06	0.17	7.46	-25.47	F
10	43.283	4.917	80	7.83	0.94	0.14	7.71	-25.00	F
11	43.306	4.915	66	6.26	0.91	0.14	7.64	-25.26	F
12	43.270	4.710	58	12.80	// // // // // // // // // // // // // // // //				F
13*	43.271	4.775	75	8.67	1.02	0.13	9.16	-25.32	F, Oxd, OxPr, pHPr, R
14*	43.264	4.821	85	7.59	1.03	0.15	8.18	-25.20	F, Oxd, OxPr, pHPr, R
15	43.272	4.874	89	6.86	// // // // // // // // // // // // // // // //				F
16*	43.269	4.968	83	12.05	0.82	0.15	6.42	-23.88	F, Oxd, OxPr, pHPr, R
17*	43.248	4.731	73	12.97	0.93	0.14	7.57	-24.52	F, Oxd, OxPr, pHPr, R
18	43.248	4.790	85	10.15	// // // // // // // // // // // // // // // //				F
19	43.242	4.885	98	10.31	0.82	0.16	6.03	-24.35	F
20	43.256	4.928	92	10.62	0.85	0.14	7.05	-24.18	F
22*	43.220	4.697	74	17.12	0.89	0.14	7.32	-24.27	F, Oxd, OxPr, pHPr, R
23	43.217	4.766	90	14.10	0.91	0.14	7.59	-24.17	F
24	43.232	4.833	95	10.94	// // // // // // // // // // // // // // // //				F

Table 2-1. Geographical position of the sampling stations (numbers, cored stations; asterisks indicate Lander profiler stations), their water depth, distance from the river mouth (point R in Fig. 2-1), % organic carbon, % total nitrogen,  $\delta^{13}\text{C}$  of organic matter, C/N ratio and an inventory of other analyses performed at these stations (F, foraminiferal analyses; Oxd, Dissolved oxygen; OxPr, Oxygen profiles in the sediment measured by the microelectrodes; pHPr, pH profiles in the sediment measured by the microelectrodes; R, Resistivity).

## 2.5 RESULTS

During sampling in June 2005, active Mistral and Tramontane winds, in combination with the geostrophic circulation (Liguro-Provencal surface current), were responsible for the deviation of the river plume in southwestern direction. Therefore, the study area was, at this time, subject to the input of sediments, nutrients and continentally derived organic matter by the Rhône River.

### 2.5.1 $C_{org}$ , Total nitrogen, C/N atomic ratio and $\delta^{13}C$ of organic matter

Figure 2-2 (a) presents the surficial distribution of organic carbon; in figure 2-2 (a'), the percentages of organic carbon are plotted in function of the distance to the river mouth. High values ( $\sim 1.80$  % d.w.) are recorded close to the river mouth, which gradually decrease towards the farthest stations ( $\sim 0.80$  % d.w.). At the same distance from the river mouth, the eastern stations present lower carbon values compared to western stations translating the preferentially southwestern direction of the river plume.

Figure 2-2 (b) presents the surficial distribution of total nitrogen whereas figure 2-2 (b') presents the percentage of total nitrogen plotted in function of the distance to the river mouth. Similarly to organic carbon, high values of total nitrogen ( $\sim 0.20$  % d.w.) are recorded close to the river mouth, which gradually decrease towards the farthest stations ( $\sim 0.13$  % d.w.). The enrichment in SW direction is less clear than for organic carbon.

Figure 2-2 (c) presents the surficial distribution of the C/N atomic ratio, and in figure 2-2 (c') the values are plotted in function of the distance to the river mouth. Organic matter in marine sediments is often described as a binary mixture of terrestrial and marine elements. Since terrestrial organic matter is depleted in nitrogen, C/N ratios in sediments are often used to estimate the fraction of terrestrially derived organic carbon in marine sedimentary environments. In general, this ratio is about 15 for organic matter from terrestrial sources and about 5 for marine organic matter (*Zeebe and Wolf-Gladrow, 2001*). In the Rhône prodelta, this ratio indicates a larger contribution of a terrestrial source close to the river mouth (C/N  $\sim 10.00$ ), which gradually decreases with increasing distance from the river mouth (C/N  $\sim 6.00$ ). A very clear difference can be observed between stations west of the river mouth, with a high continental contribution, and stations east of the river mouth, with predominantly marine organic matter.

## Spatial distribution of benthic foraminifera in the Rhône prodelta

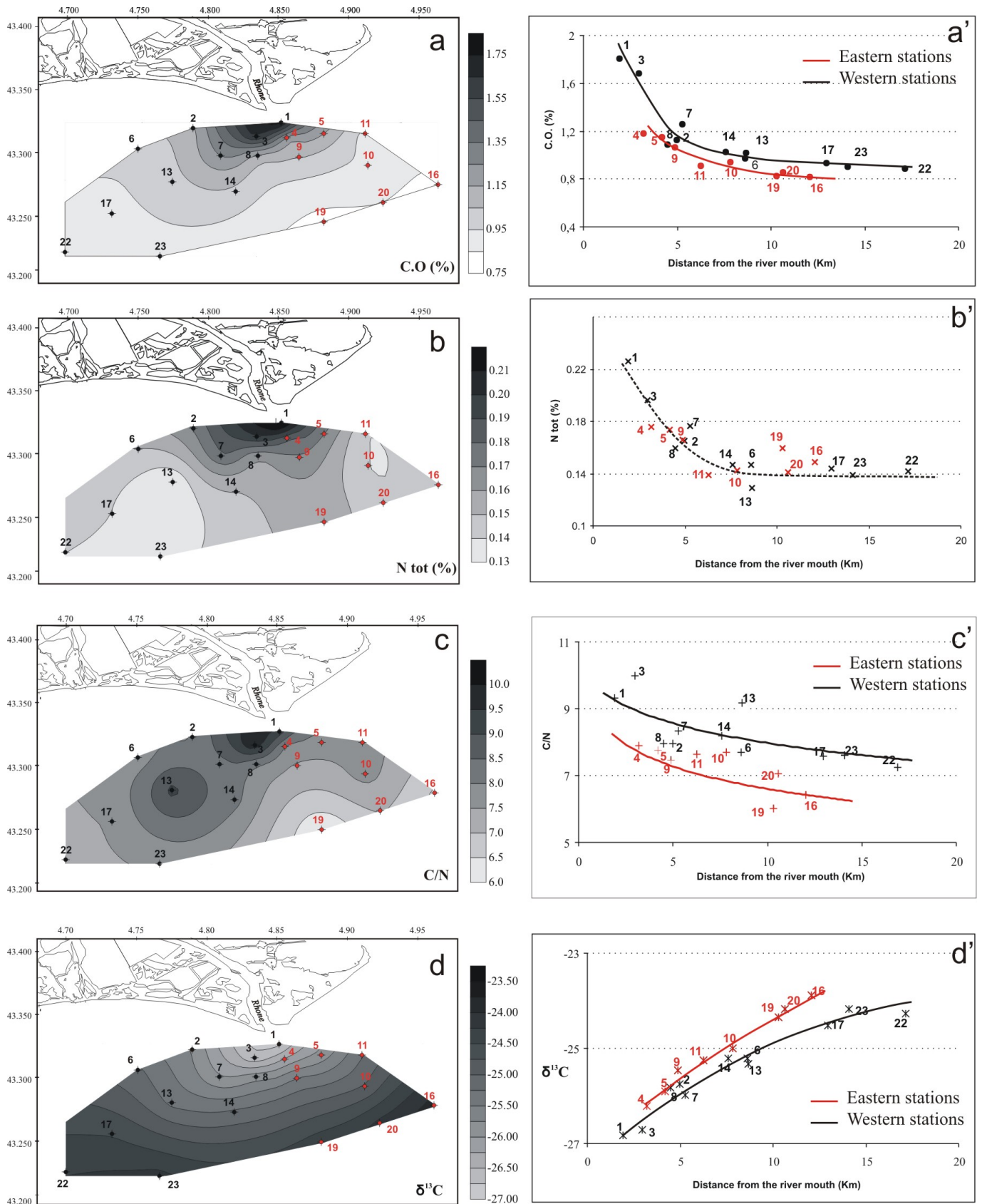


Figure 2-2. Surficial distribution of (a) organic carbon (% d.w.), (b) total nitrogen (% d.w.), (c) C/N atomic ratio and (d) stable isotope composition of organic carbon ( $\delta^{13}C$ ) and (2-2a'-d') distribution of these parameters in function of the distance to the river mouth.



Figure 2-2 (d) presents the surficial distribution of  $\delta^{13}\text{C}$  and figure 2-2 (d') presents this ratio in function of the distance to the river mouth. Also this ratio informs us about the origin of the organic matter. Values from -25 ‰ to -27 ‰ indicate a terrestrial origin while values between -20 ‰ and -25 ‰ are indicative of a marine source of organic carbon (Zeebe and Wolf-Gladrow, 2001). In our study area, organic matter is clearly of continental origin close to the river mouth where the  $\delta^{13}\text{C}$  is about -27 ‰. Further away from this area,  $\delta^{13}\text{C}$  values gradually increase indicating an increased contribution of marine organic carbon. The systematically lighter values in the western stations clearly show the southwestern spreading of continental organic matter introduced by the Rhône River.

## 2.5.2 Oxygen analyses

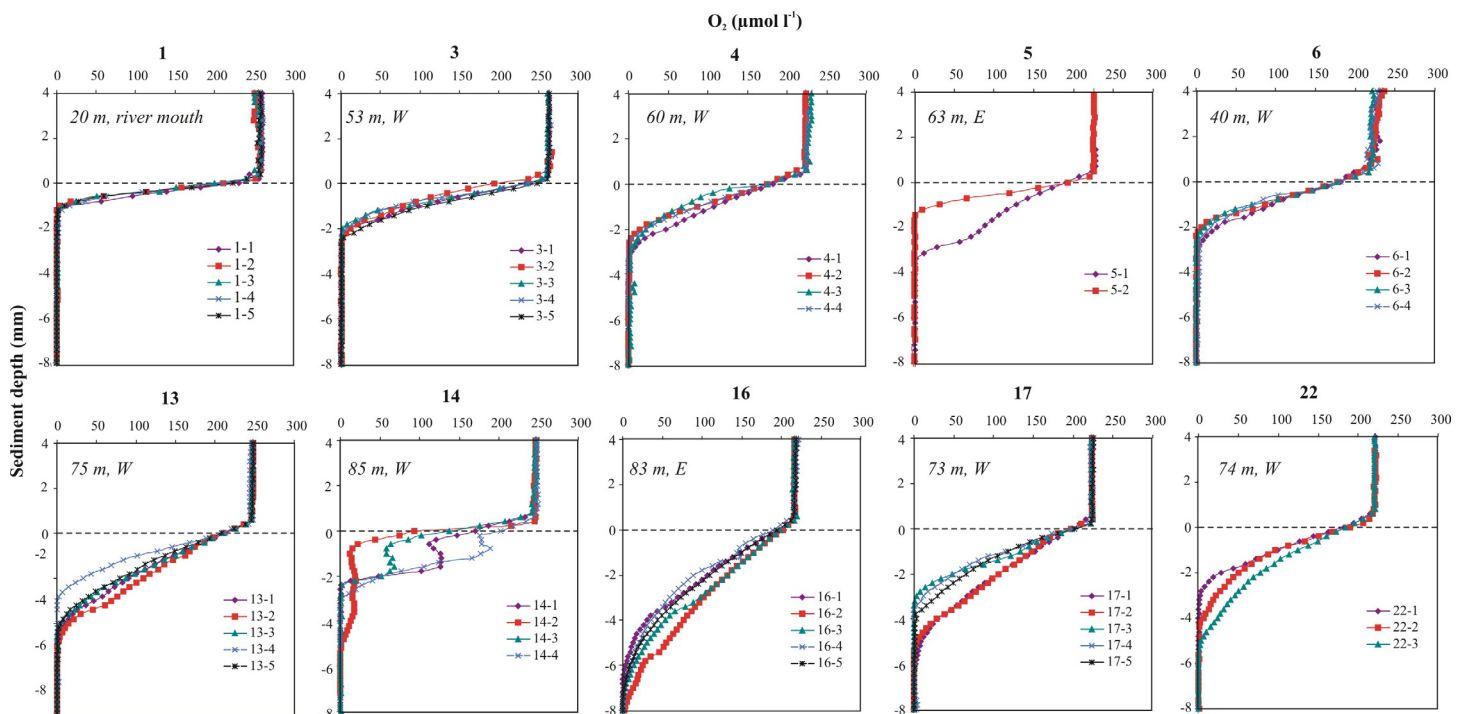


Figure 2-3. In-situ oxygen profiles measured by a Lander profiler equipped with microelectrodes at 10 stations in the Rhône prodelta and indications of their water depths and their position W or E from the river mouth.

In situ oxygen profiles obtained by the Lander Profiler microelectrodes are presented in figure 2-3. The sediment-water interface is estimated in function of the strong shift in the curve related to diffusion from the bottom water into the sediment. The penetration of oxygen into the sediment at station 1 close to the river mouth, at a water depth of 20 m is only about 1 mm. Stations 4, 5, 3 and 6, at water depths between 40 and 63 m, present an oxygen

penetration of 2 to 3 mm. The deepest stations (from 74 m to 85 m water depths) present a more important oxygen penetration, from 3 to 6 mm for stations west of the Rhône delta (13, 14, 17 and 22) and from 6 to 8 mm for station 16 east of the Rhône delta.

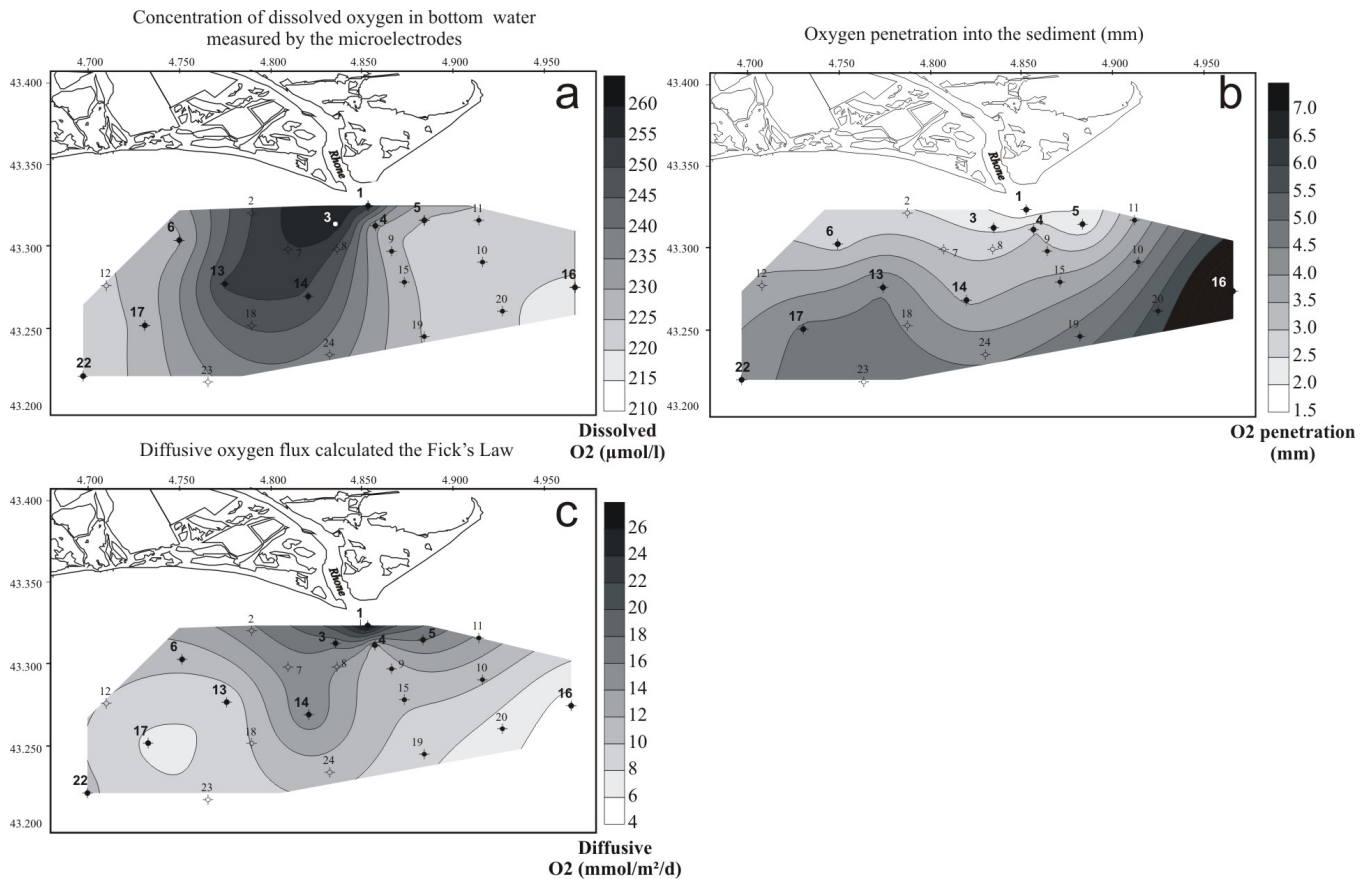


Figure 2-4. (a) Concentration of dissolved oxygen in the bottom water measured by in-situ microelectrodes ( $\mu\text{mol/l}$ ); (b) Oxygen penetration into the sediment (mm); (c) Diffusive oxygen flux calculated by Fick's law ( $\text{mmol/m}^2/\text{d}$ ). Only bold numbers represent the stations where dissolved oxygen measurements were performed.

Figure 2-4 (a) presents the dissolved oxygen of the bottom water measured by in-situ microelectrodes at the 10 same stations in the Rhône prodelta. The positions of the other stations, where no oxygen measurements have been performed, are also indicated on the graphs. Relatively high oxygen concentrations of about 260  $\mu\text{mol/l}$  are found at stations in the vicinity of the river mouth. These values gradually decrease towards the farthest stations, until values of about 215  $\mu\text{mol/l}$  are reached at station 16 located east of the river mouth. Figure 2-4 (b) shows the oxygen penetration into the sediment that is low in front of the river mouth and gradually increases towards the farthest stations. Figure 2-4 (c) presents the spatial distribution of benthic fluxes of diffusive oxygen calculated by Fick's Law. These fluxes represent the biological, chemical and physical processes that occur simultaneously during

organic matter recycling in the sediment (*Boudreau, 1986; Soetaert et al., 1996*). We can notice that in the vicinity of the river mouth, the O<sub>2</sub> demand is important (stations A; 28.5 mmolO<sub>2</sub>/m<sup>2</sup>/d). Further away, the oxygen diffusive flux gradually decreases. The O<sub>2</sub> demand is more important in the western than in the eastern part of the prodelta. Surprisingly, in the Rhône prodelta, the oxygen penetration into the sediment is minimal where the bottom water concentration is maximal (station 1; O<sub>2</sub> penetration ~ 1 mm, O<sub>2</sub> concentration ~ 260 µmol/l). However, it should be noticed that the bottom waters are in general well oxygenated and the difference between the closest stations and the farthest ones is rather small. High oxygen concentrations near the river mouth may be due to strong hydrodynamics in this area.

### 2.5.3 pH

The data presented in figure 2-5 show variation of pH relative to the overlying water pH (corresponding to the reference value, i.e., ΔpH = 0) as a function of the sediment depth at the 10 stations visited by the Lander Profiler. Due to the fact that most pH standards are not adapted to salt water, we prefer to express pH variation between stations in relative and not in absolute terms. Figure 2-5 (a) shows the pH profiles at the stations closest to the river mouth. This figure shows a strong decrease of about 1.0 pH unit in the first two millimetres of the sediment at station 1 and a strong decrease from 0.6 to 0.8 pH units in the first four millimetres of the sediment at stations 3, 4, 5 and 6. A slight increase is present below this level whereas deeper down, the pH again decreases progressively. The decrease of pH in the first millimetres of the sediment is related to the organic matter recycling for which generally oxic mineralisation and the denitrification processes are responsible. *Luther III et al. (1999)* have shown, by comparing *in-situ* profiles of O<sub>2</sub>, Mn<sup>2+</sup>, Fe<sup>2+</sup> and pH measured simultaneously, that the small increase of pH in the anoxic zone of the sediment corresponds to the reduction of MnO<sub>2</sub> and that the further decrease of pH below this zone can be attributed to the precipitation of the carbonatic phases that may incorporate Mn and generate CO<sub>2</sub> and H<sub>2</sub>O (*Boudreau et al., 1998*). This type of profile indicates then an important anaerobic diagenesis. Figure 2-5 (b) shows the pH profiles in stations farther away from the river mouth. These profiles show a uniform and less brutal decrease in pH by about 0.8 units. There is no small increase in the upper part of the anoxic zone. This is probably due to the presence of sufficient quantities of oxygen to recycle most of the organic matter. We can conclude that the Rhône River supplies directly influence the pH profiles in the sediment column.

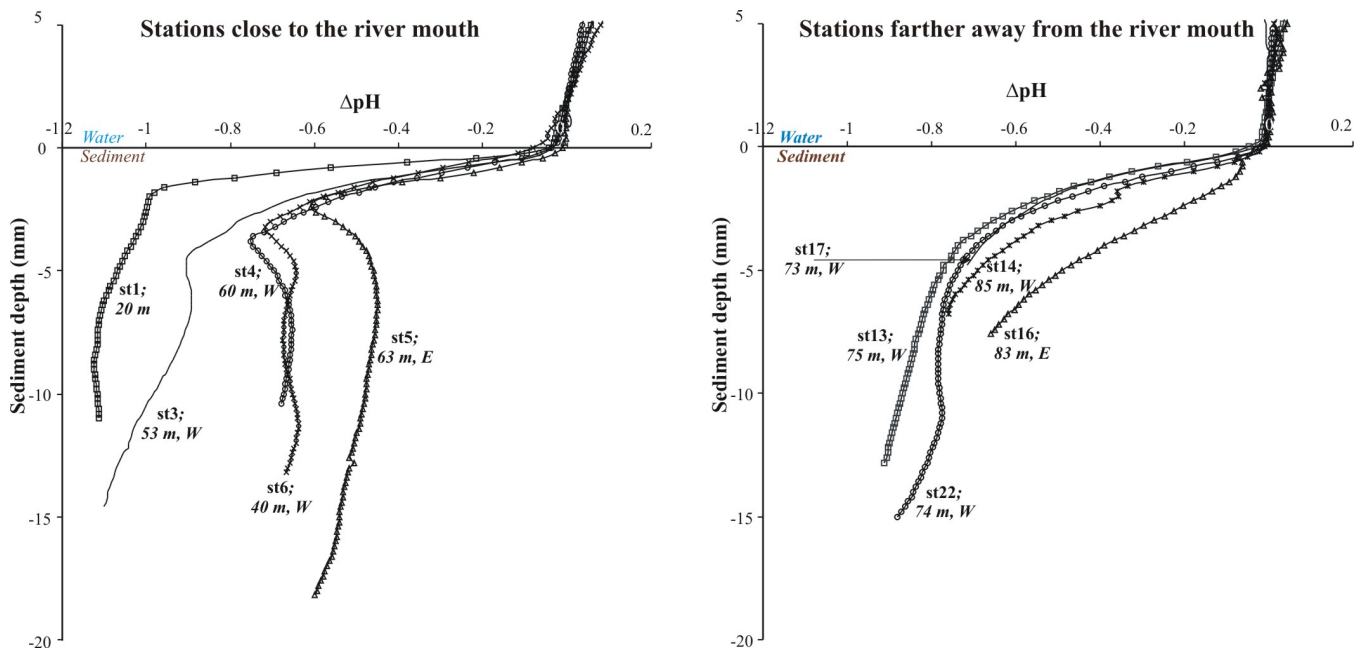


Figure 2-5.  $\Delta pH$  profiles measured by in-situ microelectrodes at 10 stations.

## 2.5.4 Foraminiferal analyses

### 2.5.4.1 Living foraminifera (> 150 $\mu\text{m}$ fraction)

The total number of living individuals (> 150  $\mu\text{m}$  fraction) found in the uppermost 5 cm of the sediment (total volume = 883  $\text{cm}^3$ ) varies between 39 at station 1 and 3327 at station 12, corresponding to a density of 22 to 1883 individuals below a 100  $\text{cm}^2$  sediment surface, at station 1 and 12, respectively (Fig. 2-6). The fauna presents minimal densities near the river mouth and decreased densities to the southwest, the dominant direction of the river plume. Farther away from the river mouth, densities increase significantly to the west as well as to the east. The species richness varies from 11 at station 1 to 42 at station 10. In general, the fauna in the > 150  $\mu\text{m}$  fraction is dominated by *Nonion scaphum*, *Cassidulina carinata*, *Valvulineria bradyana*, *Bulimina aculeata*, *Nonionella turgida*, *Eggerella scabra*, *Quinqueloculina seminula* forma *longa* and *Reophax scottii*. These species are accompanied in lower proportions by *Ammonia beccarii* forma *inflata*, *Textularia agglutinans*, *Rectuvigerina phlegeri*, *Elphidium macellum*, *Melonis barleeanus*, *Adercotryma glomeratum*, *Eratidus foliaceus* and *Reophax trochaminiformis* (Fig. 2-7).

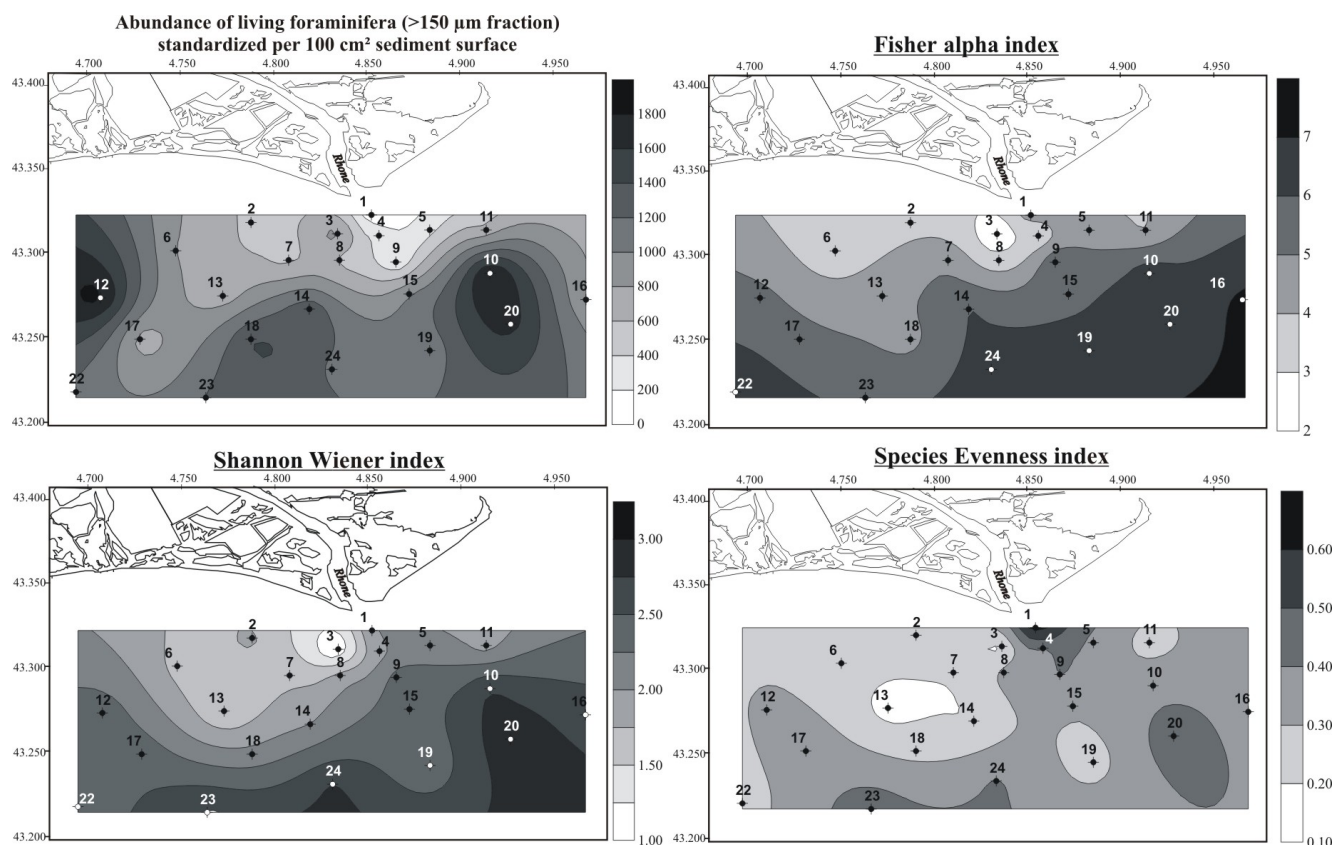


Figure 2-6. Spatial distribution of the abundance of living foraminifera ( $> 150 \mu\text{m}$ ) standardized for  $100 \text{ cm}^2$  sediment surface and biodiversity indices values (Fisher alpha, Shannon Wiener, Species Evenness).

Several biodiversity indices (Shannon Wiener, Fisher alpha and species Evenness) were computed on the basis of the abundance data at each station. Figure 2-6 presents the spatial distribution of these biodiversity indices values. Generally, the Shannon Wiener and Fisher alpha indices indicate low biodiversity near the river mouth, gradually increasing towards the distant stations. In more detail, these indices describe an asymmetric distribution, with lower values to the west and higher values to the east. These two indices are minimal in an area until some 9 Km SW of the river mouth at stations (2, 3, 6, 7, 8 and 13), under the influence of the river plume. The Evenness index has very low values at stations under the influence of the river plume where also Fisher alpha and Shannon Wiener indices show minimal values. This suggests that the foraminiferal fauna is not very well equilibrated in this area and is characterized by a strong predominance of few species. In the direct vicinity of the river mouth, on the contrary, the poor population is better equilibrated, with an evenness index of about 0.6. At the other stations towards the south and the east, the evenness index presents intermediate values.

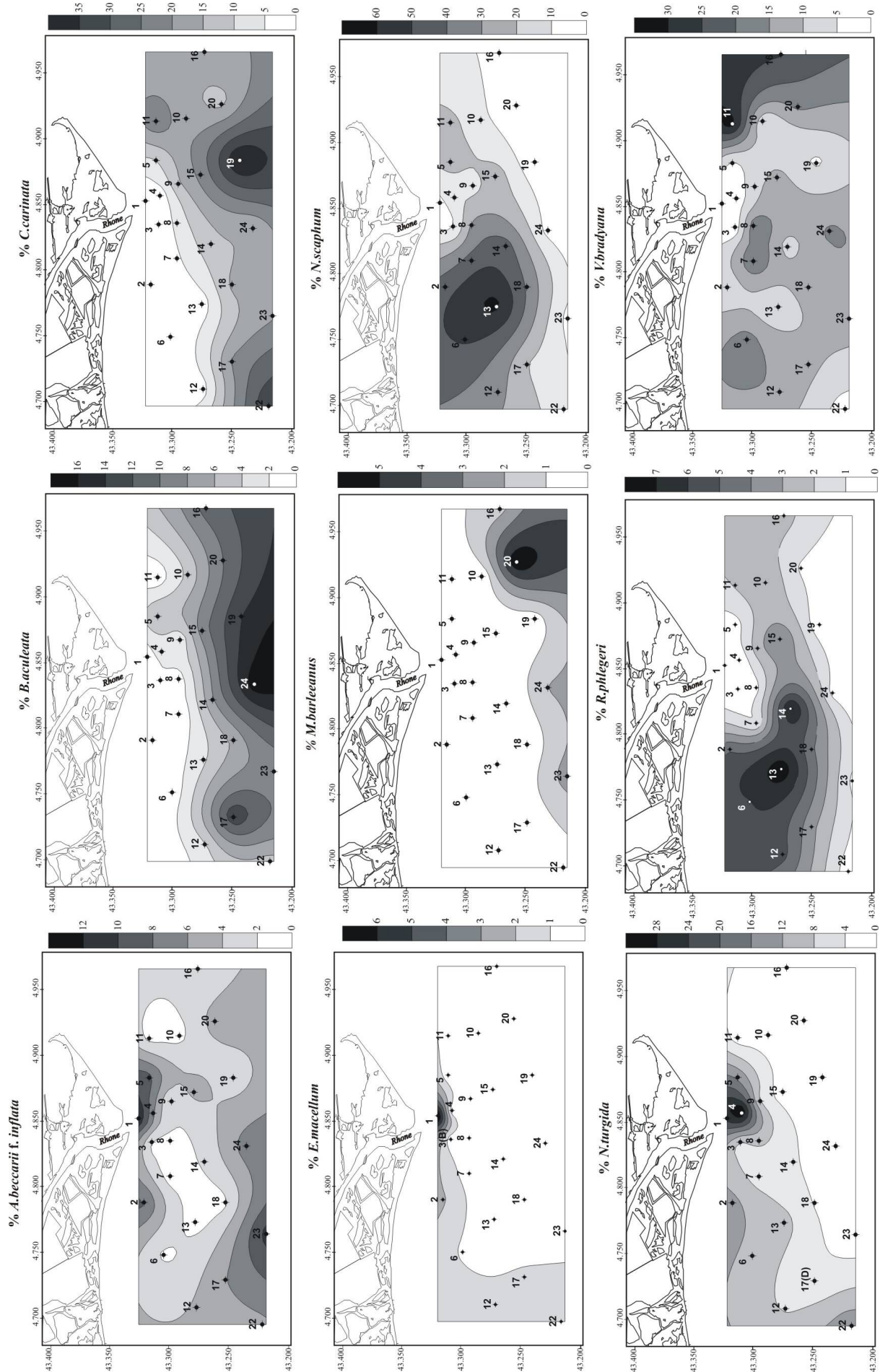


Figure 2-7. Spatial distribution of percentages of all species occurring with more than 5% in at least one sample in the > 150  $\mu$ m fraction.

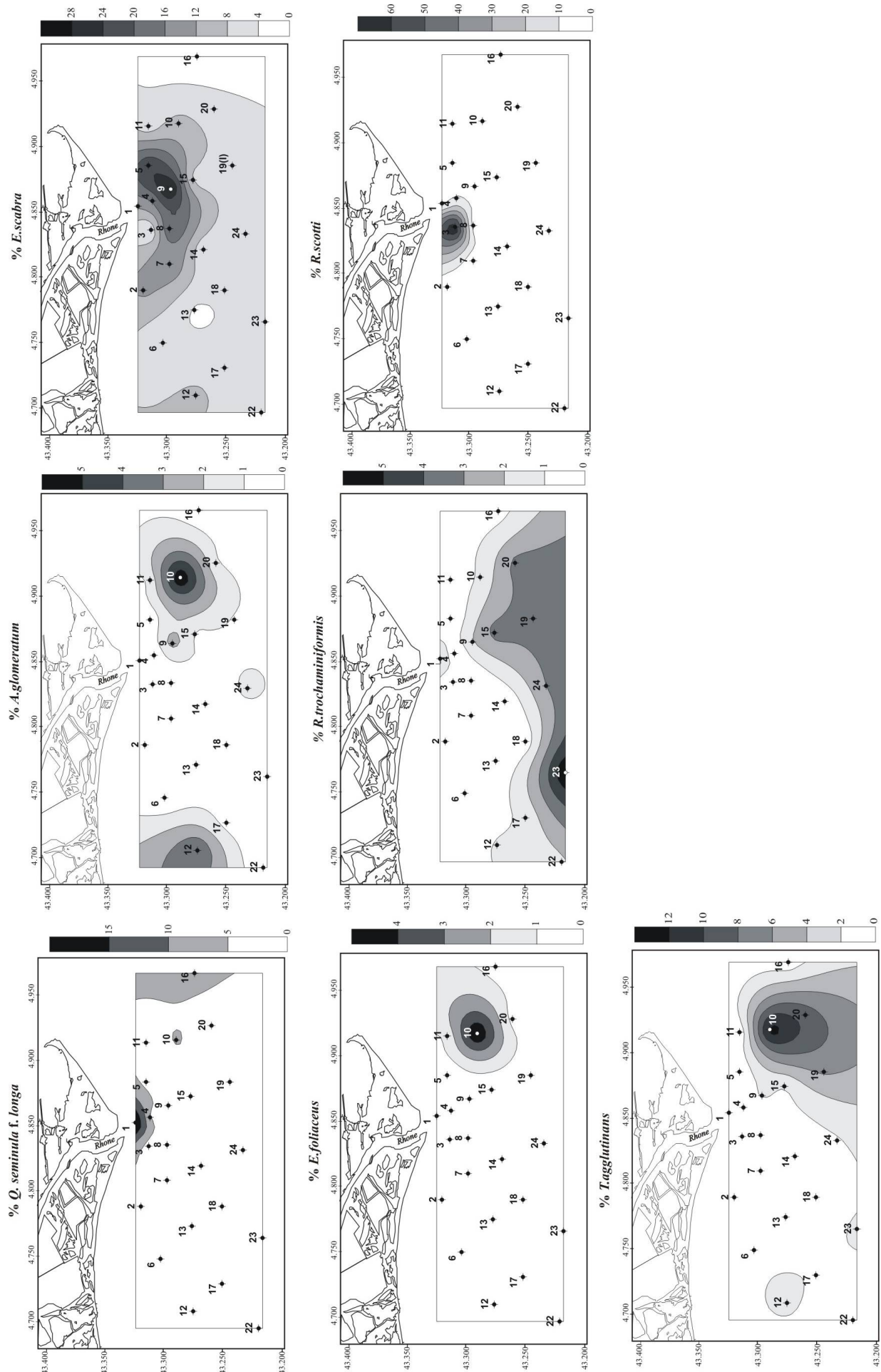


Figure 2-7. (Continued).

A Principal Component Analysis has been performed on the basis of the percentage data (> 150  $\mu\text{m}$  fraction) of all taxa occurring with more than 5 % in at least one sample. The results of this PCA are presented in figure 2-8 and in table 2-2. Axis 1 (Eigenvalue = 5.80), axis 2 (Eigenvalue = 3.58) and axis 3 (Eigenvalue = 2.42) account respectively for 30.54 %, 18.86 % and 12.77 % of the total variation in the dataset.

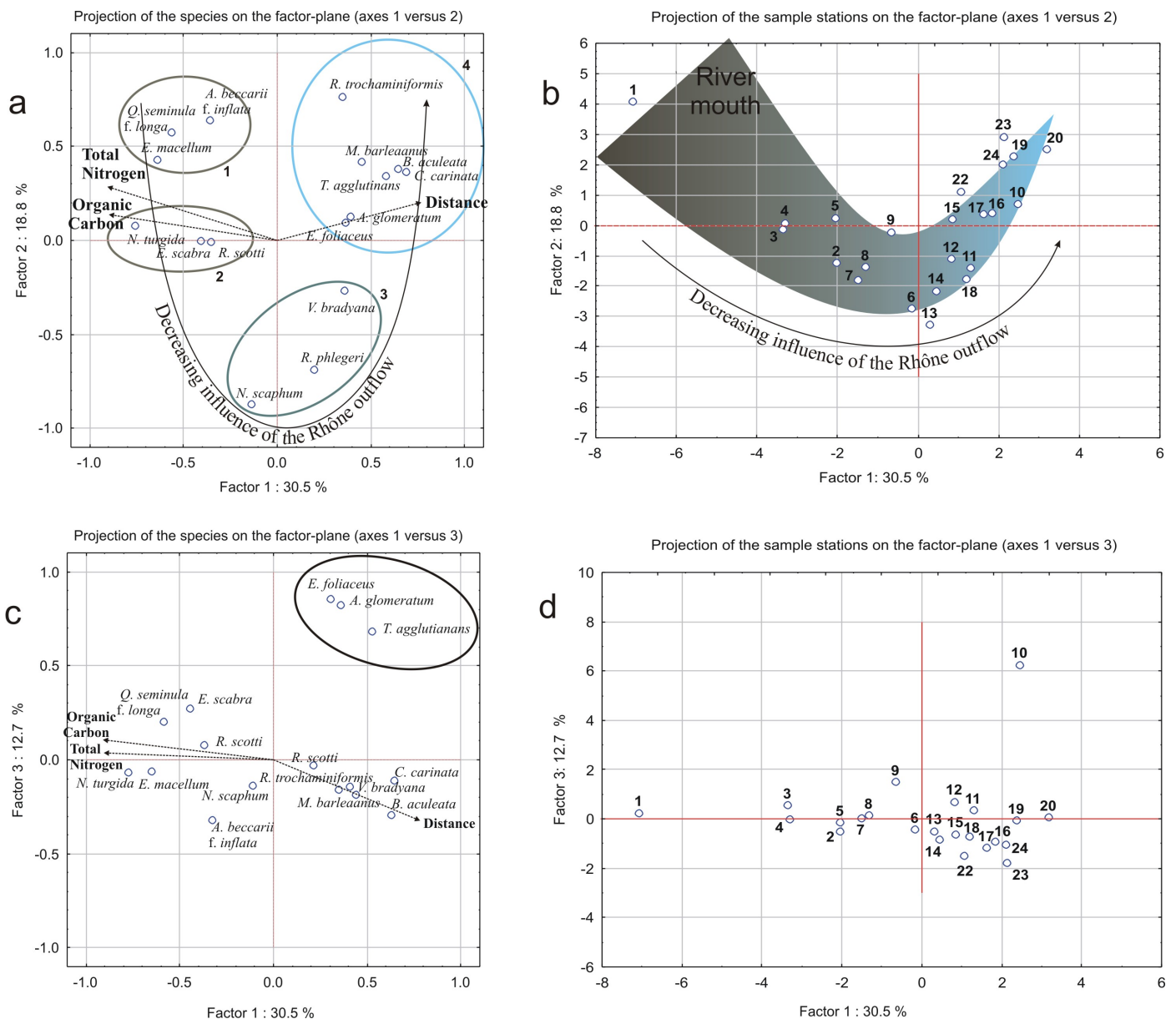


Figure 2-8. Principal Component Analysis. a. Projection of the variables (living benthic foraminifera; taxa > 150  $\mu\text{m}$  fraction) on the first two PCA axes together with organic carbon, total nitrogen and distance to the river mouth. Four distinct assemblages are recognised; b. Score plot of the 23 stations on the first two PCA axes and indication of the decreasing river influence; c. Projection of the variables on the factor-plane determined by PCA axes 1 and 3 together with organic carbon, total nitrogen and distance to the river mouth; d. Score plot of the 23 stations on the factor-plane determined by PCA axes 1 and 3.



Axis number	Eigenvalue	% Total variance	Cumulative % of variance
1	5.80	30.5	30.5
2	3.58	18.8	49.4
3	2.42	12.7	62.1
4	1.69	8.9	71.1
5	1.22	6.4	77.5
6	1.10	5.8	83.3
7	0.93	4.8	88.2
8	0.58	3.0	91.3
9	0.46	2.4	93.8
10	0.35	1.8	95.7

Table 2-2. Results of a Principal Component Analysis based on the percentages of living foraminifera in the > 150  $\mu\text{m}$  fraction.

Figure 2-8 (a) shows the position of the species on the first two PCA axes. Four faunal assemblages can be distinguished. Group 1, that has negative loadings on the first PCA axis and positive loadings on the second PCA axis, is composed of the species *Elphidium macellum*, *Quinqueloculina seminula* forma *longa* and *Ammonia beccarii* forma *inflata*. Group 2 composed of *Nonionella turgida*, *Eggerella scabra* and *Reophax scottii* has negative loadings on the first PCA axis whereas group 3 composed of the species *Eratidus foliaceus*, *Adercotryma glomeratum*, *Textularia agglutinans*, *Cassidulina carinata*, *Bulimina aculeata*, *Melonis barleeanus* and *Reophax trochaminiformis* has a positive contribution to both axes. *Nonion scaphum*, *Rectuvigerina phlegeri* and *Valvulineria bradyana*, composing group 4, have negative loadings on the second PCA axis. Together with species, we plotted organic carbon content, total nitrogen and distance to the river mouth. The first and the second assemblages dominate the faunas near the river mouth where important amounts of organic carbon and total nitrogen are found in sediments. The third assemblage is predominantly found at the deepest stations far from the river influence with low amounts of organic carbon and total nitrogen. The fourth assemblage is present at intermediate distances from the river mouth and reflects sediments with intermediate amounts of organic matter.

Figure 2-8 (b), which presents the position of the samples on the axial plot, shows a typical horse-shoe distribution (Hill and Gauch, 1980; Digby and Kempton, 1987). The faunal distribution clearly reflects a decreasing influence of the Rhône outflow from the upper left to the lower centre, to the upper right of the axis plot.

Axis 3, that still accounts for 12.77 % of the total variability, is positively loaded by the agglutinated species *E. foliaceus*, *T. agglutinans* and *A. glomeratum* (Fig. 2-8 c). This axis

allows to distinguish the very rich and peculiar fauna found at station 10 situated in the eastern part of the Rhône prodelta, sheltered from river influence (Fig. 2-8 d).

When a cut-off level of 0.3 is applied, the cluster analysis based on non-standardized percentage data (Fig. 2-9) (Davis, 1986) allows to distinguish four clusters of foraminifera (Cluster I: *E. macellum*, *Q. seminula* f. *longa*, *A. beccarii* f. *inflata*, *N. turgida*; Cluster II: *A. glomeratum*, *E. foliaceus*, *T. agglutinans*; Cluster III: *B. aculeata*, *C. carinata*, *M. barleeanus* and *R. trochaminiformis*; Cluster IV: *N. scaphum*, *R. phlegeri*). The spatial repartition of these four clusters (Fig. 2-10) indicates the presence of four biofacial zones: 1) the immediate vicinity of the river mouth where taxa of cluster I dominates the fauna; 2) the eastern stations sheltered from the river influence, where faunas are dominated by taxa of cluster II; 3) the deeper stations where the taxa of cluster III proliferate and 4) the stations influenced by the river plume where faunas are dominated by taxa of cluster IV.

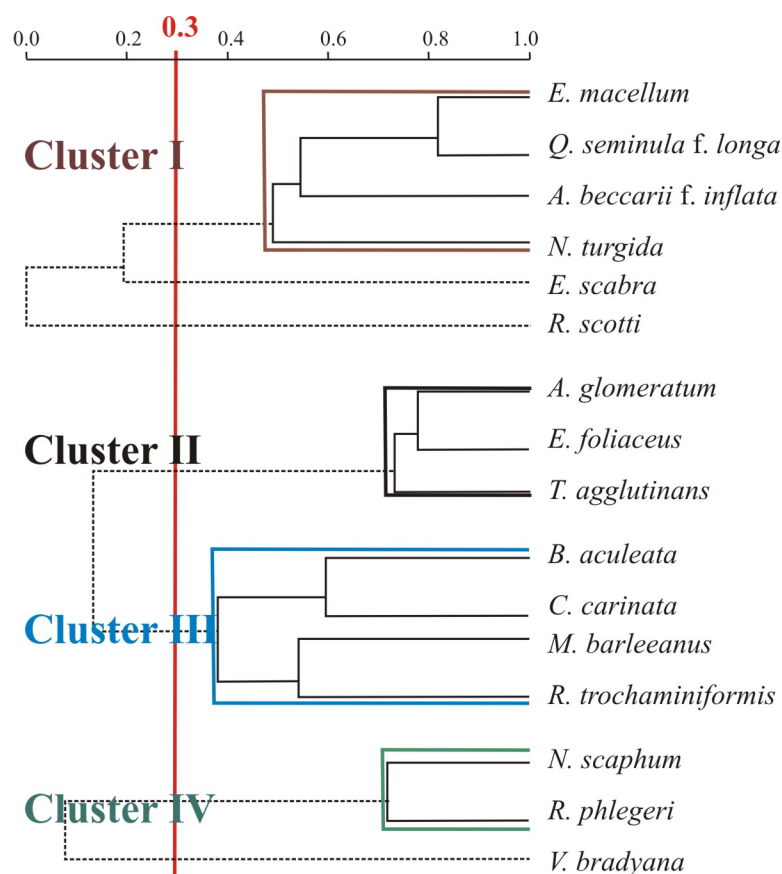


Figure 2-9. Cluster based on non-standardized percentage data of living foraminifera in the > 150  $\mu$ m fraction (Davis, 1986)

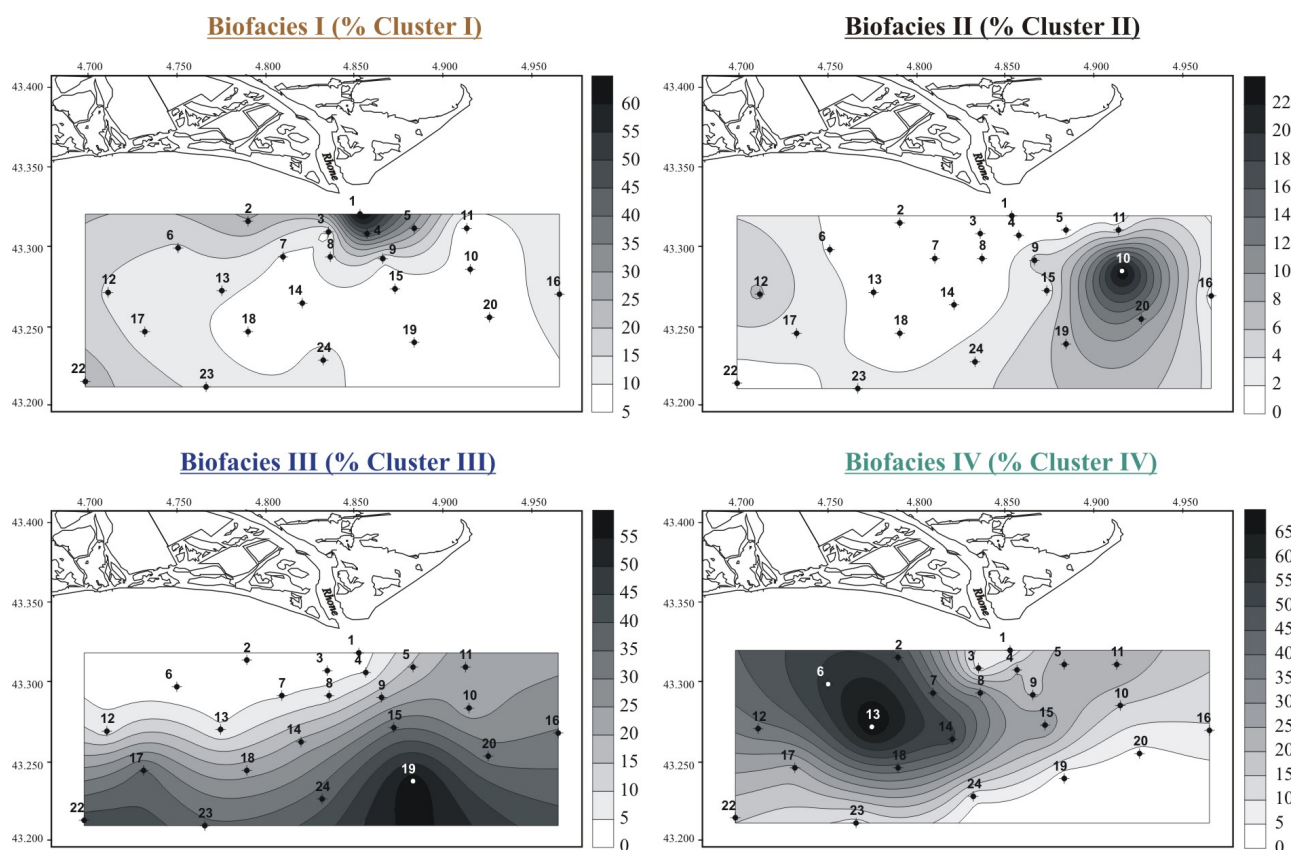


Figure 2-10. Spatial distribution of the four foraminiferal assemblages of the  $> 150 \mu\text{m}$  fraction recognised by cluster analysis (Cluster I: *E. macellum*, *N. turgida*, *Q. seminula* f. *longa*, *A. beccarii* f. *inflata*; Cluster II: *A. glomeratum*, *E. foliaceus*, *T. agglutinans*; Cluster III: *C. carinata*, *B. aculeata*, *M. barleeanus*, *R. trochaminiformis*; Cluster IV: *N. scaphum*, *R. phlegeri*).

#### 2.5.4.2 Living foraminifera ( $> 63 \mu\text{m}$ fraction = 63-150 $\mu\text{m}$ + $> 150 \mu\text{m}$ )

At all stations, the fauna of the 63-150  $\mu\text{m}$  fraction, that was only counted in the topmost centimetre, is much richer than that in the  $> 150 \mu\text{m}$  fraction. In order to represent the total fauna of the first centimetre, we summed both size fractions (63-150  $\mu\text{m}$  fraction plus  $> 150 \mu\text{m}$  fraction; total volume = 176.6  $\text{cm}^3$ ). The total number of living individuals varies from about 2180 at station 1 to about 19800 at station 14, corresponding to a density of 1230 to 11200 individuals per 100  $\text{cm}^2$  sediment surface, respectively, at stations 1 and 14 (Fig. 2-11). The fauna presents minimal densities near the river mouth, at the deepest stations and at the eastern stations. Faunal densities are also low in the main corridor influenced by the river plume (transect 3, 7, 13, 17, 22), but maximum values are sometimes observed at the outer part of this area (stations 12 and 14). The specific richness varies from 25 at station 3 to 52 at station 24. In general, the fauna in the  $> 63 \mu\text{m}$  fraction is dominated by *Bolivina dilatata*, *B.*

*aculeata*, *C. carinata*, *Fursenkoina fusiformis*, *Hopkinsina pacifica*, *N. scaphum*, *N. turgida* and *R. scottii*. These taxa are accompanied in lower proportions by the species *Bolivina spathulata*, *Epistominella vitrea*, *Nonionella bradyi*, *Nonionella iridea*, *R. phlegeri*, *V. bradyana*, *Adelosina longirostra* and *Textularia porrecta* (Fig. 2-12).

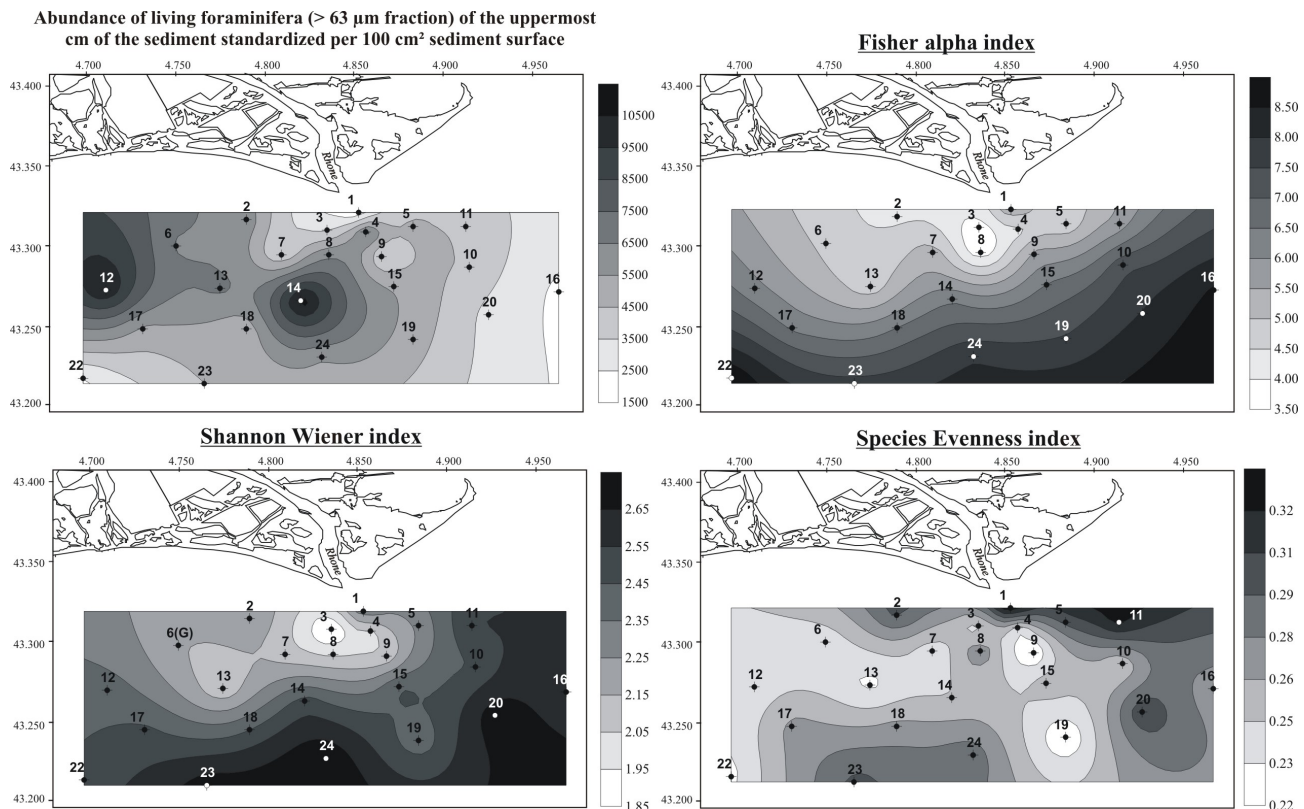


Figure 2-11. Spatial distribution of the abundance of living foraminifera (> 63  $\mu\text{m}$ ) standardized for 100  $\text{cm}^2$  sediment surface and biodiversity indices values (Fisher alpha, Shannon Wiener, Species Evenness).

Shannon Wiener, Fisher alpha and species Evenness indices have been computed on the basis of the abundance data at each station. Figure 2-11 presents the spatial distribution of the biodiversity indices. Generally, spatial patterns of these indices are very similar to those described for the > 150  $\mu\text{m}$  fraction (see Fig. 2-6). Shannon Wiener and Fisher alpha indices indicate low biodiversity near the river mouth, gradually increasing towards the more distant stations. Similarly to the > 150  $\mu\text{m}$  fraction, these diversity indices describe an asymmetric distribution, with lower values to the west and higher values to the east. These two indices are minimal in the main corridor influenced by the river mouth, at stations (2, 3, 6, 7, 8 and 13). The Evenness index has very low values at the stations under the influence of the river plume where both Fisher alpha and Shannon Wiener indices show minimal values.

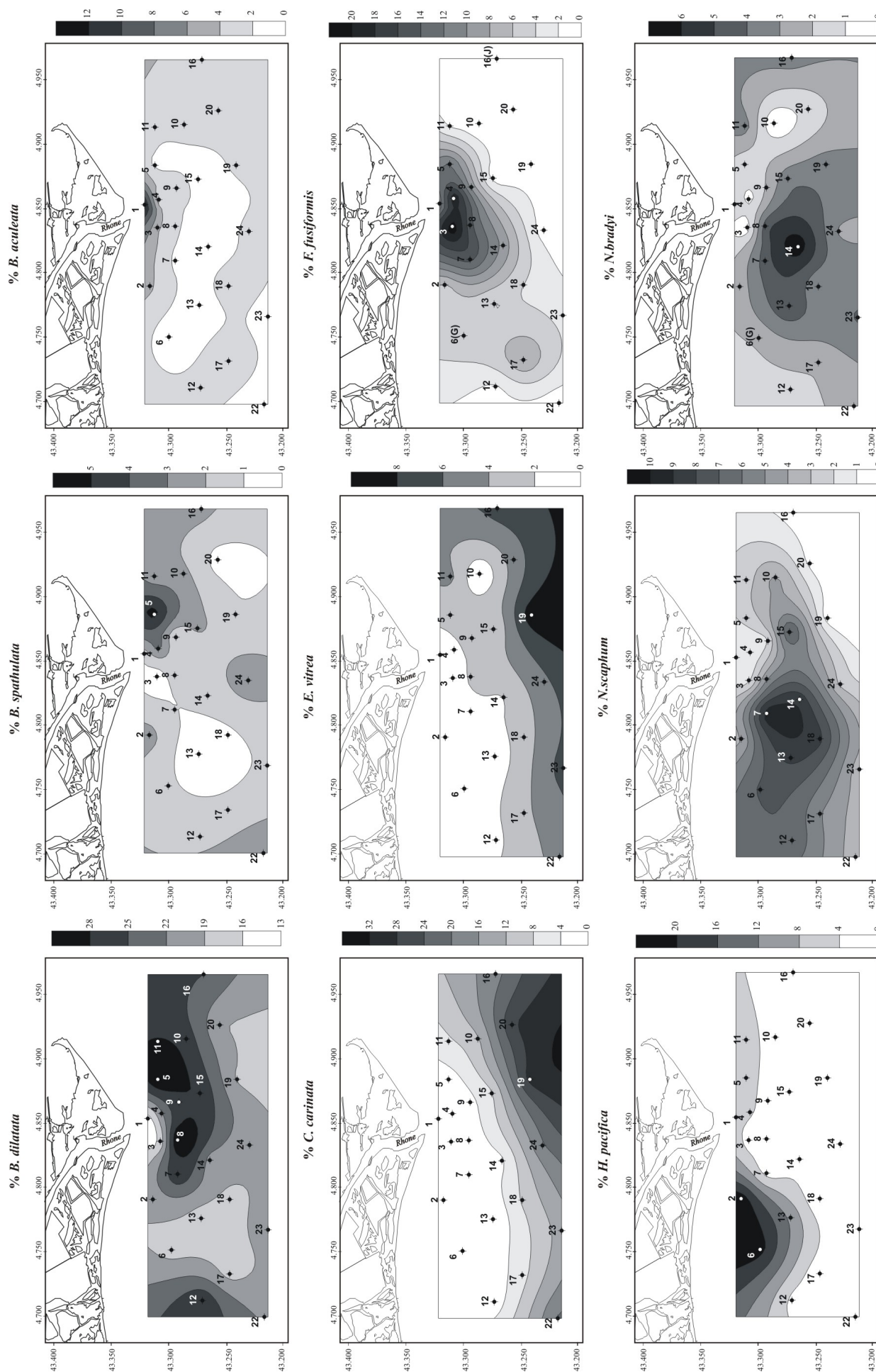


Figure 2-12. Spatial distribution of percentages of all species occurring with more than 5% in at least one sample in the > 63 μm fraction.

Spatial distribution of benthic foraminifera in the Rhône prodelta

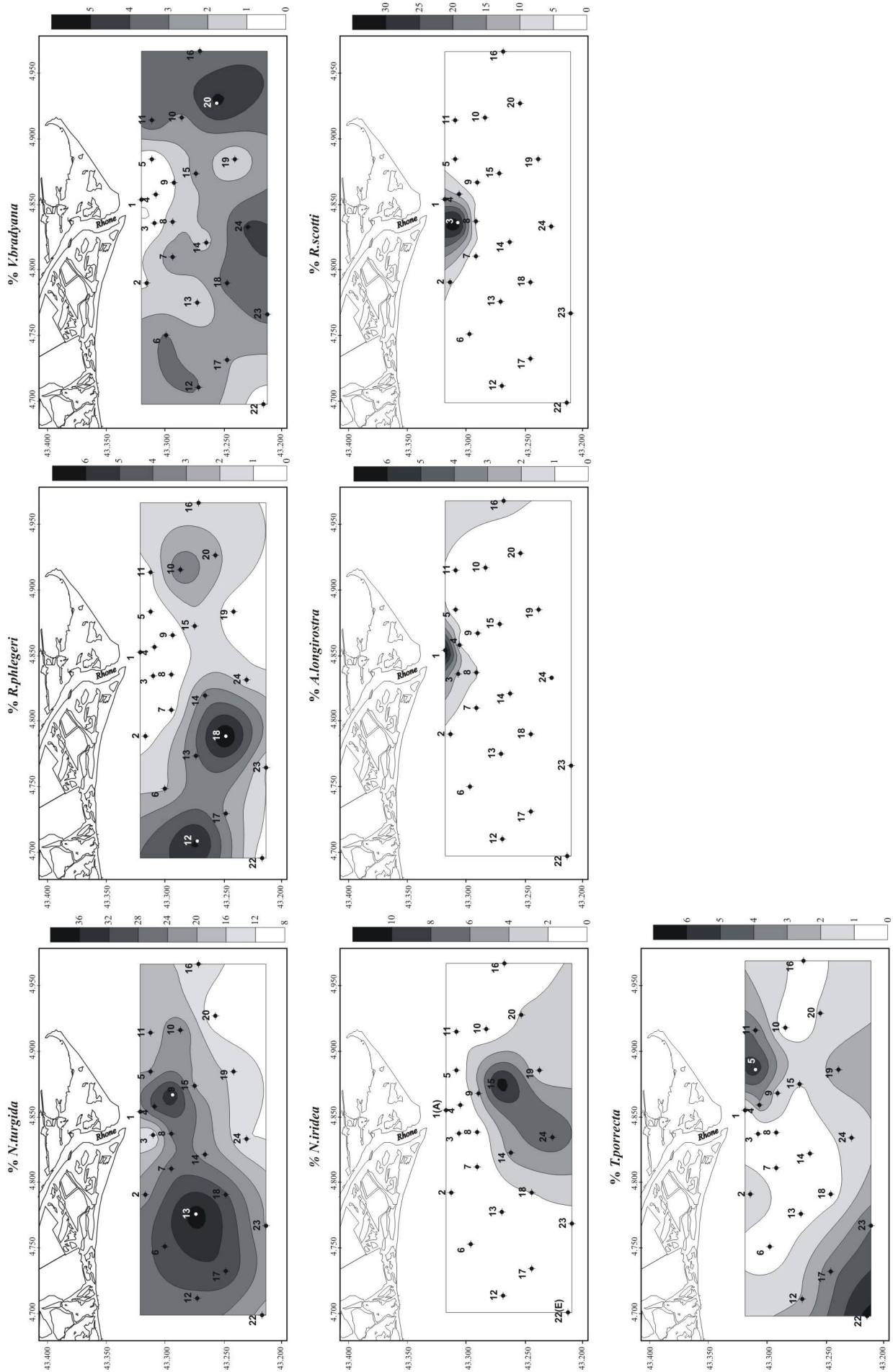


Figure 2-12 (continued).

A Principal Component Analysis has been performed on the basis on the percentage data (> 63  $\mu\text{m}$  fraction) of all taxa occurring with more than 5 % in at least one sample. The results of this PCA are presented in table 2-3 and in figure 2-13. Axis 1 (Eigenvalue = 6.25), axis 2 (Eigenvalue = 3.31) and axis 3 (Eigenvalue = 2.39) account respectively for 32.89 %, 17.45 % and 12.59 % of the total variation in the dataset.

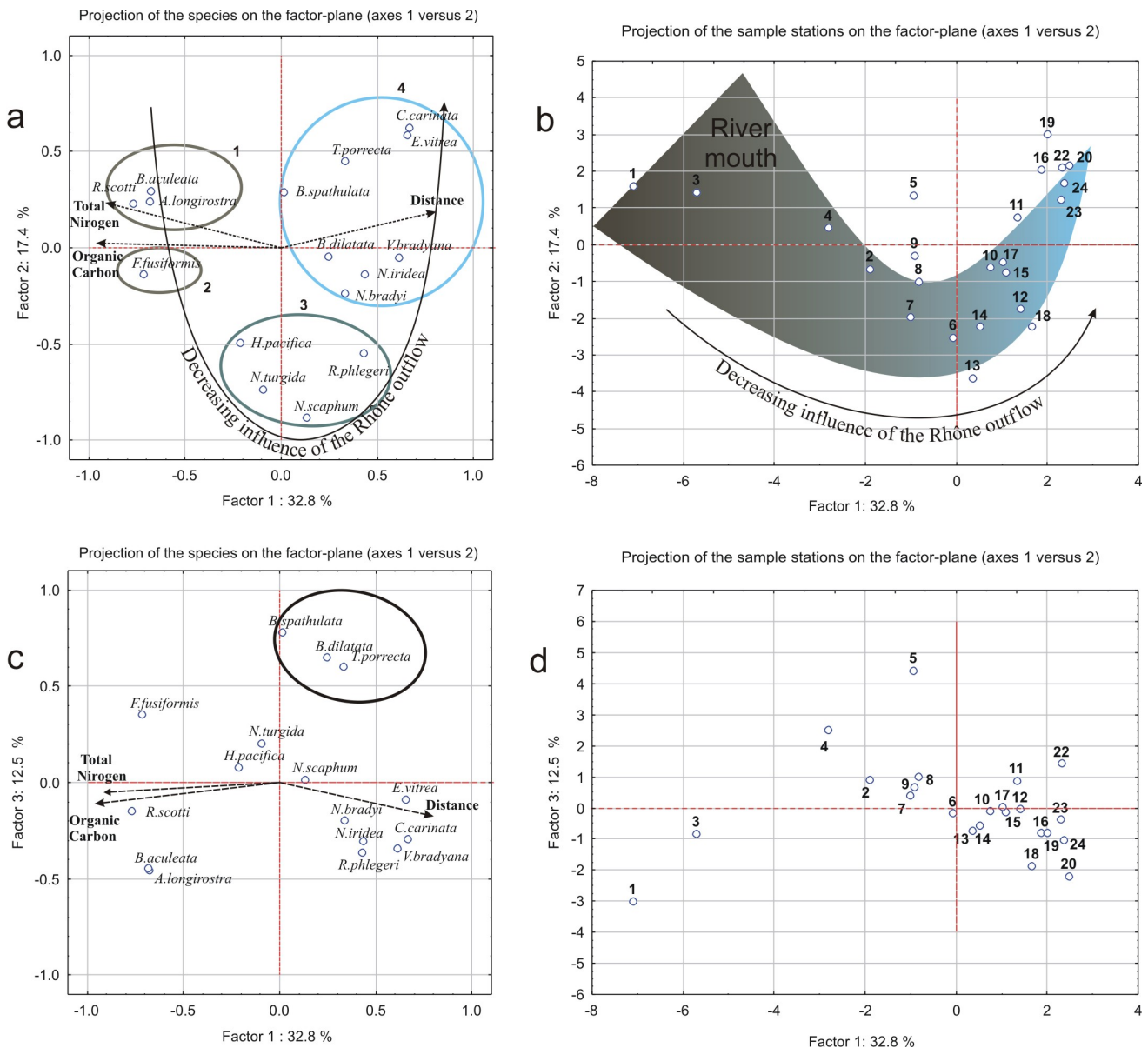


Figure 2-13. Principal Component Analysis. a. Projection of the variables (living benthic foraminifera; taxa > 63  $\mu\text{m}$  fraction) on the first two PCA axes together with organic carbon, total nitrogen and distance to the river mouth. Four distinct assemblages are recognised; b. Score plot of the 23 stations on the first two PCA axes and indication of decreasing river influence; c. Projection of the variables on the factor-plane determined by PCA axes 1 and 3 together with organic carbon, total nitrogen and distance to the river mouth; d. Score Plot of the 23 stations on the factor-plane determined by PCA axes 1 and 3.

Axis number	Eigenvalue	% Total variance	Cumulative % of variance
1	6.25	32.8	32.8
2	3.31	17.4	50.3
3	2.39	12.5	62.9
4	1.52	8.0	70.9
5	1.18	6.2	77.2
6	1.10	5.8	83.0
7	0.92	4.8	87.9
8	0.74	3.8	91.8
9	0.51	2.7	94.5
10	0.27	1.4	95.9

Table 2-3. Results of the Principal Component Analysis based on the percentages of Living foraminifera of the > 63  $\mu\text{m}$  fraction.

Figure 2-13 (a) shows the position of the species on the first two PCA axes. Also this analysis of the > 63  $\mu\text{m}$  fraction distinguishes four faunal assemblages. Group 1 composed of the species *R. scottii*, *B. aculeata*, *A. longirostra* as well as the second group composed uniquely of the species *F. fusiformis* have negative loadings on the first PCA axis whereas group 3 composed of *N. iridea/bradyi*, *V. bradyana*, *B. dilatata*, *T. porrecta*, *E. vitrea* and *C. carinata* have a positive contribution on this axis. *N. scaphum*, *R. phlegeri*, *N. turgida* and *H. pacifica*, composing the group 4, have negative loadings on the second PCA axis. Together with the species, we plotted organic carbon content, total nitrogen and distance to the river mouth. The first as well as the second assemblages dominate the faunas near the river mouth where important amounts of organic carbon and total nitrogen are recorded. The third assemblage is typical of faunas at the deeper stations far from the river influence, where low amounts of organic carbon and total nitrogen are found. The fourth assemblage dominates at intermediate distances and reflects intermediate amounts of organic matter.

Similarly to the > 150  $\mu\text{m}$  fraction (see Fig. 2-8 b), Figure 2-13 (b), which shows the position of the samples on the axial plot, puts into evidence a typical horse-shoe distribution on the factor plot (Hill and Gauch, 1980; Digby and Kempton, 1987). There appears to be a decreasing river influence from the upper left, to the lower centre, to the upper right of the plot.

Axis 3, that still accounts for 12.59 % of the total variability, is positively loaded by the small species *B. dilatata*, *B. spathulata* and *T. porrecta* (Fig. 2-13 c). This axis allows to separate the fauna of station 5 situated in the eastern part of the Rhône prodelta, at the shelter of river influence (Fig. 2-13 c).



When a cut-off level of 0.3 is applied, the cluster based on non-standardized percentage data (Fig. 2-14) (Davis, 1986) shows four major clusters with 2 subclusters in cluster III (Cluster I: *B. aculeata*, *A. longirostra*, *F. fusiformis* and *R. scottii*; Cluster II: *B. spathulata*, *T. porrecta* and *B. dilatata*; Cluster IIIa: *C. carinata*, *E. vitrea*, *V. bradyana*; Cluster IIIb: *N. iridea* and *N. bradyi*; Biofacies IV: *N. scaphum*, *R. phlegeri*, *N. turgida*). The spatial repartition of these four clusters (Fig. 2-15) indicates the presence of four major biofacial units that are very similar to those recognised by cluster analysis for the  $> 150 \mu\text{m}$  fraction: 1) the immediate vicinity of the river mouth where faunas are dominated by taxa of cluster I; 2) the eastern stations sheltered from the river influence, with faunas dominated by taxa of cluster II; 3) the deeper stations where the taxa of clusters IIIa and IIIb proliferate and 4) the stations influenced by the river plume where species of cluster IV dominate the fauna.

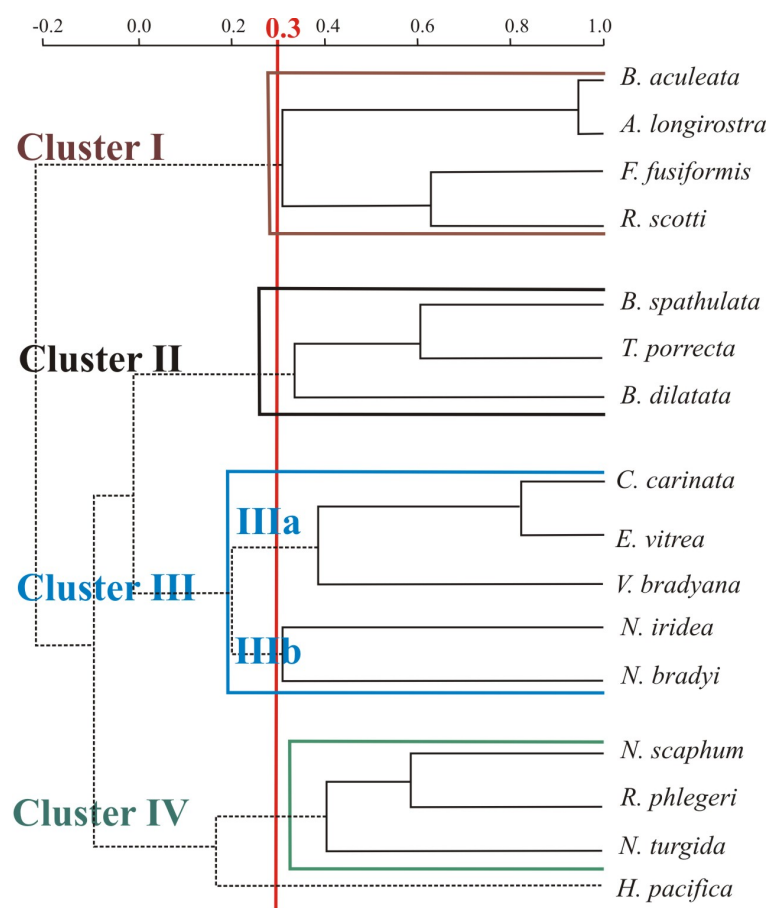


Figure 2-14. Cluster based on non-standardized percentage data of living foraminifera in the  $> 63 \mu\text{m}$  fraction (Davis, 1986).

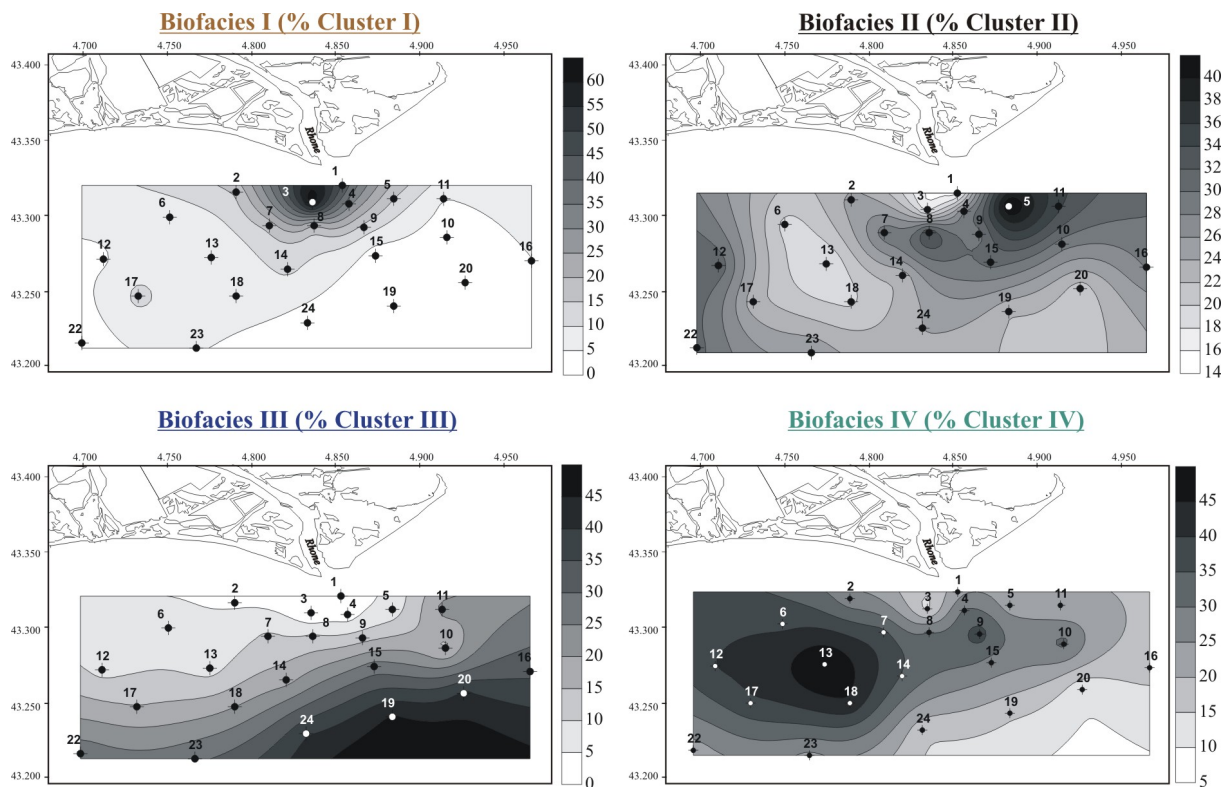


Figure 2-15. Spatial distribution of the foraminiferal assemblages of the  $> 63 \mu\text{m}$  fraction recognised by cluster analysis (Group I': *B. aculeata*, *A. longirostra*, *F. fusiformis*, *R. scottii*; Group II': *B. spathulata*, *B. dilatata*, *T. porrecta*; Group III': *C. carinata*, *V. bradyana*, *E. vitrea*, *N. iridea*, *N. bradyi*; Group IV': *N. scaphum*, *R. phlegeri*, *N. turgida*).

## 2.6 DISCUSSION

In the Rhône prodelta, due to the Rhône river supplies, a decreasing gradient of organic carbon and total nitrogen is present from the river mouth ( $C_{\text{org}} \sim 1.80 \%$  d.w.;  $N_{\text{tot}} \sim 0.21 \%$  d.w.) to the deepest stations ( $C_{\text{org}} \sim 0.80 \%$  d.w.;  $N_{\text{tot}} \sim 0.13 \%$  d.w.). The C/N ratio and the  $\delta^{13}\text{C}$  of the organic matter describe a change in the quality of the organic carbon with a clear tendency from a strong terrestrial signature close to the river mouth (C/N  $\sim 10.00$ ;  $\delta^{13}\text{C} \sim -27 \text{‰}$ ) gradually changing into a more marine signature towards the farthest stations (C/N  $\sim 6.00$ ;  $\delta^{13}\text{C} \sim -23 \text{‰}$ ). Because of the preferentially southwestern direction of the Rhône river plume due to the prevalent wind regime and the geostrophic circulation, the eastern part of the prodelta is more or less sheltered from river influence. This asymmetric distribution is clearly shown by the geographical distribution of organic carbon, the C/N ratio and the  $\delta^{13}\text{C}$  of the organic matter and also by oxygen penetration in the sediment which is a reflection of oxygen demand needed for organic matter recycling. This last parameter shows high values close to

the river mouth (Diffusive O<sub>2</sub> ~ 28.00 mmol/m<sup>2</sup>/d) where the oxygen penetration is minimal (~ 1.50 mm) and gradually decreases towards the farthest stations. The decrease in oxygen demand is strongest towards the eastern stations where minimal values are observed (Diffusive O<sub>2</sub> ~ 4.00 mmol/m<sup>2</sup>/d), and where the thickness of the oxic zone is maximal (~ 8.00 mm). We expected to find the same trend in bottom water oxygenation with low values near the river mouth gradually increasing towards the farthest stations. However, in the Rhône prodelta, the tendency is inverted. The high bottom-water oxygen concentrations close to the river mouth could be due to the strong hydrodynamics in this area. Consequently, benthic environments in this area are well oxygenated in spite of the important organic matter supply to this zone.

All these environmental parameters have to be considered when discussing the observed differences in abundance, species composition and biodiversity of the living benthic foraminiferal faunas from the river mouth towards the more distal stations. In many river influenced areas, organic enrichment and oxygen depletion in the bottom water co-occur and have an adverse effect on the benthic faunas (Jorissen, 1987; Van der Zwaan and Jorissen, 1991; Rabalais et al., 2001). We expected to find increased densities of some opportunistic taxa in the most enriched environments and eventually an increased mortality in response to seasonal hypoxia. However, in the case of our study, bottom waters were always well oxygenated. It is particularly important to quantify the interactions between these factors (organic enrichment and oxygen concentration in bottom and pore waters) in order to understand their effect on benthic ecosystems. Foraminiferal changes, caused by an increased supply of human-induced nutrients and seasonal bottom water hypoxia, have been noted in coastal seas around the world. The nutrient increase leads in some places to a strong dominance of the agglutinated faunal component (Nagy and Alve, 1987; Alve, 1991a, 1995a) and, more generally, to an increase in the abundance of opportunistic taxa (Nagy and Alve, 1987; Alve, 1991b). Barmawidjaja et al. (1995) studied changes in foraminiferal assemblages influenced by the supply of human-derived nutrients to the northern Adriatic Sea, and concluded that the increasing nutrient load and consequent oxygen stress led to the increase in abundance of a number of stress-tolerant taxa (e.g., *Nonionella turgida*, *Hopkinsina pacifica*, *Bolivina seminuda*). Platon et al. (2005) suggested that historical changes in the foraminiferal community in the Louisiana Bight were related to the increase in nutrients and bottom water hypoxia over the last 100 years. In this area, the genus *Quinqueloculina* nearly became extinct due to hypoxia, whereas several hyaline taxa, such as *Nonionella basiloba*, *Buliminella morgani* and *Epistominella vitrea*, tolerated the increase of hypoxia in the Louisiana Bight

over the last 100 years (*Platon et al., 2005*). In most benthic environments, the oxygen concentration is the prime factor limiting benthic life; low oxygen values are responsible for low faunal densities within the sediment of some of the most organic-rich areas. *Jorissen et al. (1992)* suggested that, in the Adriatic Sea, when in late autumn the oxygen concentration rises above a critical threshold value, food availability becomes the limiting factor, regulating abundance and species composition of the benthic faunas. Areas with a high downward organic flux but still bearable oxygen levels are characterized by a number of highly opportunistic taxa, which can be epifaunal as well as potentially (mobile) infaunal. These taxa would be capable to profit from the combination of high food availability and supportable oxygen levels after the recurrent reoxygenation of the bottom environment in late autumn/early winter. The areas with lower organic fluxes are characterized by a more stable fauna, consisting of less stress-tolerant epifaunal taxa in combination with less mobile infaunal species, which lack the possibility to track critical oxygen levels (*Jorissen et al., 1992*).

As we saw before, in the Rhône prodelta, the bottom water was everywhere well oxygenated ( $O_2 \sim 215\text{--}260 \mu\text{mol/l}$ ) during our sampling campaign in June 2005. However, oxygen penetration into the sediment was always very limited (1 to 8 mm), and slightly increased farther from the river mouth. Foraminiferal densities in the Rhône prodelta, vary from about 22 ind./100 cm<sup>2</sup> to 1880 ind./ 100 cm<sup>2</sup> in the > 150  $\mu\text{m}$  fraction in the first five centimetres of the sediment and of about 1225 ind./ 100 cm<sup>2</sup> to 10250 ind./ 100 cm<sup>2</sup> in the 63-150  $\mu\text{m}$  fraction in the first centimetre of the sediment. When we sum both fractions for the first centimetre of the sediment, a total of about 1250 ind./ 100 cm<sup>2</sup> to 11200 ind./ 100 cm<sup>2</sup> is found. These values are about 10 times higher than those found by *Murray (1969; 1985; 1992)* at outer shelf sites off Long Island (USA), off western Scotland and in the North Sea. The benthic foraminiferal faunas found at our stations are generally dominated by *B. aculeata*, *B. dilatata*, *B. spathulata*, *C. carinata*, *E. vitrea*, *F. fusiformis*, *H. pacifica*, *N. iridea*, *N. scaphum*, *N. turgida*, *V. bradyana*, and *T. porrecta*. This faunal composition is comparable to that found at the Portuguese continental shelf (*Levy et al., 1985, 1993*) or on the “Grande Vasière” in the French Atlantic continental shelf characterized by a large accumulation of muddy-silty sediments originating mainly from the Loire and the Garonne rivers (*Duchemin et al., 2005*) and also to the foraminiferal assemblages in the immediate vicinity of the Po river in the Northern Adriatic sea (*Barmawidjaja et al., 1992*).

We decided in this paper to present foraminiferal data from the large size fraction (> 150  $\mu\text{m}$ ) and from the addition of both large and fine fractions (> 63  $\mu\text{m}$ ) separately. In the

literature, most faunal and ecological interpretations are based on the data from the coarse fraction ( $> 150 \mu\text{m}$ ). However, faunas of the fine fraction (63-150  $\mu\text{m}$ ) contain in general higher densities of juvenile specimens of larger taxa but also several small-sized species that occur exclusively in this size fraction. It appears therefore important to study both size fractions in order to arrive at a better ecological interpretation.

On the basis of the  $> 150 \mu\text{m}$  fraction of our stations, four foraminiferal assemblages can be recognized (Fig. 2-10): Assemblage I, composed by the species *E. macellum*, *N. turgida*, *Q. seminula* f. *longa* and *A. beccarii* f. *inflata*, is mainly found close to the river mouth where it dominated faunas with low densities and biodiversity. Assemblage II is composed of the agglutinated species *A. glomeratum*, *T. agglutinans* and *E. foliaceus* that are typical of the eastern part of the Rhône prodelta that is less influenced by river input. Assemblage III dominates the faunas in the deepest stations, far from the river mouth and is composed of the species *C. carinata*, *B. aculeata*, *M. barleeanus* and *R. trochaminiformis*. Finally, assemblage IV, that seems to be characteristic of sites influenced by the river plume, is mainly composed of the species *N. scaphum* and *R. phlegeri*.

While looking at the response of the entire fauna (63-150 fraction +  $> 150 \mu\text{m}$  fraction), we can see that the small-sized species are dominant and present much higher densities (Fig. 2-12). Again, four distinct assemblages can be recognised (Fig. 2-15). They are composed of juveniles of taxa also occurring in the large fraction (e.g. *N. scaphum*, *N. turgida*, *B. aculeata*, *R. phlegeri*, *C. carinata*, *R. scottii*, *V. bradyana*) but also contain several small sized species (e.g. *B. dilatata/spathulata*, *E. vitrea*, *N. iridea/bradyi*, *F. fusiformis*, *H. pacifica*). We can notice that *B. aculeata* belongs to the group of species composing cluster III in the larger fraction whereas in whole fauna, this species makes part of taxa from cluster I and occurs especially at the river mouth. The small-sized individuals of this species occurring near the river mouth present a different morphology “*B. aculeata* forma *elongata*”. Although, these two morphotypes are close morphologically but they appear to have different ecological requirements. *Jorissen (1988)* found the *elongata* morphotypes proliferating in very shallow water (30 m depth) near the Italian coast in front of the Po River whereas the typical *aculeata* morphotype inhabit deeper stations (from 30 to 200 m depth). Likewise, the large individuals of the species *N. turgida* are concentrated in the vicinity of the river mouth (cluster I) whereas small-size individuals of the same species are very abundant and dominant at the stations influenced by the river plume (cluster IV). All other species occurring in both size fractions (e.g. *C. carinata*, *R. phlegeri*, *N. scaphum*) present the same distribution in both analyses.

It should be noticed that generally, in the Rhône prodelta, very fine sediments are present in the whole area with very low oxygen penetration. Nevertheless, in more detail, the study of foraminiferal faunas in both small and total size fractions (Figs. 2-10 and 2-15) has allowed us to recognise a spatial pattern with four main biofacies in response to the various ecological parameters. In the following discussion, we choose to concentrate on the total fraction (63-150  $\mu\text{m}$  + > 150  $\mu\text{m}$ ), which is the most representative of the total fauna.

	Location	> 63 $\mu\text{m}$ fraction	> 150 $\mu\text{m}$ fraction
Cluster I	Stations close to the river mouth	<i>B. aculeata</i> f. <i>elongata</i> , <i>A. longirostra</i> , <i>F. fusiformis</i> , <i>R. scottii</i>	<i>N. turgida</i> , <i>Q. seminula</i> f. <i>longa</i> , <i>A. beccarii</i> f. <i>inflata</i> , <i>E. macellum</i>
Cluster II	Eastern stations	<i>B. spathulata</i> , <i>T. porrecta</i> , <i>B. dilatata</i>	<i>A. glomeratum</i> , <i>E. foliaceus</i> , <i>T. agglutinans</i>
Cluster III	Deepest stations	<i>C. carinata</i> , <i>E. vitrea</i> , <i>V. bradyana</i> , <i>N. iridea</i> , <i>N. bradyi</i>	<i>B. aculeata</i> , <i>C. carinata</i> , <i>M. barleaanus</i> , <i>R. trochaminiiformis</i>
Cluster IV	Stations influenced by the river plume	<i>N. scaphum</i> , <i>R. phlegeri</i> , <i>N. turgida</i>	<i>N. scaphum</i> , <i>R. phlegeri</i>

Table 2-4. Table summarizing the main foraminiferal species found in the > 150  $\mu\text{m}$  fraction and in the > 63  $\mu\text{m}$  fraction.

- **Biofacies I** groups stations close to the river mouth. This area is characterised by high organic carbon and total nitrogen amounts, an organic matter with a partially continental signature and a very high oxygen demand leading to a very low oxygen penetration into the sediment. The fauna in this area is characterized by low densities of some species known in the literature to be tolerant to high food input and/or to oxygen depletion (*B. aculeata* forma *elongata*, *F. fusiformis*, *R. scottii* and *A. longirostra*).

*Bulimina aculeata* is an infaunal continental shelf to slope taxon (e.g. *Jorissen et al., 1998*), that has often been considered as an indicator of high food availability (see *Lutze and Colbourn, 1984*, *Jones and Charnock, 1985*; *Corliss, 1985*; *Corliss and Chen, 1988*; *Mackensen and Douglas, 1989*; *Debenay and Redois, 1997*; *Schmiedl et al., 1997*). It has been reported in a recent study as dominant taxon in an assemblage that is present in the oxygen minimum zone related to the upper Circumpolar Deep Water in Campbell and Bounty Plateaux (New Zealand) (*Hayward et al., 2007*). In a study of the impact of oil drill cutting discharges at the outer continental shelf off Congo, *Mojtahid et al. (2006)* showed that *B. marginata/aculeata* tolerates the low oxygen concentration at the discharge point, and shows an opportunistic response to anthropogenic enrichment. In the eastern Indian Ocean, this

taxon was used as an indicator of episodes of increased organic matter supply to the sea floor over the last 30 kyrs (*Murgese et al., 2007*). Moreover, the morphotype *elongata*, that occurs in the Rhône prodelta near the river mouth, has already been described by *Jorissen (1988)* as typical of very shallow waters in front of the Italian coast that is subject to important organic supplies from the Po River. *Bulimina elongata* makes part of the foraminiferal assemblage that inhabits the outer inner Guadiana shelf (Southwestern Iberia). It occurs between 12 and 40 m water depth and is influenced by high turbidity and storm waves (*Mendes et al., 2004*). *Eichler et al. (2003)* considered this species as a eutrophic taxon that flourishes under low oxygen concentration and under conditions of rapidly accumulating organic matter in the Guanabara Bay (Brazil).

High abundances of various species of *Fursenkoina* and *Stainforthia* are often indicative of a combination of high productivity and low oxygen conditions (*Leutenegger and Hansen, 1979*). In fossil records, *Fursenkoina* spp. can be found in pre- and post-sapropel assemblages and it is considered therefore to be tolerant to low oxic and dysoxic conditions (*Jorissen, 1999*). *Fursenkoina fusiformis* dominates the assemblages in the North Sea and has been considered as indicative of abundant organic matter supplies accompanied by low oxygenation (*Alve, 1994, 1995b*). This opportunistic species is typical of organically enriched sublittoral environments where it is sometimes extremely abundant (*Alve, 1994*) in infaunal microhabitats (*Moodley, 1990; Alve and Bernhard, 1995*). Rich populations of *F. fusiformis* (*Alve, 1994*) have also been recovered from sulphidic habitats in the dysoxic sediments of Norwegian fjords (*Bernhard and Bowser, 1999*).

The genus *Adelosina* makes part of the foraminiferal assemblage living in front of the Gediz River (Gulf of Izmir, Eastern Aegean Sea) affected by domestic effluents and aquaculture activities (*Bergin et al, 2006*). This genus was related to marine brackish waters in a study of reconstruction of Holocene palaeoenvironment and sedimentation history of the Ombrone alluvial plain (South Tuscany, Italy) (*Biserni et van Geel, 2005*) and is also found living in brackish waters of the Northwestern Mediterranean coast of Egypt characterized by excessive turbidity (*Samir et al., 2003*). This genus was equally found in an assemblage located in the immediate vicinity of a pipeline discharging industrial waste into two Egyptian bays (*Samir et al., 2001*).

In a recent study using benthic foraminifera of historical reconstructions in the aim to monitor pollution in North America estuaries, *Reophax scotti* is considered as an indicator of a higher influx of organic carbon to the sediment surface. Indeed, this species occurs in high

percentages in areas with a high organic load and high suspended particulate matter in the Halifax Harbour, which is affected by domestic sewage (Scott *et al.*, 2005).

In the Rhône prodelta, these characteristic species of the river mouth, seem to be resistant to the stress conditions (turbidity, important organic input, fresh water, low oxygen penetration into the sediment) occurring in this area. The cumulative frequencies of the taxa characteristic of this river-mouth biofacies (*B. aculeata*, *F. fusiformis*, *A. longirostra* and *R. scottii*) in the > 63 µm fraction show positive correlations with the percentages of organic carbon, with the presence of continental organic matter (as indicated by the low  $\delta^{13}\text{C}$  and high C/N ratio), and a negative correlation with the penetration depth of oxygen into the sediment (oxygen penetration limit was estimated according to the contouring by *Surfer software* on the basis of measurements performed at 10 stations) (Fig. 2-16). The cumulative percentages of the equivalent assemblage found in the > 150 µm fraction (cluster I) shows the same tendency but with much weaker correlations with the environmental parameters (Fig. 2-16; Table 2-4).

- Biofacies II is composed of *B. dilatata/spathulata* and *T. porrecta* that occur in general in the whole area with percentages around 20 %. This assemblage attains maximal densities in the northeastern part of the study area, where it reaches 40 % at station 5.

The dominant species of this assemblage, *B. dilatata/spathulata* are generally considered to be indicators for dysoxic environments combined with high organic matter input (e.g. Gooday, 1994; Bernhard and Sen Gupta, 1999). According to this adaptation, *B. dilatata* prefers a shallow to intermediate infaunal microhabitat (e.g. Corliss, 1991; Barmawidjaja *et al.*, 1992; De Stigter *et al.*, 1998; Jannik *et al.*, 1998). In the Mediterranean region, this species is particularly abundant in low-oxic to suboxic environments of the Marmara Sea (Alavi, 1988). In the modern Mediterranean Sea, *B. dilatata/spathulata* and *Bolivina seminuda* commonly occur together in a wide range of mesotrophic to eutrophic settings (Barmawidjaja, 1991; Barmawidjaja *et al.*, 1992, Jorissen *et al.*, 1995; De Stigter *et al.*, 1998; De Rijk *et al.*, 2000; Schmiedl *et al.*, 2000, Duijnste, 2001). Jannink *et al.* (1998) and Maas (2000) described these species from surface sediments within the oxygen minimum zone of the NE Arabian Sea.

In the Rhône prodelta, the cumulative percentage of species composing biofacies II (*B. dilatata/spathulata* and *T. porrecta*) do not have a clear correlation with the measured environmental parameters (organic carbon, oxygen penetration,  $\delta^{13}\text{C}$  and C/N ratio) (Fig. 2-17). Also, the equivalent assemblage from the > 150 µm fraction (cluster II) that occurs



mainly at station 10 does not show any correlation with environmental measurements (Fig. 2-17; Table 2-4).

- Biofacies III regroups the deepest stations farthest away from the river mouth. The sediments of this area are characterised by low organic carbon and total nitrogen amounts, an organic matter of marine signature and low oxygen demand leading to relatively high oxygen penetration into the sediment. The fauna in this area contains intermediate densities of the species *C. carinata*, *E. vitrea*, *V. bradyana*, *N. iridea* and *N. bradyi*.

In the literature, *Cassidulina* species have been considered as opportunistic species (Nees and Struck, 1999). *C. carinata*, which is a dominant species at the deepest stations, can be found in areas with sustained organic input on the continental shelf and open slope of east New Zealand (Hayward et al., 2002). At a French upper middle bathyal station in the Bay of Biscay, it appears to respond quickly to a labile organic matter input by a reproductive event (Fontanier et al., 2003).

*Epistominella vitrea* has specifically been recognized as having a preference for low-oxygen/organic-rich conditions of hypoxic areas (Blackwelder et al., 1996, Bernhard and Sen Gupta, 1999, Sen Gupta, 2001). Murray (1991b) and Mendes et al. (2004) found this species living in muddy sediments at 40 to 95 m water depths. The morphologically close species *Epistominella exigua* was found by Barmawidjaja et al. (1992) in Adriatic Sea at approximately 50 m depth in the outer part of the clayey area.

In the Adriatic Sea, Jorissen (1987) describes a minimum water depth of 40 m for *Valvulineria bradyana*, in the outer part of the organic carbon enriched clay belt. Verhallen (1991) shows that this species is an excellent marker of high benthic productivity. In a more recent study, this taxon seems to combine a preference for high quality resources (or a low tolerance for low quality food), a high competitiveness and perhaps a low tolerance for anoxic conditions (Fontanier et al., 2002).

Duchemin et al. (2005) suggest that the very high densities of *N. iridea* in spring, from the “Grande Vasière” at about 100 m water depth, on the French Atlantic continental shelf, are a response to the organic matter flux resulting from the spring phytodetritus bloom. The species *Nonionella iridea* is reported in few papers describing deep-sea faunas from the north Atlantic (Goody, 1986; Goody and Hughes, 2002), off Antarctica (Mackensen et al., 1990; Harloff and Mackensen, 1997) and the New Jersey continental margin canyons (Swallow and Culver, 1999). All these studies report *N. iridea* in relatively deep sites (456 m to 1920 m) that probably receive much lower organic fluxes than our outer shelf sites. Goody and Hughes

(2002) have shown a strong seasonal increase of *N. iridea* after a phytodetritus deposit. All available data suggest that *N. iridea* can withstand relatively low background organic flux values but responds to pulsed arrivals of phytodetritus by accelerated response allowing it to dominate the assemblages.

In the Rhône prodelta, these characteristic species of the farthest stations from the river mouth seem to compose the common assemblages that occur in such eutrophicated continental shelves at water depths ranged from about 50 to 100 m. They seem also to respond to a more labile organic matter from marine signature. Indeed, the cumulative percentages of the species composing biofacies III (*C. carinata*, *E. vitrea*, *V. bradyana* and *N. iridea/bradyi*) in the > 63 µm fraction (Table 2-4), show a negative correlation with the percentages of organic carbon, with the presence of organic matter with a marine signature (as indicated by the high  $\delta^{13}\text{C}$  and low C/N ratio), and a positive correlation with the penetration depth of oxygen into the sediment (Fig. 2-18). Again, the equivalent assemblage found in the > 150 µm fraction (cluster III) (Table 2-4) shows the same tendency but with weaker correlations with the environmental parameters (Fig. 2-18).

- Biofacies IV groups all stations under the influence of the river plume. Sediments in this area are characterised by intermediate organic carbon and total nitrogen contents, an organic matter with a partially continental signature and a high oxygen demand leading to a low oxygen penetration into the sediment. The fauna in this area presents low density in the centre of this area that contrasts with maximum densities found at the edge of this zone under the influence of the river plume (stations 12 and 14). The faunas are dominated by *N. turgida* and *N. scaphum* and *R. phlegeri*.

*Barmawidjaja et al. (1995)* studied the changes in foraminiferal assemblages influenced by the supply of human-induced nutrients to the northern Adriatic Sea, and concluded that the increasing nutrient load and consequent stress led to the increase in abundance of a number of stress-tolerant taxa (e.g., *Nonionella turgida*, *Hopkinsina pacifica*). *N. turgida* reflects upwelling in the Rías Baixas in NW Spain (*Diz et al., 2002*), while, in recent sediments of the Tagus Prodeltá in the western Iberian margin, *Rectuvigerina phlegeri* prefers sediments closer to the Tagus River plume (in *Bartels-Jónsdóttir et al., 2006*). *Diz et al., (2006)* describe this taxon as an opportunistic species that react quickly to the input of labile organic matter, probably colonising the labile organic aggregates. *Corliss and Silva (1993)* and *Silva et al. (1996)* found that *Nonionella stella* (a morphotype close to *N. turgida*) matured in less than 3 months after a phytodetritus event while *Gustafsson and Nordberg (2001)* showed that

deposited phytoplankton is the main food resource for *N. turgida* and this taxon can reproduce and arrive at an adult stage in less than a month.

Also *Nonion scaphum* is often described as an opportunistic species. Normally, this species lives at a certain depth in the sediment but it may migrate to the sediment surface in reaction to increase organic matter input at the seafloor (*Langezaal et al., 2004, Langezaal et al., 2006, Fontanier et al., 2003*). This species is also reported as characteristic for the upwelling system off Portugal (*Levy et al., 1993*).

In the Rhône prodelta, this characteristic assemblage of stations under the influence of the river plume, seem to be resistant to the stress conditions occurring in the centre of this area (important organic matter input of predominantly continental signature and low oxygen penetration into the sediment) and very opportunistic at the edge of this zone profiting from the mixture of continental and marine organic carbon. Figure 2-19 shows the correlation between cumulative percentages of the species composing biofacies IV and the physico-chemical parameters. For a better understanding of the factors that are responsible for the presence of this biofacies, we did not represent stations 1 and 3 located in the vicinity of the river mouth that present very specific conditions and are mainly inhabited by the species from biofacies I. In the Rhône prodelta, this assemblage (*N. scaphum, R. phlegeri and N. turgida*) in the > 63 µm fraction shows a positive correlation with the content of organic carbon. However, it is more visibly correlated with organic matter of partially continental signature (C/N ratio) that characterises the river plume. We can also see a weak negative correlation with oxygen penetration into the sediment. In the > 150 µm, the same tendency can be observed.

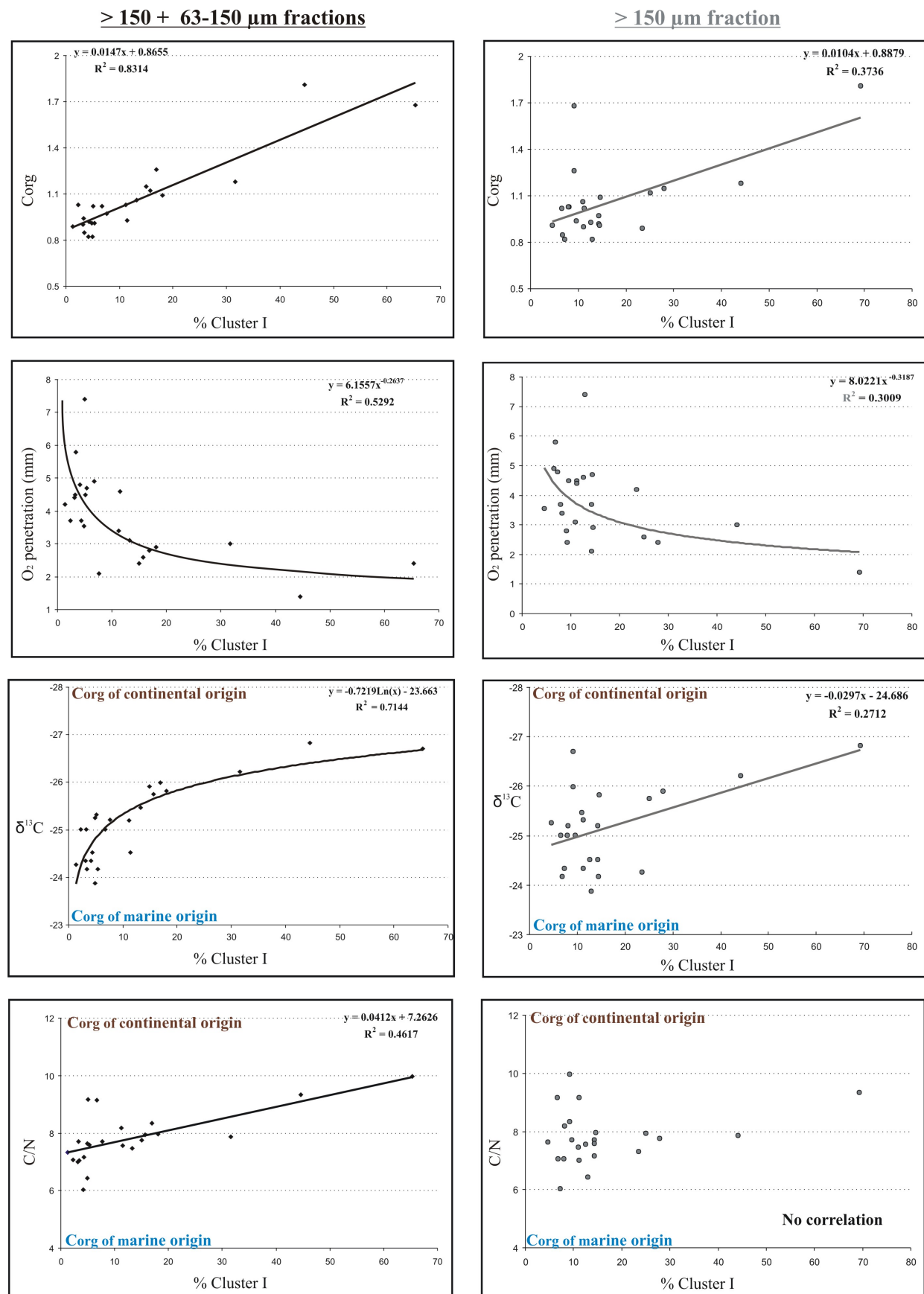


Figure 2-16. Correlation between the percentages of cluster I in the > 63 μm fraction and cluster I in the > 150 μm fraction with % of organic carbon, oxygen penetration into the sediment, δ<sup>13</sup>C and C/N ratio.

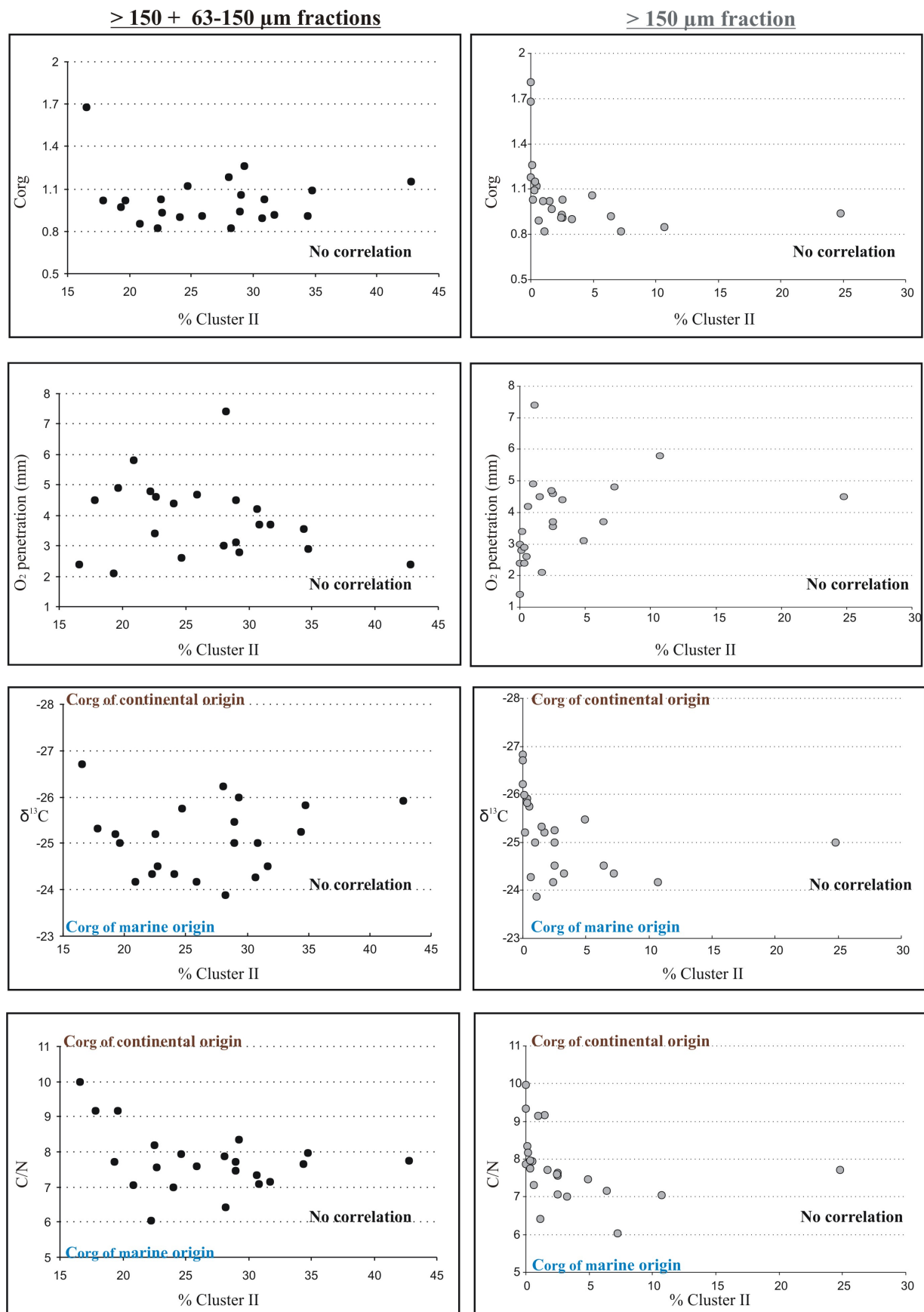


Figure 2-17. Correlation between the percentages of cluster II in the  $> 63 \mu\text{m}$  fraction and cluster III in the  $> 150 \mu\text{m}$  fraction with % of organic carbon, oxygen penetration into the sediment,  $\delta^{13}\text{C}$  and C/N ratio.

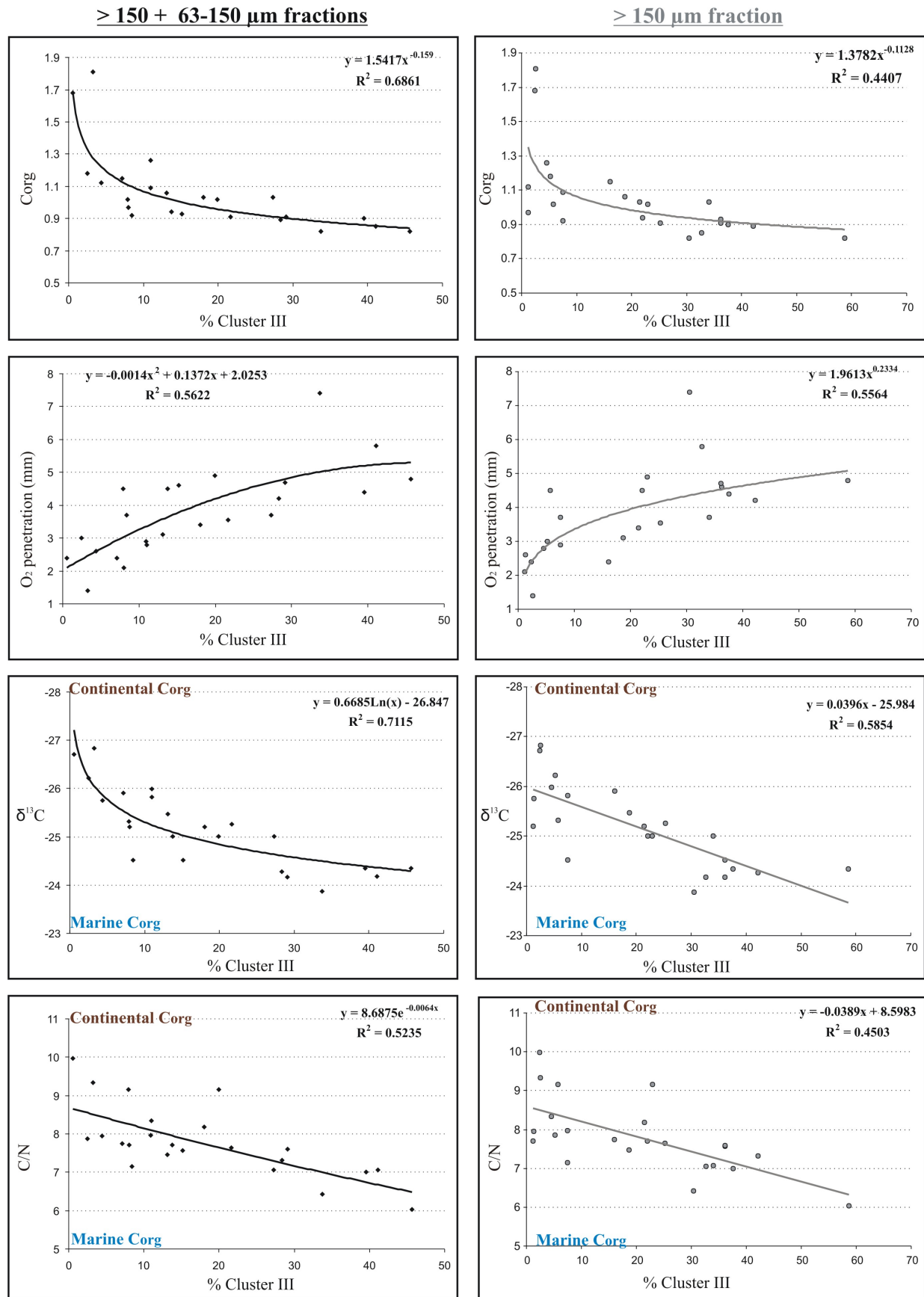


Figure 2-18. Correlation between the percentages of cluster III in the  $> 63 \mu\text{m}$  fraction and cluster III in the  $> 150 \mu\text{m}$  fraction with % of organic carbon, oxygen penetration into the sediment,  $\delta^{13}\text{C}$  and C/N ratio.

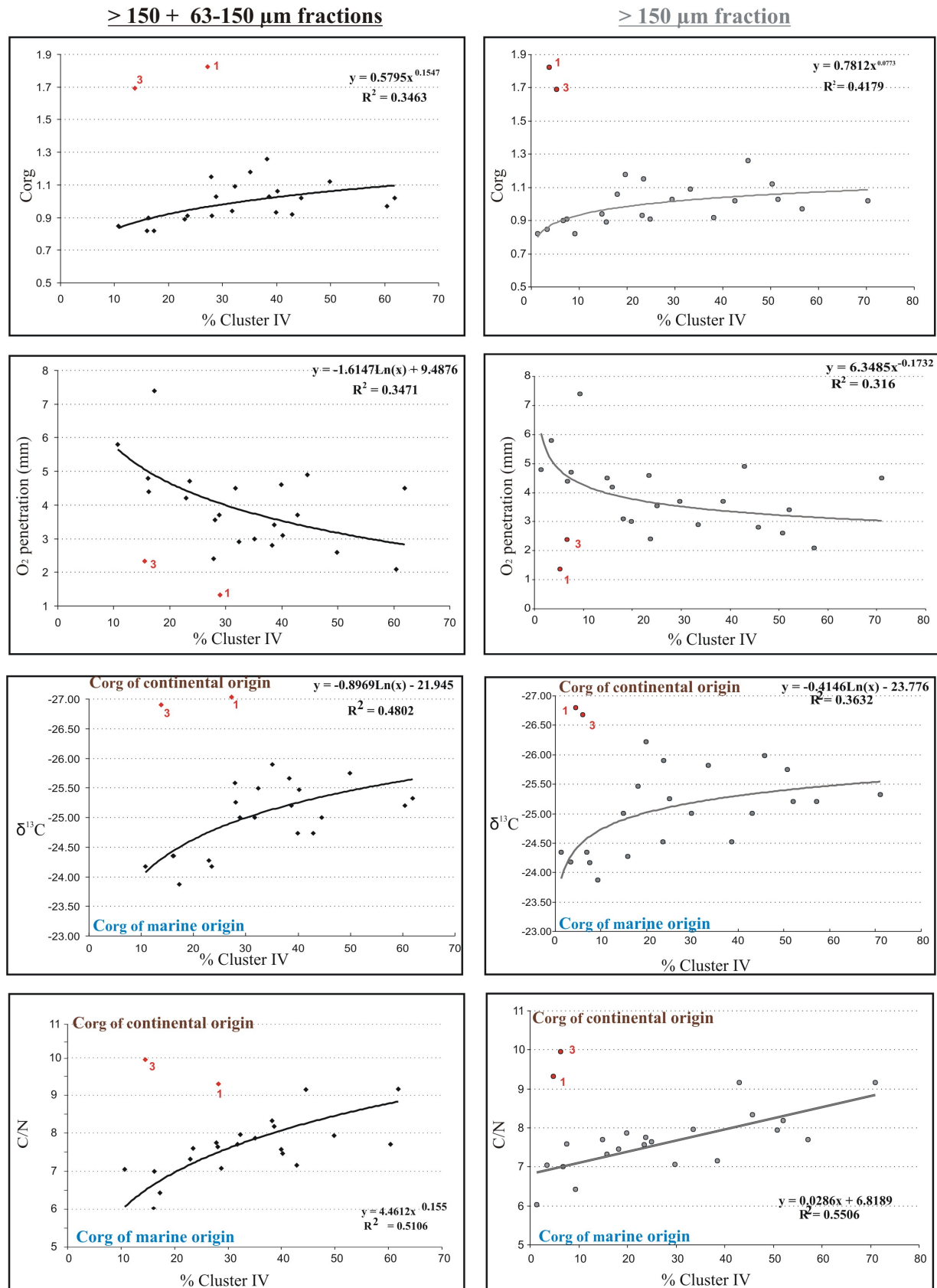


Figure 2-19. Correlation between the percentages of group IV in the > 63 μm fraction and cluster IV in the > 150 μm fraction with % of organic carbon, oxygen penetration into the sediment, δ<sup>13</sup>C and C/N ratio. Stations 1 and 3 have not been taken into account for the calculation of the correlation coefficient.

## 2.7 SYNTHESIS

It should be realised that everywhere in the Rhône prodelta, the sediment is rich in organic carbon (0.8 - 1.9 %), and oxygen penetration is very limited (1 - 8 mm only). Consequently, all faunas found in the Rhône prodelta (I - IV) are composed of taxa typical of eutrophicated and of hypoxic conditions. In spite of these overall characteristics, it has been possible to make a subdivision into four faunal assemblages representing four different biofacies which reflect the extent of the river input. The river influence is a complex of many environmental parameters. Therefore, it is not easy to identify individual factors that are responsible for the foraminiferal response. The most obvious parameters that change in function of the river input are the quality and the quantity of the organic matter. Close to the river mouth important amounts of organic carbon from mainly continental origin are present. Farther away, the organic carbon arriving at the sea floor decreases progressively and acquires a more marine signature.

It can be seen in the PCA analyses that stations are ordered along a decreasing gradient of river influence from the closest to the farthest stations from the river mouth.

Low densities and biodiversity are observed in the immediate surroundings of the river mouth (stations 1, 3, 4, 5) composed essentially of species very tolerant to stress conditions and in the southwestern main corridor under the influence of the river plume (stations 2, 6, 7, 8, 13 and 17), composed mainly of species known in the literature to have an opportunistic behaviour. Very high densities of these species are observed at the edge of this corridor (stations 12 and 14). Towards the east and towards the deepest stations, the faunal biodiversity increases. Faunas at these stations are present in intermediate densities and contain species that are typical of the outer part of the organic enriched area.

Close to the river mouth and in the southwestern direction of the river plume, environmental conditions appear to be stressful for the benthic foraminiferal fauna. In the immediate vicinity of the river mouth, this environmental stress could be due to fresh water input, to turbidity or to low oxygen penetration into the sediment. Species of biofacies I in the > 150  $\mu\text{m}$  fraction and in the > 63  $\mu\text{m}$  fraction (Table 2-4) appear to be well adapted to this environmental stress. At the southwestern stations influenced by the river plume, high organic



input with a dominantly terrestrial signature (more refractory) may be stressful for many taxa which need organic matter of a more labile quality. In this area, *N. scaphum*, *N. turgida* and *R. phlegeri* are present in low densities in response to the high organic matter input. On the edge of this area, where the carbon organic input is still important, the mixture of continental and marine organic carbon becomes more favourable to the proliferation of *N. scaphum*, *N. turgida* and *R. phlegeri*, that show high densities, reflecting their highly opportunistic behaviour. At stations sheltered from the river influence (distal and eastern stations), environmental stress appears to be less important and the fauna seems to respond to a more marine organic matter. Faunal clusters II and III in the  $> 150 \mu\text{m}$  fraction and in the  $> 63 \mu\text{m}$  fraction seem to be well adapted to these non-stressed conditions.

To better show the changes in foraminiferal composition in response to river influence, we present in figure 2-20, the relative abundance of the main species along NE-SW transect, from the vicinity of the river mouth (stations 1, 3), towards the southwest (stations 7, 13 and 17) until the deep station 22. We can see clearly the succession of the main 3 biofacies along this transect.

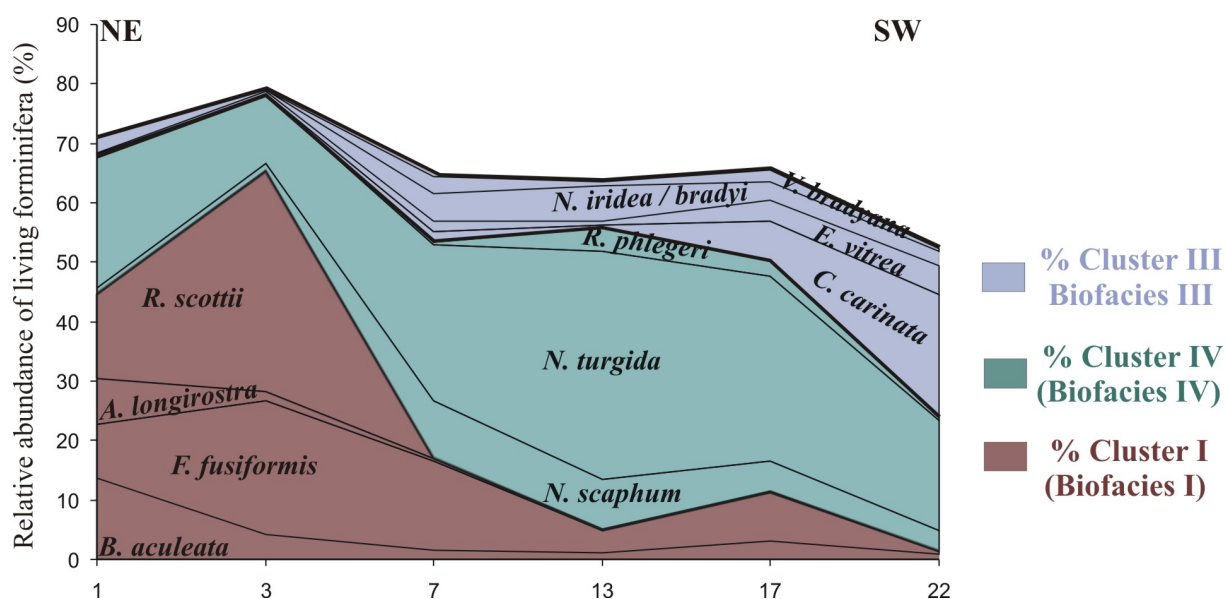


Figure 2-20. Relative abundance of the main species ( $> 63 \mu\text{m}$  fraction) found along the transect following the main NE to SW corridor under the influence of the river plume (stations 1, 3, 7, 13, 17 and 22).

To better see the enriched area at the edge of the main corridor influenced by the river plume, we present in figure 2-21, the total densities of the main faunal clusters along a NW-

SE transversal transect from the area influenced by the river plume (stations 12, 6, 13 and 14) to deepest station 19. We can see that at the edge of the river plume area (stations 12 and 14), *N. scaphum*, *N. turgida* and *R. phlegeri* show an opportunistic response to the high amount of the mixed organic matter from both continental and marine origin whereas in the centre of this area (station 6), these species seem to be resistant to the environmental stress occurring there. Towards the outer part of the organic enriched zone (station 19), densities of the opportunistic species decrease considerably and this assemblage is replaced by more stable taxa composing biofacies III (*C. carinata*, *E. vitrea*, *V. bradyana* and *N. iridea/bradyi*).

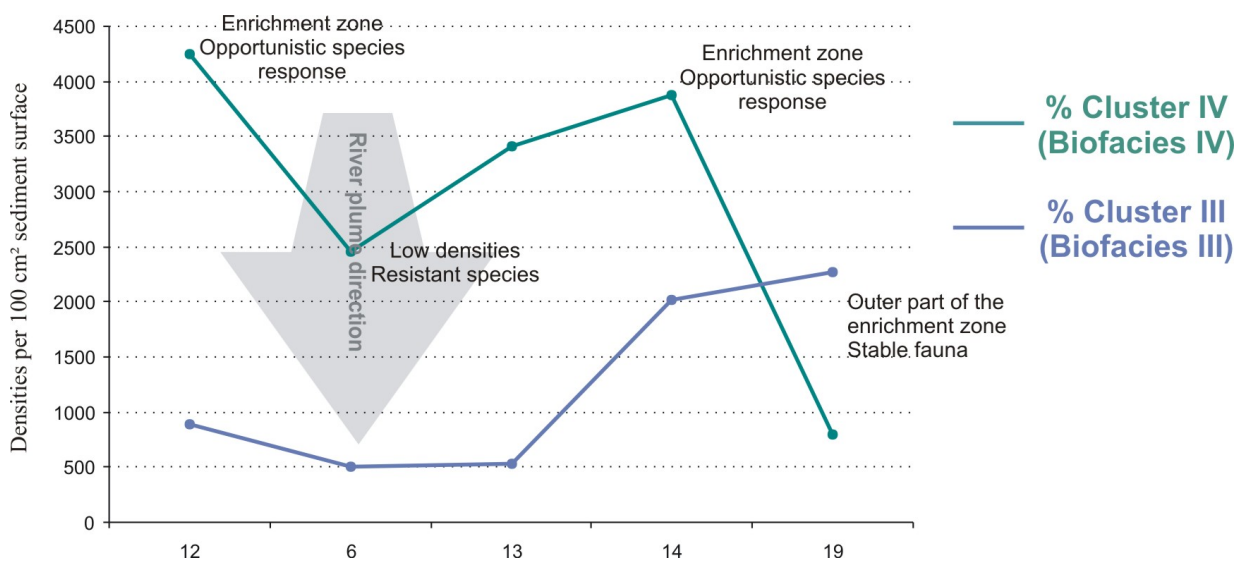


Figure 2-21. Relative abundance of the main species (> 63  $\mu\text{m}$ ) found along the transect following the main SW corridor under the influence of the river plume (stations 1, 3, 7, 13, 17 and 22).

Summarizing (Fig. 2-22), the living foraminiferal data present a typical picture, with strongly impoverished faunas composed exclusively of stress-tolerant species close to the river mouth and poor faunas composed of more opportunistic taxa to the SW under the river plume. This area is surrounded by an aureole of high density faunas dominated by opportunistic species gradually changing into a dominance of faunas with lower densities of less opportunistic species at the outer part of the enriched zone.

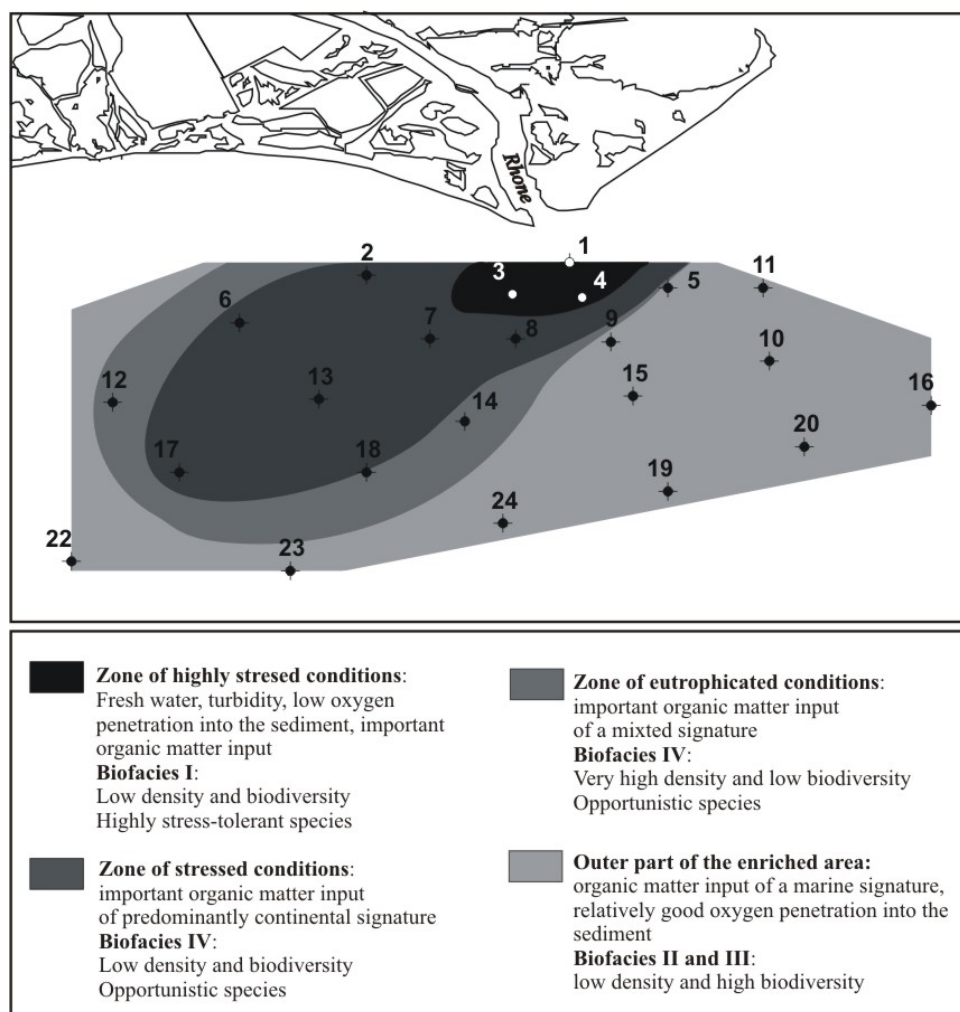


Figure 2-22. Overview map, indicating the succession of foraminiferal zones with decreasing Rhône river impact.

## 2.8 CONCLUSIONS

- The dissolved oxygen concentration of the bottom waters is not seriously influenced by the organic matter inputs. On the contrary, the oxygen content of interstitial waters show a clear linkage: at the shallowest stations in the vicinity of the river mouth, high organic matter inputs result in a redox front close to the sediment-water interface. At the deepest stations, far from the river mouth, the zero oxygen level is found deeper in the sediment, as a direct result of the decreasing organic flux.

- The use of the 63-150  $\mu\text{m}$  fraction highlights the dominance of small species which represent the majority of the fauna. Therefore, the 63-150  $\mu\text{m}$  fraction can add precious

information concerning the composition of the total fauna and especially concerning the presence in high densities of small-sized individuals of the opportunistic taxa (*Nonion scaphum*, *Nonionella turgida* and *Rectuvigerina phlegeri*). However, in general, the > 150 µm fraction alone is also representative, and can be sufficient to obtain a rapid overview of the environmental conditions in this area.

- The riverine input has a strong impact on benthic foraminiferal faunas; four biofacies of the total foraminiferal faunas which react especially to the quantity and quality of organic matter supply were identified. Bottom water oxygenation has no visible influence on benthic foraminiferal faunas.

Biofacies 1 is inhabited by species the species *Bulimina aculeata* f. *elongata*, *Fursenkoina fusiformis*, *Adelosina longirostra* and *Reophax scottii* that is present in front of the river mouth responds in this area to high amounts of refractory organic matter and low sediment oxygenation. These taxa seem to be adapted to the fresh water and the strong turbidity present in this zone.

Faunas of biofacies 2 are mainly composed of *Bolivina dilatata/spathulata* and *Textularia porrecta* which seem to be more characteristic of the eastern part of the Rhône prodelta.

Biofacies 3 is inhabited by faunas composed of *Cassidulina carinata*, *Epistominella vitrea*, *Valvulineria bradyana*, *Nonionella iridea* and *Nonionella bradyi*. These taxa are characteristic of the deepest stations, far from the river mouth; they respond to a low amount of marine organic matter and well oxygenated sediment.

Faunas of biofacies 4 are composed of the highly opportunistic species *Nonionella turgida*, *Nonion scaphum*, *Rectuvigerina phlegeri*. They profit from a predominantly riverine organic matter and seem to be characteristic of an area strongly influenced by the river plume.

## 2.9 REFERENCES

- Alavi, S.N., 1988. Late Holocene Deep-Sea Benthic Foraminifera from the Sea of Marmara. *Marine Micropaleontology*, 13, 213-237.
- Altenbach, A.V. and Sarntheim, M., 1989. Productivity Record in Benthic Foraminifera. In: W.H. Berger, V.S. Smetacek and G. Wefer (eds.) *Productivity of the Ocean: Present and Past.*, pp. 255-269. John Wiley and Sons Limited.
- Alve, E., 1991a. Benthic foraminifera in sediment cores reflecting heavy metal pollution in Sørfjord, western Norway. *Journal of Foraminiferal Research*, 21, 1-19.
- Alve, E., 1991b. Benthic foraminifera distribution and re-colonization of formerly anoxic environments in Drammensfjord, southern Norway. *Marine Micropaleontology*, 25, 169-186.
- Alve, E., 1994. Opportunistic features of the foraminifer *Stainforthia fusiformis* (Williamson): evidence from Frierfjord, Norway. *Journal of Micropaleontology*, 13, 24.
- Alve, E., 1995a. Benthic foraminiferal responses to estuarine pollution, a review. *Journal of Foraminiferal Research* 25, 190-203.
- Alve, E., 1995b. Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Drammensfjord, southern Norway. *Marine Micropaleontology*, 25, 169-186.
- Alve, E., Bernhard, J.M., 1995. Vertical migratory response of benthic foraminifera to controlled oxygen concentrations in an experimental mesocosm. *Marine Ecology Progress Series*, 116, 137-151.
- Barmawidjaja, D.M., 1991. Studies in living and fossil foraminifers from seasonally productive regions. *Geologica Ultraiectina*, 82, 221 pp.
- Barmawidjaja, D.M., Jorissen, F.J., Puskaric, S. and Van der Zwaan, G.J., 1992. Microhabitat selection by benthic foraminifera in the Northern Adriatic Sea. *Journal of Foraminiferal Research*, 22, 297-317.
- Barmawidjaja, D.M., Van Der Zwaan, G.J., Jorissen, F.J., Puskaric, S., 1995. 150 years of eutrophication in the northern Adriatic Sea, evidence from a benthic foraminiferal record. *Marine Geology*, 122, 367-384.
- Bartels-Jónsdóttir, H.B., Knudsen, K. L., Abrantes, F., Lebreiro, S., Eiriksson, J., 2006. Climate variability during the last 2000 years in the Tagus Prodelta, western Iberian Margin: Benthic foraminifera and stable isotopes. *Marine Micropaleontology*, 59, 83-103.
- Bergin, F., Kucuksezgin, F., Uluturhan, E., Barut, I.F., Meric, E., Avsar, N., Nazik, A., 2006. The response of benthic foraminifera and ostracoda to heavy metal pollution in Gulf of Izmir (Eastern Aegean Sea). *Estuarine, Coastal and Shelf Science*, 66, 368-386.
- Bernhard, J.M., 1986. Characteristic assemblages and morphologies of benthic foraminifera from anoxic, organic-rich deposits: Jurassic through Holocene. *Journal of Foraminiferal Research*, 16, 207-215.
- Bernhard, J.M. and Bowser, S.S., 1999. Benthic foraminifera of dysoxic sediments: Chloroplast sequestration and functional morphology. *Earth Science Reviews*, 46, 149-165.

Bernhard, J.M., Sen Gupta, B.K., 1999. Foraminifera of oxygen-depleted environments. In: Sen Gupta, B.K. (Ed.), *Modern Foraminifera*. Kluwer Academic Publishers, Dordrecht, pp. 201-216.

Béthoux, J. P., Prieur, L. and Bong, J. H., 1988. Le courant Ligure au large de Nice. In *Océanographie pélagique Méditerranéenne*, (Minas, H. J. & Nival, P., eds). *Oceanologica Acta*, 9, 59-67.

Biserni, G., van Geel, B., 2005. Reconstruction of Holocene palaeoenvironment and sedimentation history of the Ombrone alluvial plain (South Tuscany, Italy). *Review of Palaeobotany and Palynology*, 136, 16-28.

Boudreau, B.P., 1986. Mathematics of tracer mixing in sediments: I. Spatially-dependent, diffusive mixing. *American Journal of Science* 286, 161-198.

Boudreau, B.P., Mucci, A., Sundby, B., Luther III, G.W. and Silverberg, N., 1998. Comparative diagenesis at three sites on the Canadian continental margin. *Journal of Marine Research*, 56, 1259-1284.

Corliss, B.H., 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*, 314, 435-438.

Corliss, B.H., 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. *Marine Micropaleontology*, 17, 195-236.

Corliss, B.H., Chen, C., 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology*, 16, 716-719.

Corliss, B. and Silva, K.A., 1993. Rapid growth of deep sea benthic foraminifera. *Geology*, 21, 991-994.

Davis, J.C. 1986. *Statistics and Data Analysis in Geology*, 2nd ed., John Wiley & Sons, New York, 289 pp.

Debenay, J.P., Redois, F., 1997. Distribution of the twenty seven dominant species of shelf benthic foraminifers on the continental shelf, north of Dakar (Senegal). *Marine Micropaleontology*, 29, 237-255.

De Stigter, H.C., Jorissen, F.J., van der Zwaan, G.J., 1998. Bathymetric distribution and microhabitat partitioning of live (Rose Bengal stained) foraminifera along a shelf to bathyal transect in the southern Adriatic Sea. *Journal of Foraminiferal Research*, 28, 40-65.

De Rijk, S., Jorissen, F.J., Rohling, E.J., Troelstra, S.R., 2000. Organic flux control on bathymetric zonation of Mediterranean benthic foraminifera. *Marine Micropaleontology*, 40, 151-166.

Diaz, R.J., Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology, Annual Review*, 33, 245-303.

Digby, P.G.N. and Kempton, R.A., 1987. *Multivariate analysis of ecological communities*. Chapman and Hall, London.

Diz, P., Francés, G., Pelejero, C., Grimalt, J.O., Vilas, F., 2002. The last 3000 years in the Ría de Vigo (NW Iberian Margin): climatic and hydrographic signals. *Holocene*, 12, 459-468.

Diz, P., Frances, G. and Roson, G., 2006. Effects of contrasting upwelling-downwelling on benthic foraminiferal distribution in the Ria de Vigo (NW Spain). *Journal of Marine Systems*, 60, 1-18.

Duchemin, G., Jorissen, F.J., Andrieux-Loyer, F., Le Loc'h, F., Hily, C. et Philippon, X., 2005. Living benthic foraminifera from the "Grande Vasière", French Atlantic continental shelf: faunal composition and microhabitats. *Journal of Foraminiferal Research*, 35 (3), 198-218.

Duijnste, I.A.P., 2001. Experimental ecology of foraminifera: towards better quantitative paleoecological reconstructions, Ph.D. thesis, Utrecht University, Utrecht, Nijmegen University, Nijmegen, The Netherlands, 149 pp.

Eichler, P.P.B., Eichler, B.B.; de Miranda, L.B., Pereira, E.R.M., Kfour, P.B.P., Pimenta, F.M., Bérnago, A.L. and Vilela, C.G., 2003. Benthic Foraminiferal Response to Variations in Temperature, Salinity, Dissolved Oxygen and Organic Carbon, in the Guanabara Bay, Rio de Janeiro, Brazil. *Anuário do Instituto de Geociências – UFRJ*, 26, 36-51.

Estournel, C., Durrieu de Madron, X., Marsaleix, P., Auclair, F., Julliand, C., Vehil, R., 2003. Observations and modelisation of the winter coastal oceanic circulation in the Gulf of Lions under wind conditions influenced by the continental orography (FETCH experiment). *Journal of Geophysical Research*, 108 (C3), 8059.

Fontanier, C., Jorissen, F.J., Licari, L., Alexandre A., Anschutz P. and Carbonel, P., 2002. Live benthic foraminiferal faunas from the Bay of Biscay: faunal density, composition, and microhabitats. *Deep Sea Research Part I*, 49, 751-785.

Fontanier, C., Jorissen, F. J., Chaillou, G., David, C., Anschutz, P., Lafon, V., 2003. Seasonal and interannual variability of benthic foraminiferal faunas at 550m depth in the Bay of Biscay. *Deep Sea Research Part I*, 50, 457-494.

Gooday, A.J., 1986. Meiofaunal foraminiferans from the bathyal Porcupine Seabight (northeast Atlantic): size structure, standing stock, taxonomy composition, species diversity and vertical distribution in the sediment. *Deep Sea Research*, 33, 1345-1373.

Gooday, A.J., 1994. The biology of deep-sea foraminifera: a review of some advances and their applications in paleoceanography. *Palaios*, 9, 14-31.

Gooday, A.J. and Turley, C.M., 1990. Responses by benthic organisms to inputs of organic material to the ocean floor: a review. *Philosophical Transactions of the Royal Society London, Series A*, 331, 119-138.

Gooday, A.J. and Hughes, J.A., 2002. Foraminifera associated with phytodetritus deposits at a bathyal site in the northern Rockall Trough (NE Atlantic): seasonal contrasts and a comparison of stained and dead assemblages. *Marine Micropaleontology*, 46, 83-110.

Gibbs, R.J., 1981. Sites of river derived sedimentation in the ocean. *Geology*, 9, 77-80.

Gustafsson, M. and Nordberg, K., 2001. Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish West Coast, with comparison to Höglund's 1927 material. *Journal of Foraminiferal Research*, 31, 2-11.

Hayward, B.W., Neil, H., Carter, R., Grenfell, H.R. and Hayward, J.J., 2002. Factors influencing the distribution patterns of Recent deep-sea benthic foraminifera, east of New Zealand, Southwest Pacific Ocean. *Marine Micropaleontology*, 46, 139-176.

Hayward, B. W., Grenfell, H. R., Sabaa, A. T. and Neil, H. L., 2007. Factors influencing the distribution of Subantarctic deep-sea benthic foraminifera, Campbell and Bounty Plateaux, New Zealand. *Marine Micropaleontology*, 62, 141-166.

Harloff, J. and Mackensen, A., 1997. Recent benthic foraminiferal associations and ecology of the Scotia Sea and Argentine Basin. *Marine Micropaleontology*, 31, 1-29.

Heip, C.H.R., 1995. Eutrophication and zoobenthos dynamics. *Ophelia*, 41, 113-136.

Hill, M.O. and Gauch, H.G., 1980. Detrended correspondence analysis, an improved ordination technique. *Vegetation* 49, 47-58.

Jannik, N.T., Zachariasse, W.J., Van der Zwaan, G.J., 1998. Living (Rose Bengal stained) benthic foraminifera from the Pakistan continental margin (northern Arabian Sea). *Deep-Sea Research I*, 45, 1483-1513.

Jones, R.W., 1994. *The Challenger foraminifera*. Oxford University Press.

Jones, R.W., Charnock, M.A., 1985. Morphogroups of agglutinating foraminifera, their life positions and feeding habits and potential applicability in (paleo) ecological studies. *Paleobiology*, 4, 311-320.

Jorissen, F.J., 1987. The distribution of benthic foraminifera in the Adriatic Sea. *Marine Micropaleontology*, 12, 21-48.

Jorissen, F.J., 1988. Benthic foraminifera from the Adriatic Sea; Principles of phenotypic variation. *Utrecht Micropaleontology Bulletin*, 37, 176 pp.

Jorissen, F.J., 1999. Benthic foraminiferal successions late Quaternary Mediterranean sapropels. *Marine Geology*, 153, 91-101.

Jorissen, F.J., Barmawidjaja, D.M., Puskaric, S. and van der Zwaan, G.J., 1992. Vertical distribution of benthic foraminifera in the northern Adriatic Sea, The relation with the organic flux. *Marine Micropaleontology*, 19, 131-146.

Jorissen, F.J., De Stigter, H.C., Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology*, 26, 3-15.

Jorissen, F.J., Wittling, I., Peypouquet, J.P., Rabouille, C. and Relexans, J.C. 1998. Live benthic foraminiferal faunas off Cape Blanc, NW Africa; community structure and microhabitats. *Deep-Sea Research I*, 45, 2157-2188.

Kemp, W.M., Boynton, W.R., 1992. Benthic–pelagic interactions: nutrient and oxygen dynamics. In: Smith, D.E., Leffler, M., Mackiernan, G. (Eds.), *Oxygen Dynamics in the Chesapeake Bay, A Synthesis of Recent Research*. Maryland Sea Grant College, Maryland, pp. 149-222.

Lamy, A., Millot, C. and Molines, M., 1981. Bottom pressure and sea level measurements in the Gulf of Lions. *Journal of Physical Oceanography*, 11, 394-410.

Langezaal, A.M., van Bergen, P.F. and van der Zwaan, G.J., 2004. The recovery of benthic foraminifera and bacteria after disturbance: experimental evidence. *Journal of Experimental Marine Biology and Ecology*, 312, 137-170.

Langezaal, A.M., Jorissen, F.J., Braun, B., Chaillou, G., Fontanier, C., Anschutz, P., van der Zwaan, G.J., 2006. The influence of seasonal processes on geochemical profiles and foraminiferal assemblages on the outer shelf of the Bay of Biscay. *Continental Shelf Research*, 26, 1730-1755.



Lansard, B., Rabouille, C. and Massias, D., 2003. Variability in benthic oxygen fluxes during the winter-spring transition in coastal sediments: an estimation by in situ micro-electrodes and laboratory mini-electrodes. *Oceanologica Acta*, 26, 269-279.

Leutenegger, S., Hansen, H.J., 1979. Ultrastructural and radiotracer studies of pore-function in foraminifera. *Marine Biology*, 54, 11-16.

Levy, A., Mathieu, R., Poignant, A., Rosset-Moulinier, M. and Ubaldo, M.d.L., 1985. Distribution des foraminifères benthiques de la marge continentale sud-Portugaise, 110ème Congrès national des Sociétés savantes, Montpellier, pp. 91-101.

Levy, A., Mathieu, R., Poignant, A., Rosset-Moulinier, M., Ubaldo, M.d.L. and Ambroise, D., 1993. Recent foraminifera from the continental margin of Portugal. *Micropaleontology*, 39, 75-87.

Levy, A., Mathieu, R., Poignant, A., Rosset-Moulinier, M., Ubaldo, M.L., Lebreiro, S., 1995. Foraminifères Actuels de la Marge Continentale Portugaise-inventaire et distribution. *Memórias do Instituto Geológico e Mineiro*, Lisbon 32 (116 pp.).

Loeblich, A.R., and Tappan, H., 1964. Foraminiferal genera and their classification. Van Nostrand Reinhold C°, New York, 2 vol. 970+847 p.

Luther III, G.W., Reimers, C., Nuzzio, D.B. and Lovalvo, D., 1999. In Situ Deployment of Voltametric, Potentiometric, and Amperometric Microelectrodes from a ROV to determine Dissolved O<sub>2</sub>, Mn, Fe, S(-2), and pH in Porewaters. *Environmental Science and Technology*, 33, 4352-4356.

Lutze, G.F. and Colbourn, W.T., 1984. Recent benthic foraminifera from the continental margin of Northwest Africa, community structure and distribution. *Marine Micropaleontology*, 8, 361-401.

Maas, M., 2000. Verteilung lebendgefärbter benthischer Foraminiferen in einer intensivierten Sauerstoffminimumzone, Indo-Pakistanischer Kontinentalrand, nördliches Arabisches Meer. *Meyniana*, 52, 101-129.

Mackensen, A., Douglas, R.G., 1989. Down-core distribution of live and dead deep-water benthic foraminifera in box cores from the Weddell Sea and the California continental borderland. *Deep-Sea Research* 36 (6), 879-900.

Mackensen, A., Grobe, H., Kuhn, G. and Fütterer, D.K., 1990. Benthic foraminiferal assemblages from the eastern Weddell Sea between 68 and 73°S: Distribution, ecology and fossilization potential. *Marine Micropaleontology*, 16, 241-283.

Marsaleix, P., 1993. Modelisation Tridimensionnelle de la Circulation Océanique dans le Golfe du Lion. Thesis Toulouse, 85 pp.

McKee, B.A., Aller, R.C., Allison, M.A., Bianchi, T.S., Kineke, G.C., 2004. Transport and transformation of dissolved and particulate materials on continental margins influenced by major rivers: benthic boundary layer and seabed processes. *Continental and Shelf Research*, 24, 899-926.

Mendes, I., Gonzalez, R., Dias, J.M.A., Lobo, F., Martins, V., 2004. Factors influencing recent benthic foraminifera distribution on the Guadiana shelf (Southwestern Iberia). *Marine Micropaleontology*, 51, 171-192.

Miller, K.G. and Lohmann, G.P., 1982. Environmental distribution of recent benthic foraminifera on the northeast United States continental slope. *Geology Society of American Bulletin*, 93, 200-206.

Millot, C., 1990. The Gulf of Lions' hydrodynamics. *Continental Shelf Research*, 10, 885-894.

Mojtahid, M., Jorissen, F., Durrieu, J., Galgani, F., Howa, H., Redois, F., Camps, R. 2006. Benthic foraminifera as bio-indicators of drill cutting disposal in tropical east Atlantic outer shelf environments. *Marine Micropaleontology*, 61, 58-75.

Moodley, L., 1990. Southern North Sea seafloor and subsurface distribution of living benthic foraminifera. *Netherlands Journal of Sea Research*, 27, 57-71.

Murgese, D. S. and De Deckker, P. 2007. The Late Quaternary evolution of water masses in the eastern Indian Ocean between Australia and Indonesia, based on benthic foraminifera faunal and carbon isotopes analyses. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 247, 382-401.

Murray, J.W., 1969. Recent foraminifera from the Atlantic continental shelf of the United States. *Micropaleontology*, 15, 401-419.

Murray, J.W., 1985. Recent foraminifera from the North Sea (Forties and Ekofisk areas) and the continental shelf west of Scotland. *Journal of Micropalaeontology*, 4, 117-125.

Murray, J.W., 1991. *Ecology and paleoecology of benthic foraminifera*. Longman, Harlow, 397pp.

Murray, J.W., 1992. Distribution and population dynamics of benthic foraminifera from the southern North Sea. *Journal of Foraminiferal Research*, 22, 114-128.

Nagy, J. and Alve, E., 1987. Temporal changes in foraminiferal faunas and impact of pollution in Sandebukta, Oslo fjord. *Marine Micropaleontology* 12, 109-128.

Nees, S. and Struck, U., 1999. Benthic foraminiferal response to major paleoceanographic changes. In: F. Abrantes and A. Mix (Editors), *Reconstructing Ocean History: A Window into the Future*. Kluwer Academic Publishers/Plenum, pp. 195-216.

Parker, F.L., 1964. Foraminifera from the experimental Mohole drilling near Guadalupe Island, Mexico: *Journal of Paleontology*, 38, 617-637.

Petrenko, A., Leredde, Y., Marsaleix, P., 2005. Circulation in a stratified and wind-forced Gulf of Lions, NW Mediterranean Sea: in situ and modelling data. *Continental Shelf Research*, 25, 7-27.

Phleger, F.B. and Soutar, A., 1973. Production of benthic foraminifera in three east Pacific oxygen minima. *Micropaleontology*, 19, 110-115.

Platon, E., Sen Gupta, B.K., Rabalais, N.N., Turner, R.E., 2005. Effect of seasonal hypoxia on the benthic foraminiferal community of the Louisiana inner continental shelf, The 20th century record. *Marine Micropaleontology* 54, 263-283.

Rabalais, N.N., Turner, R.E., Wiseman, W.J., 2001. Hypoxia in the Gulf of Mexico. *Journal of Environmental Quality*, 33, 320-329.

Rabouille, C., Denis, L., Dedieu, K., Stora, G., Lansard, B. and Grenz, C. 2003. Oxygen demand in coastal marine sediments: comparing in situ microelectrodes and laboratory core incubations. *Journal of Experimental Marine Biology and Ecology*, 285-286, P. 49-69.

Roussiez, V., Aloisi, J.C., Monaco, A., Ludwig, W., 2005. Early muddy deposits along the Gulf of Lions shoreline: A key for a better understanding of land-to-sea transfer of sediments and associated pollutant fluxes. *Marine Geology*, 222-223, 345-358.

Samir, A.M., El-Din, A.B., 2001. Benthic foraminiferal assemblages and morphological abnormalities as pollution proxies in two Egyptian bays. *Marine Micropaleontology*, 41, 193-227.

Samir, A.M., Abdou, H.F., Zazou, S.M., El-Menhawey, W.H., 2003. Cluster analysis of recent benthic foraminifera from the Northwestern Mediterranean coast of Egypt. *Revue de Micropaleontologie*, 46, 111-130.

Schiebel, R., 1992. Rezente benthische Foraminiferen in Sedimenten des Schelfes und oberen Kontinentalhanges im Golf von Guinea (Westafrika). *Berichte Geologisch-Paläontologisches Institut und Museum Christian-Albrechts-Universität Kiel, Deutschland*, n° 51, 126 pp.

Schmiedl, G., Mackensen, A., Müller, P.J., 1997. Recent benthic foraminifera from the eastern South Atlantic Ocean: dependence on food supply and water masses. *Marine Micropaleontology*, 32, 249-287.

Schmiedl, G., de Bovée, F., Buscail, R., Charrière, B., Hemleben, C., Medernach, L., Picon, P., 2000. Trophic control of benthic foraminiferal abundance and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea. *Marine Micropaleontology*, 40, 167-188.

Scott, D.B., Tobin, R., Williamson, M., Medioli, F.S., Latimer, J.S., Boothman, W.A., Asioli, A. and Haury, V., 2005. Pollution monitoring in two North American estuaries: Historical reconstructions using benthic foraminifera. *Journal of Foraminiferal Research*, 35, 65-82.

Seiglie, G.A., 1968. Foraminiferal assemblages as bio-indicators of high organic carbon content in sediment and polluted waters. *American Association of Petroleum Geologists Bulletin*, 52, 2231-2241.

Sempéré, R., Charriere, B., Cauwet, G., Van Wambecke, F., 2000. Carbon inputs of the Rhône River to the Mediterranean Sea: biogeochemical implications. *Global Biogeochemical Cycles*, 14, 669-681.

Silva, K.A., Corliss, B., Rathburn, A.E., Thunell, R., 1996. Seasonality of living benthic foraminifera from San Pedro basin, California borderland. *Journal of Foraminiferal Research*, 26, 71-93.

Soetaert, K., Herman P.M.J. and Middelburg, J.J., 1996. A model of early diagenetic processes from the shelf to abyssal depths. *Geochimica Cosmochimica Acta*, 60, 1019-1040.

Swallow, J.E. and Culver, S.J., 1999. Living (rose Bengal stained) benthic Foraminifera from New Jersey continental margin canyons. *Journal of Foraminiferal Research*, 29, 104-116.

Van der Zwaan, G.J., 1982. Paleocology of Late Miocene Mediterranean foraminifera. *Utrecht Micropaleontological Bulletin*, 25, 202 pp.

Van der Zwaan, G.J. and Jorissen, F., 1991. Biofacial patterns in river-induced shelf anoxia. In: R.V. TYSON & T.H. PEARSON (Eds.): "Modern and Ancient Continental Shelf Anoxia". Geological Society, Special Publication, 58, 65-82.

Verhallen, P.J.J.M., 1991. Late Pliocene to Early Pleistocene Mediterranean mud-dwelling foraminifera; influence of a changing environment of community structure and evolution. *Utrecht Micropaleontological Bulletin*, 40, 1-219.

Wollast, R., 1991. The coastal organic carbon cycle: fluxes, sources, and sinks. In: R.F.C. Mantoura, J.M. Martin and R. Wollast (Ed.), *Ocean Margin Processes in Global Change*. John Wiley & Sons, pp. 469.

Zeebe, R. and Wolf-Gladrow, D., 2001: *CO<sub>2</sub> in Seawater: Equilibrium, kinetics, isotopes*. Elsevier Oceanography Series, 65.

Appendix 2-1: Census data (non-standardized) of live benthic foraminifera of > 150 µm fraction.

Sediment depth (cm)		St1 20m depth							St2 40m depth					St3 53m depth									
		0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	0-0.5	0.5-1	1-2	2-5	Total	0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	
Perforates	Taxa																						
	<i>Ammodiscus</i> sp.																						
	<i>Ammonia beccarii</i> f. <i>inflata</i>	2						3	5	7	8	10	31	62	87	6	2	3	1	3	6	1	22
	<i>Amphicoryna scalaris</i>																						
	<i>Astacolus insolitus</i>																						
	<i>Bolivina alata</i>																						
	<i>Bolivina dilatata</i>																						
	<i>Bolivina spathulata</i>																						
	<i>Bolivina subaenariensis</i>																						
	<i>Bulimina aculeata</i>																						
	<i>Bulimina costata</i>																						
	<i>Bulimina marginata</i>																						
	<i>Cassidulina carinata</i>																						
	<i>Cassidulina oblonga</i>																						
	<i>Chilostomella ovoidea</i>																						
	<i>Dentalina bradyensis</i>																						
	<i>Elphidium advenum</i>																						
	<i>Elphidium macellum</i>	2				1			3	2	3	1	8	16	22			1		1	1	1	4
	<i>Fursenkoina complanata</i>																						
	<i>Fursenkoina concava</i>																						
	<i>Gavelinopsis praegeri</i>																						
	<i>Globobulimina affinis</i>																						
	<i>Globobulimina pyrula</i> var. <i>pseudospitescens</i>																						
	<i>Globulina rotundata</i>																						
	<i>Gyroidinoides cf soldanii</i>																						
	<i>Hanzawaia boueana</i>																						
	<i>Hyalinea balthica</i>																						
	<i>Lagena</i> sp.																						
	<i>Lenticulina atlantica</i>																						
	<i>Lenticulina peregrina</i>																						
	<i>Melonis barleeanus</i>																						
	<i>Nonion scaphum</i>	2							2	70	135	162	51	102	469	33	14	13	6	6	21	14	107
	<i>Nonionella turgida</i>	2		3	2	1	1	1	10	34	35	44	12	24	137	51		4	6	8	21	9	99
	<i>Procerolagena gracillina</i>																						
	<i>Pseudoeponides falsobeccarii</i>																						
<i>Rectuvigerina phlegeri</i>																							
<i>Saidovina karrieriana</i>																							
<i>Uvigerina mediterranea</i>	1							1		1				1								0	
<i>Valvulineria bradyana</i>		1						1	26	30	3	2	4	63								0	
Miliolids	<i>Adelosina longirostra</i>																						
	<i>Pyrgo subsphaerica</i>																						
	<i>Quinqueloculina badenensis</i>																						
	<i>Quinqueloculina grata</i>																						
	<i>Quinqueloculina seminula</i> f. <i>longa</i>	1	4	2		1		1	9	2	2		3	6	10	8	2	6	3	2	1		22
	<i>Quinqueloculina</i> sp.1																						
	<i>Quinqueloculina</i> sp.2																						
<i>Spiroloculina canaliculata</i>																							
Agglutinates	<i>Adercotryma glomeratum</i>																						
	<i>Bigenerina nodosaria</i>																						
	<i>Clavulina cylindrica</i>																						
	<i>Cribrostomoides jeffreysii</i>																						
	<i>Cribrostomoides subglobosus</i>																						
	<i>Eggerella scabra</i>	1					4		5	14	11	2	53	106	133	12	3	1	2	15	16	2	51
	<i>Eratidus foliaceus</i>																						
	<i>Lagenammmina difflugiformis</i>																						
	<i>Recurvoides trochaminiformis</i>																						
	<i>Reophax fusiformis</i>																						
	<i>Reophax scorpiurus</i>																						
	<i>Reophax scotti</i>																						
<i>Textularia agglutinans</i>			1					1			1	2	4	5	789	255	88	97	16			1245	
Total hand sorted (t)	11	5	6	2	3	5	7	39	177	247	232	183	366	1022	912	280	124	120	53	79	34	1602	
splitted (s)	1	1	1	1	1	1	1	7	1	1	1	2			1	1	1	1	1	1	1	7	
TOTAL = t+s	11	5	6	2	3	5	7	39	177	247	232	183	366	1022	912	280	124	120	53	79	34	1602	



Appendix 2-1: Continued.

Sediment depth (cm)		St8 65m depth					St9 65m depth								St10 80m depth				
		0-0.5	0.5-1	1-2	2-5	Total	0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	0-0.5	0.5-1	1-2	2-5	Total
Perforates	<i>Ammodiscus</i> sp.					0								0					0
	<i>Ammonia beccarii</i> f. <i>inflata</i>	6	2	1	5	14		1	1	1		1	1	5	15	11	14	6	46
	<i>Amphicoryna scalaris</i>					0								0	12	1			13
	<i>Astacolus insolitus</i>					0								0	0				0
	<i>Bolivina alata</i>					0		1						1	3		1		4
	<i>Bolivina dilatata</i>					0								0	0				0
	<i>Bolivina spathulata</i>				2	2								0	4				4
	<i>Bolivina subaenariensis</i>					0								0	0	1	2		3
	<i>Bulimina aculeata</i>	1	4	0	2	7	3	1	3	1				8	98	12	13	20	143
	<i>Bulimina costata</i>					0			1					1	0				0
	<i>Bulimina marginata</i>	1		4		5			1		1			2	37	11	13	1	62
	<i>Cassidulina carinata</i>	44	3	1	16	64	34	8	5	1	1		1	50	452	51	15	25	543
	<i>Cassidulina oblonga</i>					0								0	0				0
	<i>Chilostomella ovoidea</i>					0								0	0		1	1	2
	<i>Dentalina bradyensis</i>					0								0	0				0
	<i>Elphidium advenum</i>	1		1	1	3								0	1		1		2
	<i>Elphidium macellum</i>	6		2	1	9	1							1	2	1			3
	<i>Fursenkoina complanata</i>					0	1							1	0				0
	<i>Fursenkoina concava</i>					0								0	1				1
	<i>Gavelinopsis praegeri</i>					0								0	1		3		4
	<i>Globobulimina affinis</i>					0								0	0	2	3		5
	<i>Globobulimina pyrula</i> var. <i>pseudospitescens</i>					0			1					1	3			2	5
	<i>Globulina rotundata</i>					0								0	0				0
	<i>Gyroidinoides</i> cf. <i>soldanii</i>					0								0	2				2
	<i>Hanzawaia boueana</i>					0								0	3				3
	<i>Hyalinea balthica</i>			1		1			1					1	7	2	3		12
	<i>Lagena</i> sp.					0								0	0				0
	<i>Lenticulina atlantica</i>					0								0	1			1	2
	<i>Lenticulina peregrina</i>					0								0	0				0
	<i>Melonis barleaanus</i>					0								0	0				0
	<i>Nonion scaphum</i>	157	56	38	60	311	26	18	8		2			54	59	180	146	12	397
	<i>Nonionella turgida</i>	40	19	18	14	91	15	4	2	1	1			23	14	27	23	7	71
	<i>Procerolagena gracillina</i>					0								0	0				0
<i>Pseudoeponides falsobeccarii</i>					0	2		1		2	1		6	18	4	5	2	29	
<i>Rectuvigerina phlegeri</i>	2	3	1		6	2	2	2	1	2			9	34	41	11	6	92	
<i>Saidovina karreriana</i>					0								0	0				0	
<i>Uvigerina mediterranea</i>	1				1								0	3				3	
<i>Valvulineria bradyana</i>	108	32	20	24	184	12	8	7	2				29	84	59	21	8	172	
Miliolids	<i>Adelosina longirostra</i>	9		2	3	14	1						1	13	3	5	13	34	
	<i>Pyrgo subsphaerica</i>					0	2	3	1	2			8	4	1	2	4	11	
	<i>Quinqueloculina badenensis</i>					0							0	16	4		12	32	
	<i>Quinqueloculina grata</i>					0							0	19		21	6	46	
	<i>Quinqueloculina seminula</i> f. <i>longa</i>	15	1	1	7	24	3	1	2	3			9	82	32	69	12	195	
	<i>Quinqueloculina</i> sp.1					0		1		1			2	32	1	14	3	50	
	<i>Quinqueloculina</i> sp.2					0							0	0				0	
<i>Spiroloculina canaliculata</i>					0							0	1				1		
Agglutinates	<i>Adercotryma glomeratum</i>					0	2	5		2			9	149	27	23	4	203	
	<i>Bigenerina nodosaria</i>					0							0	4				4	
	<i>Clavulina cylindrica</i>			3	1	5	3	3					6	53	19	17	5	94	
	<i>Cribrostomoides jeffreysii</i>					0				1			1	15		1		16	
	<i>Cribrostomoides subglobosus</i>					0							0	1				1	
	<i>Eggerella scabra</i>	64	15	29	94	202	17	23	23	11	20	9	104	167	58	60	38	323	
	<i>Eratidus foliaceus</i>					0							0	66	41	40	24	171	
	<i>Lagenammina difflugiformis</i>					0							0	0				0	
	<i>Recurvoides trochamminiformis</i>					0	2	4		1			7	12	16	10		38	
	<i>Reophax fusiformis</i>					0							0	2				2	
	<i>Reophax scoriurus</i>					0							0	0				0	
	<i>Reophax scotti</i>	1				1							0	0				0	
<i>Textularia agglutinans</i>	1	1	1		3	2	4		2			8	139	121	122	58	440		
Total hand sorted (t)	457	139	121	230		128	87	59	30	29	11	3	1629	726	659	270			
split (s)	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1			
TOTAL = t*s	457	139	121	230	947	128	87	59	30	29	11	3	347	1629	726	659	270	3284	

Spatial distribution of benthic foraminifera in the Rhône prodelta

Appendix 2-1: Continued.

St11 66m depth						St12 58m depth					St13 75m depth								St14 85m depth							
Brut	0-0.5	0.5-1	1-2	2-3	Total	0-0.5	0.5-1	1-2	2-5	Total	0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total
0	0	0	0	0	0	67	8	17	48	140	3			1	1	3	8	16	31	4	3	1	7	8	7	61
1	2	10	4		16	4	2	0	1	7	1			1		1		3	1		3	1	7	8	7	1
0	0				0	0	0	0	0	0	1	1						2		2						2
0	0				0	1	1	0	0	2	1							1	1							1
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
1	2		1		3	1	0	0	0	1	1							1	5	9	1		1			16
2	4	1	1	3	9	68	7	7	37	119	12	3	1	2	3	16	6	43	114	14	8	10	20	13	10	189
0	0				0	0	0	0	0	0								0	3							3
3	6	2			8	7	2	5	28	42	3	1			2	3	2	11	3	1		2	6	3		15
90	180	79	10	9	278	62	3	3	14	82	16	2	1	1	2	2		24	228	75	7		6	6		322
0	0				0	1	0	0	1	2	2							2	2							2
0	0				0	0	1	0	0	1								0		1						1
0	0				0	0	0	0	0	0								0	1							1
0	0				0	0	3	4	2	9		1				2		3								0
2	4	1		2	7	23	3	6	11	43	1	1					1	3	5		2	3	1			11
0	0				0	0	0	2	2	4								0	1	1						2
0	0				0	0	0	0	0	0				1			1	2	1			1				2
0	0				0	0	0	6	10	16								0	1			1				0
0	0				0	1	0	0	3	4								0	2	3	3	3				11
0	1				1	0	0	0	1	1								0								0
0	0				0	0	0	0	0	0								0								0
1	2				2	0	0	0	0	0	1	1						2	1	5						6
0	0				0	0	0	0	0	0								0	1				1			2
0	0				0	1	1	0	4	6							1	1	1	1	1	1		2		6
0	0				0	0	0	0	0	0								0								0
0	0		1		1	1	0	0	0	1								0	1					1		2
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
21	42	55	88	79	264	150	83	249	622	1104	188	127	125	138	105	33	39	755	295	369	178	146	73	9	4	1074
0	0	8	5	12	25	22	33	46	148	249	16	23	28	25	20	1	2	115	15	27	20	32	12		2	108
0	0				0	0	0	0	0	0								0								0
1	2	2			4	16	1	3	3	23						1	1	2				1	1			2
1	2	8	13	1	24	60	72	40	6	178	49	13	3	5	6	12	6	94	58	103	6	1		7	3	178
0	0				0	0	0	0	0	0								0								0
0	0				0	1	0	1	0	2								0	1							1
41	82	160	130	6	378	127	116	164	63	470	26	12	5	3	1		2	49	102	64	4	3	1	2		176
0	0		1	4	5	14	3	1	10	28							2	2	3	1				1		5
0	0				0	2	0	0	0	2								0				1	1			2
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
2	4	1			5	23	3	2	14	42								0	11		1	2	1			15
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	0	0	0	0	0								0								0
0	0				0	14	1	8	52	75	2	1		3		4	3	13				1	2		1	4
200	400	329	277	146		916	398	640	1373		326	193	171	185	141	91	89		994	713	247	212	149	61	29	
2		1	1	1		1	1	1	1		1	1	1	1	1	1	1		1	1	1	1	1	1	1	
400		329	277	146	1152	916	398	640	1373	3327	326	193	171	185	141	91	89	1196	994	713	247	212	149	61	29	2405



Appendix 2-1: Continued.

Sediment depth (cm)		St15 89m depth								St16 83m depth							St17 73 m depth								
		0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	0-0.5	0.5-1	1-2		2-5		Total	0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	
Taxa																									
									Brut	%(s)	Brut		%(s)												
	<i>Ammodiscus sp.</i>							0	2						0	0									0
	<i>Ammonia beccarii f. inflata</i>	37	12	4	5	13	8	8	7	14	5	7	5	13	40	11	17	5	1	4	13	23		74	
	<i>Amphicoryna scalaris</i>	4	1	1	1	1		8	2				1	3	5									0	
	<i>Astacolus insolitus</i>							0						0	0									0	
	<i>Bolivina alata</i>	2	1					3	8	8	12	16	4	11	43		2							2	
	<i>Bolivina dilatata</i>							0						0	0									0	
	<i>Bolivina spathulata</i>							0						0	0									0	
	<i>Bolivina subaenariensis</i>	3	7	1			1	12	10	5	1	1	3	8	24	3							1	4	
	<i>Bulimina aculeata</i>	81	11	9	0	22	25	15	163	37	36	8	11	26	69	153	51	53	3	3	17	25	21	173	
	<i>Bulimina costata</i>	1						1						0	0	3								3	
	<i>Bulimina marginata</i>	4			4	2		10		3	7	9	1	3	15	6	3					1	3	13	
	<i>Cassidulina carinata</i>	269	34	13	16	21	20	10	383	106	49	22	29	23	61	246	93	94	4	3	13	29	22	258	
	<i>Cassidulina oblonga</i>	3						4				4	5	1	3	8								0	
	<i>Chilostomella ovoidea</i>		1		1	2		4						0	0									0	
	<i>Dentalina bradyensis</i>					1		1		1				0	1									0	
	<i>Elphidium advenum</i>							0		1				0	1		1	1			1	2	6	11	
	<i>Elphidium macellum</i>						1	1	1	1				0	1	1	2			2	4	6	15		
	<i>Fursenkoina complanata</i>							0						0	0									0	
	<i>Fursenkoina concava</i>							0						0	0									0	
	<i>Gavelinopsis praegeri</i>							0			1	1		0	1				1	1				2	
	<i>Globobulimina affinis</i>	1	1	2	1	1	1	1	8	2	3	4	5	13	35	45			2					2	
	<i>Globobulimina pyrula</i> <i>var. pseudospitescens</i>							0	1	2	3	2	5	9	9									0	
	<i>Globulina rotundata</i>							0						0	0									0	
	<i>Gyroidinoides cf soldanii</i>	3					1	4					1	3	3	1	1							2	
	<i>Hanzawaia boueana</i>				1			1	6	1	1	1		0	8					1				1	
	<i>Hyalinea balthica</i>				2	10	4	3	19	5	8	3	4	2	5	22	1	3	3		2	6	2	17	
	<i>Lagena sp.</i>							0						0	0									0	
	<i>Lenticulina atlantica</i>	1						1						0	0									0	
	<i>Lenticulina peregrina</i>							0	2					0	2									0	
	<i>Melonis barleanus</i>		2					2	4	7	3	4	3	8	23		1					2		3	
	<i>Nonion scaphum</i>	87	72	103	108	60	19	11	460	1	15	33	44	14	37	97	45	120	50	17	11	2	5	250	
	<i>Nonionella turgida</i>	5	5	11	9	12	3	1	46	3	6	8	11	8	21	41	10	18	17	3	10			58	
	<i>Procerolagena gracillina</i>							0						0	0									0	
	<i>Pseudoepionides falsobeccarii</i>	2	3	1		1	1	1	9	10	4	2	3	1	3	19							1	1	
	<i>Rectuvigerina phlegeri</i>	16	33	5	8	6	3	1	72	2	3	5	7	8	21	33	7	20	4	3	3	1	3	41	
	<i>Saidovina karreriana</i>							0						0	0									0	
	<i>Uvigerina mediterranea</i>	3	1					4	2	1				0	3	3		1						1	
	<i>Valvulineria bradyana</i>	71	84	26	8	9	7	4	209	58	36	99	132	49	131	357	42	85	8	1	1	4		141	
Miliolids	<i>Adelosina longirostra</i>	3			1	1	1	1	7			1	1	3	4									0	
	<i>Pyrgo subsphaerica</i>							0						0	0									0	
	<i>Quinqueloculina badenensis</i>							0		3			1	3	6									0	
	<i>Quinqueloculina grata</i>							0						0	0									0	
	<i>Quinqueloculina seminula f. longa</i>	8						8	1	11	26	35	20	53	100	5	3						1	9	
	<i>Quinqueloculina sp.1</i>							0						0	0									0	
	<i>Quinqueloculina sp.2</i>							0						0	0									0	
	<i>Spiroloculina canaliculata</i>							0						0	0									0	
Agglutinates	<i>Adercotryma glomeratum</i>	5	2		1	1	3	1	13			1	1	0	1			2	3	1		1		7	
	<i>Bigennerina nodosaria</i>	1				1		2				2	3	0	3									0	
	<i>Clavulina cylindrica</i>	26	8		1		1	1	37	2	6	7	9	1	3	20	1	7						8	
	<i>Cribrostomoides jeffreysii</i>							0						0	0				1					1	
	<i>Cribrostomoides subglobosus</i>							0						0	0									0	
	<i>Eggerella scabra</i>	68	2	1	11	8	11	6	107	5	6	6	8	2	5	24	9	15	7	3	12	15	16	77	
	<i>Eratidus foliaceus</i>							0	2	3			0	1	3	8								0	
	<i>Lagenamma difflugiformis</i>	3	1			3	3	10	2		1	1	3	8	11	6	8	4		2	1	3	24		
	<i>Recurvovides trochamminiformis</i>	37	2		7	8	6	60		3	3	4	0	7	7		8			2	2	3	15		
	<i>Reophax fusiformis</i>							0	1					0	1									0	
	<i>Reophax scorpiurus</i>							0					5	13	13	3	1							4	
	<i>Reophax scotti</i>							0						0	0									0	
	<i>Textularia agglutinans</i>	15			3	7	2	5	32			5	7		0	7		2	2	4	1	5	7	3	24
Total hand sorted (t)	759	283	177	188	190	121	70		281	233	272	363	199	531		301	468	114	37	88	120	113			
split (s)	1	1	1	1	1	1	1		1	1	1.3333		2.66667		1	1	1	1	1	1	1	1			
TOTAL = t*s	759	283	177	188	190	121	70	1788	281	233	363		531	1407		301	468	114	37	88	120	113	1241		

Spatial distribution of benthic foraminifera in the Rhône prodelta

Appendix 2-1: Continued.

St18 85m depth								St19 98m depth								St20 92m depth															
0-0.5cm		0.5-1cm		1-2cm		2-5cm		Total	0-0.5cm		0.5-1cm		1-1.5cm		1.5-2cm		2-3cm		3-4cm		4-5cm		Total	0-0.5cm		0.5-1cm		1-2cm		2-5cm	
Brut	%(s)	Brut	%(s)	Brut	%(s)	Brut	%(s)		Brut	%(s)	Brut	%(s)	Brut	%(s)	Brut	%(s)	Brut	%(s)	Brut	%(s)	Brut	%(s)		Brut	%(s)	Brut	%(s)	Brut	%(s)	Brut	%(s)
	0		0		0		0	0																							0
3	12	2	4	2	8	5	13	37	22	6		1	11	6	8	54	41	33	15	14	56	145	6	8	6		0	20			
	0		0		0	1	3	3	4				1			5							0		0					0	
	0		0		0		0	0	0	1						1							0		0					0	
2	8		0		0		0	8	9	1	1			1	12	8	18	19	4	16	61	0		0					0		
	0		0		0		0	0	0							0							0		0					0	
	0		0		0		0	0	0							0							1	0		0				1	
	0	1	2		0	1	3	5	11	2	1				14	6	13	4	1	4	27	6	13	4	1	4			27		
21	84	12	24	2	8	16	43	159	167	29	12	8	24	20	1	261	87	62	30	29	116	295	5	6	3		0	14			
	0		0		0		0	0	6							6							5	6	3		0	14			
3	12	1	2		0	1	3	17	6						6	6	4	5	4	3	12	25	4	5	4	3	12	25			
77	308	19	38	7	28	12	32	406	601	118	13	13	13	10	1	769	182	121	47	11	44	394	3	5	1		0	9			
	0		0		0	1	3	3	4		1					5							3	5	1		0	9			
	0		0		0		0	0	16	3	14	2	9	2	1	47	1	3	5	4	16	25	1	3	5	4	16	25			
	0	1	2		0		0	2	2							2								0		0		0	0		
	0		0		0		0	0	0		1					1								0		0		0	0		
	0		0		0		0	0	0				1			3							1		0		0	1			
	0		0		0		0	0	0							0		1	1		0	2		1	1		0	2			
	0		0		0		0	0	0							0								0		0		0	0		
	0		0		0		0	0	0							0								0		0		0	0		
	0	4	8	1	4	7	19	31	3	5	4	6	3	3	24		16	2	12	48	66			2	12	48	66				
1	4		0		0		0	4	3	2			1	1	7										1		0	0		0	
	0		0		0		0	0	0							0								0		0		0	0		
	0		0		0		0	0	2							2								3	0	0		0	3		
	0		0		0		0	0	1							1								1		0		1			
	0	1	2	1	4	5	13	19	39	6	3	1	1	1	51	17	9	8	13	52	86			8	13	52	86				
	0		0		0		0	0	2			1			3									0		0		0	0		
	0		0		0	1	3	3	0						0		3	1	1		0	5		3	1	1		0	5		
	0		0		0		0	0	0							0								3	0		0	3			
	0		0		0	1	3	3	8						8		35	69	39	9	36	179			39	9	36	179			
51	204	120	240	83	332	73	195	971	4	8	4	2	3		21	2	13	41	5	20	76			41	5	20	76				
5	20	9	18	7	28	10	27	93	6	4	3	6	2		22		5	9	1	4	18			9	1	4	18				
	0		0		0		0	0	0						0										0		0	0			
	0	1	2	2	8	3	8	18	4			2		3	9	1	16	7	7	28	52			7	7	28	52				
13	52	10	20	5	20	5	13	105	2		1	1			4	2	3	12	2	8	25			12	2	8	25				
	0		0		0		0	0	0						0										0		0	0			
	0	2	4		0	1	3	7	8	1	2	1			12	12	16	6	1	4	38			6	1	4	38				
41	164	41	82	16	64	19	51	361	43	19	11	1			74	68	178	177	15	60	483			177	15	60	483				
	0	1	2		0	2	5	7	1						1										1	1	4	5			
	0		0		0		0	0	0						0									0		0		0	0		
	0		0		0		0	0	0						0									0		0		0	0		
	0		0		0	1	3	3	0						0									0		0		0	0		
3	12		0	3	12	4	11	35	44	8		1	2	1	56	9	8	7	3	12	36			7	3	12	36				
	0		0		0		0	0	0						0										0		0	0			
	0		0		0		0	0	0						0										0		0	0			
	0		0		0		0	0	0						0										0		0	0			
1	4		0		0	2	5	9	12		1		1	3	17	9	15	7		0	31			7		0	31				
	0		0		0		0	0	13				1		14	22	29	15	14	56	122			15	14	56	122				
2	8	3	6	1	4	3	8	26	5			1		6	5	20	8	3	12	45			8	3	12	45					
	0		0		0		0	0	1						1										0		0	0			
	0		0		0		0	0	0						0		8	13	2	4	16	39			2	4	16	39			
10	40	1	2	2	8	25	67	117	112	10	7		7	3	139	51	38	18	14	56	163			18	14	56	163				
	0		0		0		0	0	0						0										0		4	16	16		
2	8	1	2		0	7	19	29	14	1			2	1	19	18	11	8	4	16	53			8	4	16	53				
1	4		0		0	1	3	7	50	6	2		2		60	42	37	7	3	12	98			7	3	12	98				
	0		0		0		0	0	0						0										0		0	0			
	0		0		0		0	0	16						16	11		2	2	8	21			2	2	8	21				
	0		0		0		0	0	0						0										0		0	0			
1	4	1	2	1	4	2	5	15	105	1	2	2	5	3	118	122	48	48	13	52	270			48	13	52	270				
238	952	231	462	133	532	209	557		1348	231	83	48	90	58	13	781	827	561	198												
4		2	4		2.6667				1	1	1	1	1	1	1	1	1	1	4												
952		462	532		557		2503		1348	231	83	48	90	58	13	1871	781	827	561	792	2957										

## Appendix 2-1: Continued.

Sediment depth (cm)		St22 74m depth							St23 90m depth					St24 95m depth					
		0-0.5	0.5-1	1-1.5	1.5-2	2-3	3-4	4-5	Total	0-0.5	0.5-1	1-2	2-5	Total	0-0.5	0.5-1	1-2	2-5	Total
Perforates	<i>Ammodiscus</i> sp.							0					0					0	
	<i>Ammonia beccarii</i> f. <i>inflata</i>	28	31	15	8	15	8	6	111	102	46	53	33	234	69	17	25	34	145
	<i>Amphicoryna scalaris</i>	3	1	4					8	3	1	5		9	6	2	0	2	10
	<i>Astacolus insolitus</i>								0					0	2	0	0		2
	<i>Bolivina alata</i>		1						1	40	13	15	9	77	40	32	7	1	80
	<i>Bolivina dilatata</i>								0					0					0
	<i>Bolivina spathulata</i>								0					0					0
	<i>Bolivina subaenariensis</i>	2	2			1			5	16	2	1	4	23	18	16	5	2	41
	<i>Bulimina aculeata</i>	18	21	9	10	28	13	3	102	89	28	24	38	179	143	47	61	104	355
	<i>Bulimina costata</i>					1			1	18	4	2	6	30	4	2	2	1	9
	<i>Bulimina marginata</i>		7	2	1	8	4		22	3	4	1		8					0
	<i>Cassidulina carinata</i>	219	218	116	61	81	10	2	707	170	97	84	59	410	227	47	19	19	312
	<i>Cassidulina oblonga</i>		1		1	1			3					0	3	3		1	7
	<i>Chilostomella ovoidea</i>								0	1		7	11	19	10	7	11	6	34
	<i>Dentalina bradyensis</i>								0					0	1				1
	<i>Elphidium advenum</i>	1	4	2	1	2	5	4	19					0					0
	<i>Elphidium macellum</i>	14	4	9	4	6	1	1	39	6	1	2	3	12	1	1	3	2	7
	<i>Fursenkoina complanata</i>		1						1	1	1			2					0
	<i>Fursenkoina concava</i>								0					0					0
	<i>Gavelinopsis praegeri</i>		1		1				2					0					0
	<i>Globobulimina affinis</i>			1	3	5			9	2		8	4	14	10	6	8	3	27
	<i>Globobulimina pyrula</i> var. <i>pseudospitescens</i>		2	2	1	2		1	8		2	3	3	8			2	1	3
	<i>Globulina rotundata</i>		1						1					0					0
	<i>Gyroidinoides</i> cf. <i>soldanii</i>		1						1					0	2				2
	<i>Hanzawaia boueana</i>	1							1					0	11		1	1	13
	<i>Hyalinea balthica</i>	10	6	8	2	4	1	3	34	12	3	5	10	30	21	5	7	3	36
	<i>Lagena</i> sp.					1			1	2		1		3	7				7
	<i>Lenticulina atlantica</i>								0			1		1					0
<i>Lenticulina peregrina</i>		1			2			3	6	1	3	1	11	1				1	
<i>Melonis barleaanus</i>		5	2			1		8	24	11	10	9	54	17	14	3	8	42	
<i>Nonion scaphum</i>	12	59	54	69	84	20	15	313	22	21	32	68	143	15	21	77	14	127	
<i>Nonionella turgida</i>	8	39	38	65	106	33	22	311	6	5	7	12	30		9	19	5	33	
<i>Procerolagena gracillina</i>				1				1					0					0	
<i>Pseudoeponides falsobeccarii</i>	11	12	7	5	6	1		42	40	8	14	13	75		1	1	3	5	
<i>Rectuvigerina phlegeri</i>	1	5		2				8	8	8	1		17	5	6	2		13	
<i>Saidovina karveriana</i>								0					0					0	
<i>Uvigerina mediterranea</i>		2	3					5	12		18	1	31	33	7		3	43	
<i>Valvulineria bradyana</i>		13	14	14	7	1		49	112	78	61	21	272	120	142	63	1	326	
Miliolids	<i>Adelosina longirostra</i>							0					0					0	
	<i>Pyrgo subsphaerica</i>							0					0					0	
	<i>Quinqueloculina badenensis</i>							0					0					0	
	<i>Quinqueloculina grata</i>							0					0					0	
	<i>Quinqueloculina seminula</i> f. <i>longa</i>	2	6	3		3			14	10	14	4	4	32	31	8	5		44
	<i>Quinqueloculina</i> sp.1							0					0					0	
	<i>Quinqueloculina</i> sp.2							0					0					0	
	<i>Spiroloculina canaliculata</i>							0					0					0	
Agglutinates	<i>Adercotryma glomeratum</i>							0		1		2	3	13	3	4	5	25	
	<i>Bigenerina nodosaria</i>	2						2	3	1	5	7	16	9	5	2	6	22	
	<i>Clavulina cylindrica</i>		1					1	26	4	11	9	50	8	4	2		14	
	<i>Cribrostomoides jeffreysii</i>		1	1	1			3					0	3	4	4	2	13	
	<i>Cribrostomoides subglobosus</i>				1			1	2	2	10	4	18					0	
	<i>Eggerella scabra</i>	21	40	16	7	11	1	3	99	36	30	23	44	133	52	20	23	13	108
	<i>Eratidus foliaceus</i>							0				1	1	4		1		5	
	<i>Lagenammina difflugiformis</i>	7	13	9	2	6			37	2	3		4	9	12	6	11	9	38
	<i>Recurvoides trochaminiformis</i>	2		12	12	10			36	53	14	40	24	131	31	15	10	6	62
	<i>Reophax fusiformis</i>		1			1			2					0	1				1
	<i>Reophax scorpiurus</i>							0	2		1	5	8	1				1	
	<i>Reophax scotti</i>							0					0					0	
<i>Textularia agglutinans</i>	7	1	1	2	2			13	12	5	6	25	48	13	7	6	11	37	
Total hand sorted (t)		369	501	328	274	393	99	60	841	408	458	434		944	457	384	266		
split (s)		1	1	1	1	1	1	1	1	1	1	1		1	1	1	1		
TOTAL = t+s		369	501	328	274	393	99	60	2024	841	408	458	434	2141	944	457	384	266	2051

## Spatial distribution of benthic foraminifera in the Rhône prodelta

Appendix 2-2: Census data (non-standardized) of live benthic foraminifera of 63-150 µm fraction.

Sediment depth (cm)		St1 20m depth				St2 40m depth				St3 53m depth				St4 60 m depth							
		0-0.5cm		0.5-1cm		0-0.5cm		0.5-1cm		0-0.5cm		0.5-1cm		0-0.5cm		0.5-1cm					
Taxa		Brut	* (s)		Total	Brut	* (s)	Brut	* (s)	Total	Brut	* (s)	Brut	* (s)	Total	Brut	* (s)	Brut	* (s)	Total	
Perforates	<i>Ammonia beccarii</i> f. <i>inflata</i>	9	72	5	77	0	3	24	24	24	1	8	1	8	16	0		0		0	
	<i>Amphicoryna scalaris</i>	0	1		1	0			0	0	0				0	0				0	
	<i>Astacolus insolitus</i>																				
	<i>Bolivina alata</i>	2	16		16	0				0	0				0	0					0
	<i>Bolivina dilatata</i>	33	264	31	295	127	1016	156	1248	2264	69	552	43	344	896	109	872	113	1808	2680	
	<i>Bolivina seminuda</i>	2	16		16	0	5	40	40	40	2	16			16	0	4	64			64
	<i>Bolivina spathulata</i>	2	16	11	27	14	112	20	160	272	2	16	1	8	24	26	208	13	208		416
	<i>Bolivina subaenariensis</i>	0	1		1	0	6	48	48	48	0				0	1	8	1	16		24
	<i>Bulimina aculeata</i>	37	296	2	298	42	336	20	160	496	28	224	1	8	232	13	104	9	144		248
	<i>Bulimina costata</i>																				
	<i>Bulimina marginata</i>		0		0	0	2	16	16	16	3	24			24	1	8			8	8
	<i>Cassidulina carinata</i>	1	8	5	13	0	2	16	16	16	0				0	8	64	1	16		80
	<i>Cassidulina oblonga</i>		0		0	0			0	0	0				0	0					0
	<i>Dentalina bradyensis</i>																				
	<i>Elphidium advenum</i>		0		0	0	0			0	0	0			0	0					0
	<i>Elphidium macellum</i>		0	1		1	0			0	0	0			0	0					0
	<i>Epistominella exigua</i>				4	4	8	64	5	40	104	1	8	2	16	24	11	88	2	32	120
	<i>Fissurina</i> sp.																				
	<i>Fursenkoina complanata</i>		0		0	2	16	12	96	112	1	8			8	1	8	1	16		24
	<i>Fursenkoina concava</i>		0		0	0	0			0	0	0			0	0					0
	<i>Fursenkoina fusiformis</i>	22	176	19	195	35	280	39	312	592	72	576	89	712	1288	60	480	127	2032		2512
	<i>Gavelinopsis praegeri</i>																				
	<i>Globobulimina affinis</i>																				
	<i>Gyroidinoides</i> cf. <i>soldanii</i>																				
	<i>Hanzawaia boueana</i>		0		0	0	0			0	0	0			0	0	0				0
	<i>Haynesina germanica</i>	1	8		8	1	8			8	8	0			0	0					0
	<i>Hopkinsina pacifica</i>	15	120	3	123	138	1104	186	1488	2592	5	40	11	88	128	12	96	29	464		560
	<i>Hyalinea balthica</i>		0			0	0			0	0	0			0	0					0
	<i>Lagena</i> sp.	1	8	1	9	0				0	0	0			0	0					0
	<i>Lenticulina atlantica</i>		0		0	0	2	16	16	16	1	8			8	2	16			16	16
	<i>Melonis barleeanus</i>	1	8	5	13	1	8			8	1	8			8	0					0
	<i>Nonion scaphum</i>	3	24		24	8	64	19	152	216	1	8	3	24	32	7	56	2	32		88
	<i>Nonionella bradyi</i>	6	48	3	51	16	128	18	144	272	1	8			8	8	64				64
	<i>Nonionella iridea</i>		2		2	0				0	0				0	4	32				32
	<i>Nonionella turgida</i>	55	440	36	476	115	920	187	1496	2416	27	216	49	392	608	107	856	167	2672		3528
	<i>Procerolagena gracillina</i>		0	1	1	0				0	0	0			0	0					0
	<i>Pseudoepionides falsobeccarii</i>		0		0	0	0			0	0	0			0	0					0
	<i>Rectuvigerina phlegeri</i>		0		0	0	4	32	32	32	0	1	8	8	8	0					0
	<i>Trifarina pauperata</i>			1		1	0			0	0	0			0	0					0
	<i>Uvigerina mediterranea</i>		0		0	0	0			0	0	0			0	0					0
<i>Uvigerina peregrina</i>					1	8	5	40	48	0				0	0			1	16	16	
<i>Valvulineria bradyana</i>		0		0	2	16	3	24	40	0	0			0	0					0	
Miliolids	<i>Adelosina longirostra</i>	21	168	2	170	1	8	6	48	56	5	40	6	48	88	6	48	1	16	64	
	<i>Pyrgo subsphaerica</i>		0		0	0			0	0	0			0	0	0				0	
	<i>Quinqueloculina badenensis</i>		0		0	0			0	0	0			0	0	0				0	
	<i>Quinqueloculina grata</i>		0		0	3	24	3	24	48	0	2	16	16	16	5	40	1	16	56	
	<i>Quinqueloculina seminula</i> f. <i>longa</i>	3	24		24	0				0	0				0	0					0
	<i>Quinqueloculina</i> sp.1		0		0	0			0	0	0			0	0	0					0
	<i>Quinqueloculina</i> sp.2		0		0	0			0	0	0			0	0	0					0
	<i>Spiroloculina canaliculata</i>		0		0	0	0			0	0			0	0	0					0
Agglutinates	<i>Adercotryma glomeratum</i>		0		0	0			0	0	0			0	0					0	
	<i>Bigenerina nodosaria</i>		0		0	0			0	0	0			0	0					0	
	<i>Clavulina cylindrica</i>		0		0	0			0	0	0			0	0					0	
	<i>Cribrostomoides jeffreysii</i>		0		0	1	8	5	40	48	0			0	0	1	8	1	16	24	
	<i>Cribrostomoides subglobosus</i>		0		0	0			0	0	0			0	0	0				0	
	<i>Eggerella advena</i>		0		0	6	48	8	64	112	0			0	0	1	8	1	16	24	
	<i>Eggerella scabra</i>		0		0	0			0	0	0			0	0	0				0	
	<i>Eratidus foliaceus</i>		0		0	0			0	0	0			0	0	0				0	
	<i>Lagenammina difflugiformis</i>	1	8		8	0			0	0	0			0	0	0				0	
	<i>Recurvoides trochamminiformis</i>		0		0	0	1	8	8	8	0			0	0	0			1	16	16
	<i>Reophax fusiformis</i>		0		0	0			0	0	0			0	0	0					0
	<i>Reophax scorpiurus</i>		0		0	0			0	0	0			0	0	0					0
	<i>Reophax scotti</i>	38	304	4	308	59	472	17	136	608	64	512	73	584	1096	8	64	61	976		1040
	<i>Reophax</i> sp.		0		0	1	8			8	0			0	0	1	8			8	8
<i>Textularia agglutinans</i>		0		0	0			0	0	0			0	0	0					0	
<i>Textularia porrecta</i>			2	2	6	48	21	168	216	0	4	32	32	32	22	176	12	192		368	
<i>Textularia</i> sp.																					
<b>Total hand sorted (t)</b>	253	2024	138		580	4640	734	5872		284	2272	282	2256		392	3136	536	8576			
<b>splīt (s)</b>	8	1			8	8				8	8				8	16					
<b>TOTAL = t*s</b>				2164				10728		2272		2256	4560	3136		8576		12080			

Appendix 2-2: Continued.

Sediment depth (cm)		St5 63m depth					St6 40m depth					St7 65m depth					
		0-0,5cm		0,5-1cm		Total	0-0,5cm		0,5-1cm		Total	0-0,5cm		0,5-1cm		Total	
		Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)		
Perforates	Taxa																
	<i>Ammonia beccarii</i> f. <i>inflata</i>	0		0		0	0		0		0	0		0		0	
	<i>Amphicoryna scalaris</i>	0		0		0	0		0		0	1		8		8	
	<i>Astacolus insolitus</i>																
	<i>Bolivina alata</i>	0		0		0	0		0		0	0		0		0	
	<i>Bolivina dilatata</i>	107	856	111	1776	2632	141	1128	108	864	1992	96	768	106	848	1616	
	<i>Bolivina seminuda</i>	2		16		16	0		0		0	0		0		0	
	<i>Bolivina spathulata</i>	20	160	19	304	464	9	72	8	64	136	4	32	3	24	56	
	<i>Bolivina subaenariensis</i>	1		8		24	0		0		0	3		24		24	
	<i>Bulimina aculeata</i>	7	56	3	48	104	5	40	7	56	96	3	24	8	64	88	
	<i>Bulimina costata</i>																
	<i>Bulimina marginata</i>	0		0		0	0		0		0	0		1		8	
	<i>Cassidulina carinata</i>	7	56	5	80	136	6	48	0		48	6	48	3	24	72	
	<i>Cassidulina oblonga</i>																
	<i>Dentalina bradyensis</i>																
	<i>Elphidium advenum</i>	0		0		0	0		0		0	3		24		24	
	<i>Elphidium macellum</i>	0		0		0	1	8	0		8	0		0		0	
	<i>Epistominella exigua</i>	22	176	4	64	240	6	48	2	16	64	5	40	8	64	104	
	<i>Fissurina</i> sp.	1		0		0	0		0		0	0		0		0	
	<i>Fursenkoina complanata</i>	7	56	5	80	136	2	16	4	32	48	5	40	2	16	56	
	<i>Fursenkoina concava</i>	0		3		48	0		5		40	0		0		0	
	<i>Fursenkoina fusiformis</i>	25	200	53	848	1048	21	168	56	448	616	44	352	65	520	872	
	<i>Gavelinopsis praegeri</i>																
	<i>Globobulimina affinis</i>																
	<i>Gyroidinoides</i> cf <i>soldanii</i>																
	<i>Hanzawaia boueana</i>	0		0		0	1	8	0		8	0		0		0	
	<i>Haynesina germanica</i>	0		0		0	0		0		0	0		0		0	
	<i>Hopkinsina pacifica</i>	12	96	23	368	464	118	944	188	1504	2448	9	72	4	32	104	
	<i>Hyalinea balthica</i>																
	<i>Lagena</i> sp.	0		0		0	0		0		0	0		0		0	
	<i>Lenticulina atlantica</i>	0		0		0	0		1		8	0		0		0	
	<i>Melonis barleaanus</i>																
	<i>Nonion scaphum</i>	5	40	7	112	152	38	304	22	176	480	29	232	16	128	360	
<i>Nonionella bradyi</i>	11	88	2	32	120	14	112	17	136	248	16	128	17	136	264		
<i>Nonionella iridea</i>	5		40		40	23		184		184	1		8		8		
<i>Nonionella turgida</i>	63	504	69	1104	1608	215	1720	191	1528	3248	63	504	125	1000	1504		
<i>Procerolagena gracillina</i>																	
<i>Pseudoeponides falsobeccarii</i>																	
<i>Rectuvigerina phlegeri</i>	1	8	0		8	16	128	1	8	136	1	8	1	8	16		
<i>Trifarina pauperata</i>																	
<i>Uvigerina mediterranea</i>	0		1		16	0		0		0	0		0		0		
<i>Uvigerina peregrina</i>	5	40	0		40	13	104	7	56	160	0		0		0		
<i>Valvulineria bradyana</i>	0		0		0	11	88	4	32	120	6	48	1	8	56		
Miliolids	<i>Adelosina longirostra</i>	0		0		0	1	8	1	8	16	0		2		16	
	<i>Pyrgo subsphaerica</i>	0		0		0	0		1		8	0		0		0	
	<i>Quinqueloculina badenensis</i>																
	<i>Quinqueloculina grata</i>	3	24	0		24	6	48	2	16	64	1	8	1	8	16	
	<i>Quinqueloculina seminula</i> f. <i>longa</i>																
	<i>Quinqueloculina</i> sp.1																
	<i>Quinqueloculina</i> sp.2																
<i>Spiroloculina canaliculata</i>																	
Agglutinates	<i>Adercotryma glomeratum</i>	0		1		16	1	8	1	8	16	0		0		0	
	<i>Bigenerina nodosaria</i>	0		0		0	0		0		0	0		0		0	
	<i>Clavulina cylindrica</i>																
	<i>Cribrostomoides jeffreysii</i>	0		0		0	0		1		8	0		0		0	
	<i>Cribrostomoides subglobosus</i>																
	<i>Eggerella advena</i>																
	<i>Eggerella scabra</i>	2	16	4	64	80	3	24	5	40	64	0		1		8	
	<i>Eratidus foliaceus</i>																
	<i>Lagenamina difflugiformis</i>																
	<i>Recurvoides trochamminiformis</i>	0		0		0	0		0		0	0		1		8	
	<i>Reophax fusiformis</i>																
	<i>Reophax scorpiurus</i>																
	<i>Reophax scotti</i>	0		5		80	80	3	24	12	96	120	0		0		0
	<i>Reophax</i> sp.	1	8	3	48	56	0		1		8	8	1	8	0	8	
	<i>Textularia agglutinans</i>																
	<i>Textularia porrecta</i>	23	184	19	304	488	2	16	3	24	40	1	8	2	16	24	
	<i>Textularia</i> sp.																
Total hand sorted (t)	307	2448	319	5104		654	5232	645	5160		296	2368	366	2928			
split (s)	8		16			8		8			8		8				
TOTAL = t+s	2456		5104		8040	5232		5160		10432	2368		2928		5320		

Spatial distribution of benthic foraminifera in the Rhône prodelta

Appendix 2-2: Continued.

St8 65m depth					St9 65m depth					St10 80m depth					St11 66m depth				
0-0.5cm		0.5-1cm		Total	0-0.5cm		0.5-1cm		Total	0-0.5cm		0.5-1cm		Total	0-0.5cm		0.5-1cm		Total
Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	0	0	8
0	0	0	0	0	0	0	0	0	0	2	16	0	0	18	2	16	1	8	24
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
329	2632	68	1088	3720	94	752	99	792	1544	144	1152	84	672	2052	129	1032	140	1120	2152
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	144	1	16	160	2	16	4	32	48	19	152	0	0	171	16	128	7	56	184
0	0	0	0	0	0	0	0	0	0	3	24	0	0	27	9	72	1	8	80
19	152	7	112	264	18	144	6	48	192	10	80	2	16	108	17	136	7	56	192
0	0	0	0	0	0	0	0	0	0	12	96	1	8	117	2	16	3	24	40
18	144	1	16	160	13	104	4	32	136	39	312	0	0	351	30	240	9	72	312
0	0	0	0	0	1	8	0	0	8	1	8	0	0	9	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	8	0	0	8
0	1	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	184	6	96	280	10	80	17	136	216	27	216	7	56	254	31	248	13	104	352
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	216	0	0	216	6	48	0	0	48	14	112	1	8	135	20	160	8	64	224
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	448	72	1152	1600	26	208	40	320	528	5	40	62	496	67	5	40	11	88	128
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	136	4	64	200	8	64	12	96	160	5	40	4	32	86	28	224	43	344	568
0	0	0	0	0	0	0	0	0	0	1	8	0	0	9	0	0	0	0	0
0	0	0	0	0	1	8	0	0	8	0	0	0	0	0	2	16	0	0	16
1	8	1	16	24	1	8	0	0	8	4	32	0	0	36	3	24	0	0	24
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	272	5	80	352	6	48	1	8	56	7	56	3	24	90	7	56	5	40	96
44	352	12	192	544	10	80	5	40	120	23	184	4	32	216	20	160	14	112	272
0	0	0	0	0	24	192	0	0	192	71	568	0	0	639	20	160	0	0	160
144	1152	104	1664	2816	99	792	155	1240	2032	40	320	156	1248	1764	81	648	83	664	1312
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	8	0	0	8	0	0	0	0	0	13	104	13	104	234	2	16	4	32	48
0	0	0	0	0	1	8	0	0	8	3	24	5	40	72	1	8	0	0	8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	8	8	8	0	0	0	0	0	0	0	3	24	24
6	48	1	16	64	3	24	1	8	32	7	56	0	0	63	7	56	0	0	56
13	104	1	16	120	2	16	1	8	24	0	0	0	0	0	5	40	0	0	40
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	24	0	0	24	1	8	1	8	16	2	16	2	16	36	5	40	0	0	40
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	8	1	16	24	6	48	2	16	64	0	0	1	8	9	15	120	9	72	192
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	8	8	9	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	24	1	16	40	1	8	1	8	16	0	0	2	16	18	1	8	0	0	8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	16	2	32	48	5	40	5	40	80	1	8	0	0	9	21	168	15	120	288
759	6072	287	4592		334	2672	350	2800		452	3616	349	2792		464	3712	363	2904	
8	16				8	8				8	8				8	8			
6072	4592		10712		2672	2800		5552		3616	2792		5337		3712	2904		6904	

Appendix 2-2: Continued.

Sediment depth (cm)		St12 58m depth					St13 75m depth					St14 85m depth				
		0-0.5cm		0.5-1cm		Total	0-0.5cm		0.5-1cm		Total	0-0.5cm		0.5-1cm		Total
Taxa	Taxa	Brut	*(s)	Brut	*(s)	Total	Brut	*(s)	Brut	*(s)	Total	Brut	*(s)	Brut	*(s)	Total
Perforates	<i>Ammonia beccarii f. inflata</i>	2	32		0	32		0		0	0		0		0	0
	<i>Amphicoryna scalaris</i>	2	32	1	8	40		0	1	8	8		0		0	0
	<i>Astacolus insolitus</i>					0					0					0
	<i>Bolivina alata</i>		0		0	0		0		0	0		0		0	0
	<i>Bolivina dilatata</i>	250	4000	153	1224	5224	87	1392	84	672	2064	99	3168	110	880	4048
	<i>Bolivina seminuda</i>		0		0	0		0		0	0		0		0	0
	<i>Bolivina spathulata</i>	19	304	3	24	328		0		0	0	9	288		0	288
	<i>Bolivina subaenariensis</i>	2	32		0	32		0		0	0		0		0	0
	<i>Bulimina aculeata</i>	18	288	9	72	360	6	96	3	24	120	3	96	2	16	112
	<i>Bulimina costata</i>					0					0					0
	<i>Bulimina marginata</i>	3	48		0	48		0	1	8	8		0	5	40	40
	<i>Cassidulina carinata</i>	13	208		0	208	2	32	2	16	48	9	288	2	16	304
	<i>Cassidulina oblonga</i>	2	32		0	32		0		0	0		0		0	0
	<i>Dentalina bradyensis</i>					0					0					0
	<i>Elphidium advenum</i>	1	16	2	16	32		0	2	16	16		0	1	8	8
	<i>Elphidium macellum</i>	1	16		0	16		0		0	0		0		0	0
	<i>Epistominella exigua</i>	17	272	2	16	288	4	64	3	24	88	10	320	6	48	368
	<i>Fissurina sp.</i>		0		0	0		0		0	0		0		0	0
	<i>Fursenkoina complanata</i>	16	256	4	32	288	10	160	3	24	184	26	832	11	88	920
	<i>Fursenkoina concava</i>		0		0	0	3	48		0	48		0	2	16	16
	<i>Fursenkoina fusiformis</i>	15	240	5	40	280	13	208	29	232	440	33	1056	102	816	1872
	<i>Gavelinopsis praegeri</i>	3	48		0	48		0		0	0		0		0	0
	<i>Globobulimina affinis</i>					0					0					0
	<i>Gyroidinoides cf soldanii</i>					0	1	16		0	16		0		0	0
	<i>Hanzawaia boueana</i>		0		0	0		0		0	0		0		0	0
	<i>Haynesina germanica</i>		0		0	0		0		0	0		0		0	0
	<i>Hopkinsina pacifica</i>	19	304	25	200	504	40	640	88	704	1344	18	576	29	232	808
	<i>Hyalinea balthica</i>		0		0	0		0		0	0		0		0	0
	<i>Lagena sp.</i>	6	96		0	96		0		0	0	2	64		0	64
	<i>Lenticulina atlantica</i>		0		0	0		0		0	0		0		0	0
	<i>Melonis barleaanus</i>		0		0	0		0		0	0		0		0	0
	<i>Nonion scaphum</i>	47	752	38	304	1056	32	512	20	160	672	28	896	22	176	1072
	<i>Nonionella bradyi</i>	13	208	14	112	320	22	352	31	248	600	38	1216	15	120	1336
<i>Nonionella iridea</i>	7	112		0	112	5	80	1	8	88	29	928		0	928	
<i>Nonionella turgida</i>	243	3888	134	1072	4960	168	2688	233	1864	4552	78	2496	238	1904	4400	
<i>Procerolagena gracillina</i>		0		0	0		0		0	0		0		0	0	
<i>Pseudoeponides falsobeccarii</i>		0		0	0		0		0	0		0		0	0	
<i>Rectuvigerina phlegeri</i>	45	720	43	344	1064	18	288	13	104	392	14	448	8	64	512	
<i>Trifarina pauperata</i>	40	640	16	128	768	24	384	11	88	472	7	224	4	32	256	
<i>Uvigerina mediterranea</i>		0		0	0		0		0	0		0		0	0	
<i>Uvigerina peregrina</i>		0		0	0	2	32		0	32	3	96		0	96	
<i>Valvulineria bradyana</i>	21	336		0	336	3	48	2	16	64	5	160		0	160	
Miliolids	<i>Adelosina longirostra</i>	3	48		0	48		0		0	0	3	96	1	8	104
	<i>Pyrgo elongata</i>		0		0	0		0		0	0		0		0	0
	<i>Quinqueloculina badenensis</i>		0		0	0		0		0	0		0		0	0
	<i>Quinqueloculina grata</i>	6	96		0	96		0	2	16	16		0	1	8	8
	<i>Quinqueloculina seminula f. longa</i>		0		0	0		0		0	0		0		0	0
	<i>Quinqueloculina sp.1</i>		0		0	0		0		0	0		0		0	0
	<i>Quinqueloculina sp.2</i>		0		0	0		0		0	0		0		0	0
<i>Spiroloculina canaliculata</i>		0		0	0		0		0	0		0		0	0	
Agglutinates	<i>Adercotryma glomeratum</i>	3	48		0	48		0		0	0	3	96		0	96
	<i>Bigenerina nodosaria</i>		0		0	0		0		0	0		0		0	0
	<i>Clavulina cylindrica</i>		0		0	0		0		0	0		0		0	0
	<i>Cribratomoides jeffreysii</i>	2	32		0	32		0		0	0		0		0	0
	<i>Cribratomoides subglobosus</i>		0		0	0		0		0	0		0		0	0
	<i> Eggerella advena</i>					0					0					0
	<i>Eggerella scabra</i>	16	256	2	16	272	2	32		0	32	4	128	4	32	160
	<i>Eratidus foliaceus</i>		0		0	0		0		0	0		0		0	0
	<i>Lagenamma difflugiformis</i>		0		0	0		0		0	0		0		0	0
	<i>Recurvoides trochamminiformis</i>		0		0	0		0		0	0		0		0	0
	<i>Reophax fusiformis</i>		0		0	0		0		0	0		0		0	0
	<i>Reophax scorpurus</i>		0		0	0		0		0	0		0		0	0
	<i>Reophax scotti</i>	2	32		0	32	2	32		0	32		0		0	0
	<i>Reophax sp.</i>		0		0	0		0		0	0		0		0	0
	<i>Textularia agglutinans</i>		0		0	0		0		0	0		0		0	0
<i>Textularia porrecta</i>	22	352	3	24	376	3	48	2	16	64	3	96	4	32	128	
<i>Textularia sp.</i>					0					0					0	
<b>Total hand sorted (t)</b>	<b>837</b>	<b>13392</b>	<b>451</b>	<b>3608</b>		<b>444</b>	<b>7104</b>	<b>529</b>	<b>4232</b>		<b>421</b>	<b>13472</b>	<b>563</b>	<b>4504</b>		
<b>splitted (s)</b>	<b>16</b>		<b>8</b>			<b>16</b>		<b>8</b>			<b>32</b>		<b>8</b>			
<b>TOTAL = t*s</b>	<b>13392</b>		<b>3608</b>		<b>17376</b>	<b>7104</b>		<b>4232</b>		<b>11400</b>	<b>13472</b>		<b>4504</b>		<b>18104</b>	

Spatial distribution of benthic foraminifera in the Rhône prodelta

Appendix 2-2: Continued.

St15 89m depth			St16 83m depth			St17 73 m depth			St18 85m depth																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																						
0-0.5cm		Total	0.5-1cm		Total	0-0.5cm		Total	0-0.5cm		Total																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
Brut	*(s)		Brut	*(s)		Brut	*(s)		Brut	*(s)		Brut	*(s)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
	0	0		0	0		0	0		0	0	1	8	16			8			0			8		0	0		0	0		0	0		0	0	189	1512	2664	61	488	1016	111	888	1640	110	880	1544		0	0		0	0		0	0		0	0	27	216	216	8	64	96	9	72	128	8	64	64	1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976
1	8	16			8			0			8		0	0		0	0		0	0		0	0	189	1512	2664	61	488	1016	111	888	1640	110	880	1544		0	0		0	0		0	0		0	0	27	216	216	8	64	96	9	72	128	8	64	64	1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976												
	0	0		0	0		0	0		0	0	189	1512	2664	61	488	1016	111	888	1640	110	880	1544		0	0		0	0		0	0		0	0	27	216	216	8	64	96	9	72	128	8	64	64	1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																								
189	1512	2664	61	488	1016	111	888	1640	110	880	1544		0	0		0	0		0	0		0	0	27	216	216	8	64	96	9	72	128	8	64	64	1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																				
	0	0		0	0		0	0		0	0	27	216	216	8	64	96	9	72	128	8	64	64	1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																
27	216	216	8	64	96	9	72	128	8	64	64	1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																												
1	8	24		0	0	3	24	24	2	16	16		0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																								
	0	24	2	16	72	16	128	184	14	112	128		0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																				
	0	0		0	0		0	0		0	0	10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																
10	80	80	6	48	96	7	56	72	3	24	24	40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																												
40	320	384	47	376	600	41	328	424	43	344	376	2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																								
2	16	16	4	32	40		0	0		0	0		0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																				
	0	0	1	8	16		0	0	1	8	8		0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																
	0	0		0	8	6	48	80		0	8		0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																												
	0	0		0	0		0	0		0	0	23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																								
23	184	208	22	176	280	33	264	328	21	168	256		0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																				
	0	0		0	0		0	0		0	0	21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																
21	168	272	2	16	32	29	232	304	17	136	144		0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																												
	0	0		0	0		0	0	1	8	8	4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																								
4	32	80		0	0	34	272	760	8	64	328		0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																				
	0	0		0	0		0	8		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																
	0	0		0	0	1	8	8		0	0		0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																												
	0	0		0	0	2	16	24		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																								
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																				
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																
	0	0		0	0		0	0		0	0	3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																												
3	24	64	1	8	8	3	24	96	2	16	32		0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																								
	0	0		0	0		0	0		0	0		0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																				
	0	0	2	16	16		0	16	1	8	8		0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																
	0	0	1	8	8		0	0	1	8	8		0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																												
	0	0		0	0		0	0		0	0	38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																								
38	304	560		0	8	12	96	304	15	120	256	41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																				
41	328	360	11	88	144	19	152	200	24	192	240	143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																
143	1144	1144	9	72	72	10	80	80	20	160	160	128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																												
128	1024	1784	27	216	608	139	1112	2856	122	976	2360		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																								
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	0		0	0		0	0		0	0	5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																												
5	40	144	4	32	48	13	104	232	48	384	536	9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
9	72	96		0	8	4	32	32	10	80	80		0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0		0	0		0	0		0	0	15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
15	120	144	1	8	8	10	80	144	12	96	136	6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
6	48	72	2	16	24	6	48	64	5	40	48		0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	0	24	4	32	56		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	0		0	0		0	0		0	0	3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
3	24	40		0	0	6	48	72	11	88	96		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
	0	0		0	0		0	0		0	0	2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
2	16	24	6	48	88	2	16	16	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	0		0	0		0	0		0	0	1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
1	8	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	0	0		0	0		0	0		0	0	1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
1	8	8		0	0		0	0		0	0		0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	16		0	0	3	24	24		0	8		0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
	0	0		0	0		0	0		0	0		0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	0	0	6	48	48	2	16	16	3	24	24		0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	8		0	8		0	8	1	8	8		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
	0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	0	0		0	0		0	0		0	0		0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0		0	0	1	8	16		0	0		0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
	0	8		0	0	1	8	8		0	0		0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
	0	0		0	0		0	0		0	0	11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
11	88	88	4	32	32	31	248	336	5	40	40		0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	0	0	4	32	80		0	0		0	0	716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
716	5728	8576	228	1824	3544	525	4200	8512	505	4040	6976	8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
8	8		8	8		8	8		8	8		5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
5728		8576	1824	1608	3544	4200	3976	8512	4040	2896	6976																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				



Appendix 2-2: Continued.

Sediment depth (cm)		St12 58m depth					St13 75 m depth					St14 85m depth				
		0-0,5cm		0,5-1 cm		Total	0-0,5cm		0,5-1 cm		Total	0-0,5cm		0,5-1 cm		Total
Taxa		Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)	
Perforates	<i>Ammonia beccarii</i> f. <i>inflata</i>	2	32		0	32	0			0	0	0			0	0
	<i>Amphicoryna scalaris</i>	2	32	1	8	40	0		1	8	8	0			0	0
	<i>Astacolus insolitus</i>					0					0					0
	<i>Bolivina alata</i>	0		0		0	0			0	0	0			0	0
	<i>Bolivina dilatata</i>	250	4000	153	1224	5224	87	1392	84	672	2064	99	3168	110	880	4048
	<i>Bolivina seminuda</i>	0		0		0	0			0	0	0			0	0
	<i>Bolivina spathulata</i>	19	304	3	24	328	0			0	0	9	288		0	288
	<i>Bolivina subaenariensis</i>	2	32		0	32	0			0	0	0			0	0
	<i>Bulimina aculeata</i>	18	288	9	72	360	6	96	3	24	120	3	96	2	16	112
	<i>Bulimina costata</i>					0					0					0
	<i>Bulimina marginata</i>	3	48		0	48	0		1	8	8	0		5	40	40
	<i>Cassidulina carinata</i>	13	208		0	208	2	32	2	16	48	9	288	2	16	304
	<i>Cassidulina oblonga</i>	2	32		0	32	0			0	0	0			0	0
	<i>Dentalina bradyensis</i>					0					0					0
	<i>Elphidium advenum</i>	1	16	2	16	32			2	16	16			1	8	8
	<i>Elphidium macellum</i>	1	16		0	16				0	0				0	0
	<i>Epistominella exigua</i>	17	272	2	16	288	4	64	3	24	88	10	320	6	48	368
	<i>Fissurina</i> sp.					0					0					0
	<i>Fursenkoina complanata</i>	16	256	4	32	288	10	160	3	24	184	26	832	11	88	920
	<i>Fursenkoina concava</i>					0	3	48		0	48				2	16
	<i>Fursenkoina fusiformis</i>	15	240	5	40	280	13	208	29	232	440	33	1056	102	816	1872
	<i>Gavelinopsis praegeri</i>	3	48		0	48				0	0				0	0
	<i>Globobulimina affinis</i>					0					0					0
	<i>Gyroidinoides cf soldanii</i>					0	1	16		0	16				0	0
	<i>Hanzawaia boueana</i>					0					0				0	0
	<i>Haynesina germanica</i>					0					0				0	0
	<i>Hopkinsina pacifica</i>	19	304	25	200	504	40	640	88	704	1344	18	576	29	232	808
	<i>Hyalinea bathica</i>					0					0				0	0
	<i>Lagena</i> sp.	6	96		0	96					0	2	64		0	64
	<i>Lenticulina atlantica</i>					0					0				0	0
	<i>Melonis barleanus</i>					0					0				0	0
	<i>Nonion scaphum</i>	47	752	38	304	1056	32	512	20	160	672	28	896	22	176	1072
	<i>Nonionella bradyi</i>	13	208	14	112	320	22	352	31	248	600	38	1216	15	120	1336
	<i>Nonionella iridea</i>	7	112		0	112	5	80	1	8	88	29	928		0	928
	<i>Nonionella turgida</i>	243	3888	134	1072	4960	168	2688	233	1864	4552	78	2496	238	1904	4400
	<i>Procerolagena gracillina</i>					0					0				0	0
	<i>Pseudoeponides falsobecarii</i>					0					0				0	0
	<i>Rectuvigerina phlegeri</i>	45	720	43	344	1064	18	288	13	104	392	14	448	8	64	512
	<i>Trifarina pauperata</i>	40	640	16	128	768	24	384	11	88	472	7	224	4	32	256
	<i>Uvigerina mediterranea</i>					0					0				0	0
	<i>Uvigerina peregrina</i>					0	2	32		0	32	3	96		0	96
	<i>Valvulineria bradyana</i>	21	336		0	336	3	48	2	16	64	5	160		0	160
Miliolids	<i>Adelosina longirostra</i>	3	48		0	48				0	3	96	1	8	104	
	<i>Pyrgo subsphaerica</i>					0				0				0	0	
	<i>Quinqueloculina badenensis</i>					0				0				0	0	
	<i>Quinqueloculina grata</i>	6	96		0	96			2	16	16			1	8	8
	<i>Quinqueloculina seminula</i> f. <i>longa</i>					0				0				0	0	
	<i>Quinqueloculina</i> sp.1					0				0	0			0	0	
	<i>Quinqueloculina</i> sp.2					0				0	0			0	0	
	<i>Spiroloculina canaliculata</i>					0				0	0				0	
Agglutinates	<i>Adercotryma glomeratum</i>	3	48		0	48				0	3	96		0	96	
	<i>Bigenerina nodosaria</i>					0				0				0	0	
	<i>Clavulina cylindrica</i>					0				0				0	0	
	<i>Cribrostomoides jeffreysii</i>	2	32		0	32				0	0			0	0	
	<i>Cribrostomoides subglobosus</i>					0				0				0	0	
	<i>Eggerella advena</i>					0				0				0	0	
	<i>Eggerella scabra</i>	16	256	2	16	272	2	32		0	32	4	128	4	32	160
	<i>Eratidus foliaceus</i>					0				0	0				0	
	<i>Lagenamma difflugiformis</i>					0				0	0				0	
	<i>Recurvoides trochaminiformis</i>					0				0	0				0	
	<i>Reophax fusiformis</i>					0				0	0				0	
	<i>Reophax scoriurus</i>					0				0	0				0	
	<i>Reophax scotti</i>	2	32		0	32	2	32		0	32				0	
	<i>Reophax</i> sp.					0				0	0				0	
	<i>Textularia agglutinans</i>					0				0	0				0	
	<i>Textularia porrecta</i>	22	352	3	24	376	3	48	2	16	64	3	96	4	32	128
	<i>Textularia</i> sp.					0				0	0				0	
<b>Total hand sorted (t)</b>	<b>837</b>	<b>13392</b>	<b>451</b>	<b>3608</b>		<b>444</b>	<b>7104</b>	<b>529</b>	<b>4232</b>		<b>421</b>	<b>13472</b>	<b>563</b>	<b>4504</b>		
<b>split (s)</b>	<b>16</b>		<b>8</b>			<b>16</b>		<b>8</b>			<b>32</b>		<b>8</b>			
<b>TOTAL = t+s</b>	<b>13392</b>		<b>3608</b>		<b>17376</b>	<b>7104</b>		<b>4232</b>		<b>11400</b>	<b>13472</b>		<b>4504</b>		<b>18104</b>	

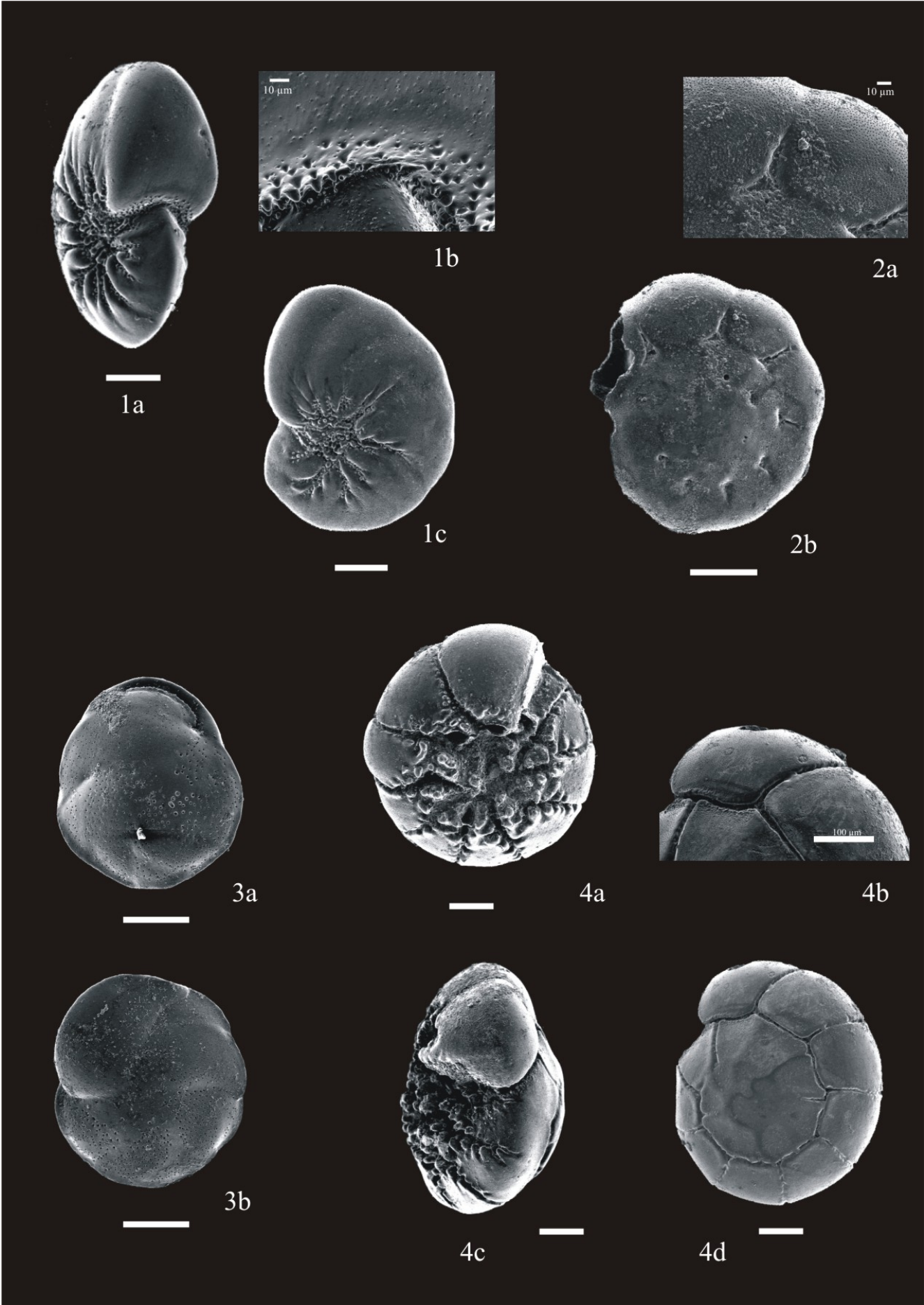
Appendix 2-2: Continued.

St23 90m depth					St24 95m depth				
0-0.5cm		0.5-1cm		Total	0-0.5cm		0.5-1cm		Total
Brut	*(s)	Brut	*(s)		Brut	*(s)	Brut	*(s)	
1	8		0	8		0		0	0
	0	2	8	8		0	1	8	8
1	8		0	8		0		0	0
	0		0	0		0		0	0
158	1264	100	400	1664	79	1264	92	736	2000
	0		0	0		0		0	0
9	72	6	24	96	15	240	2	16	256
	0		0	0	1	16		0	16
	0		0	0	2	32		0	32
	0		0	0		0		0	0
12	96	8	32	128	20	320	4	32	352
70	560	68	272	832	89	1424	31	248	1672
1	8		0	8	7	112	1	8	120
1	8	1	4	12		0		0	0
	0		0	0	1	16		0	16
	0		0	0		0		0	0
58	464	22	88	552	28	448	13	104	552
	0		0	0		0		0	0
21	168	4	16	184	6	96		0	96
	0		0	0		0		0	0
25	200	16	64	264	2	32	7	56	88
	0		0	0		0		0	0
	0	1	4	4		0		0	0
6	48		0	48	2	32		0	32
	0		0	0	1	16		0	16
	0		0	0		0		0	0
	0		0	0		0		0	0
	0	1	4	4	1	16		0	16
1	8		0	8	1	16	1	8	24
2	16		0	16	1	16		0	16
	0		0	0		0	1	8	8
24	192	8	32	224	8	128	13	104	232
36	288	12	48	336	17	272	1	8	280
11	88		0	88	45	720		0	720
125	1000	136	544	1544	35	560	79	632	1192
	0		0	0		0		0	0
	0		0	0		0		0	0
4	32	5	20	52	4	64	8	64	128
	0		0	0	5	80		0	80
	0		0	0		0		0	0
10	80		0	80	3	48	5	40	88
9	72	1	4	76	5	80	10	80	160
6	48		0	48		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
3	24	3	12	36	4	64	1	8	72
	0		0	0		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
7	56	5	20	76	1	16	2	16	32
	0		0	0		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
2	16	2	8	24	1	16		0	16
	0		0	0		0		0	0
	0	3	12	12	2	32		0	32
	0		0	0	1	16		0	16
	0		0	0		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
	0		0	0		0		0	0
26	208	28	112	320	7	112	2	16	128
2	16	3	12	28	1	16		0	16
603	4824	404	1616		387	6192	272	2176	
8		4			16		8		
4824		1616		6788	6192		2176		8512

**Plate 2-1**

1. *Nonion scaphum* (Fichtel and Moll, 1798), station 10 (80 m), 1a: apertural view, 1b: magnification of the aperture, 1c: side view.
2. *Pseudoeponides falsobeccarii* (Rouvillois, 1974), station 10 (80 m), 2a: detail of last chambers, 2b: dorsal side.
3. *Cassidulina carinata* (Silvestri, 1896), station 10 (80 m), 3a: ventral side, 4b: dorsal side.
4. *Ammonia beccarii* forma *inflata* (Seguenza, 1979), station 10 (80 m), 4a: ventral side, 4b: detail of last chambers, 4c: apertural view, 4d: dorsal side.

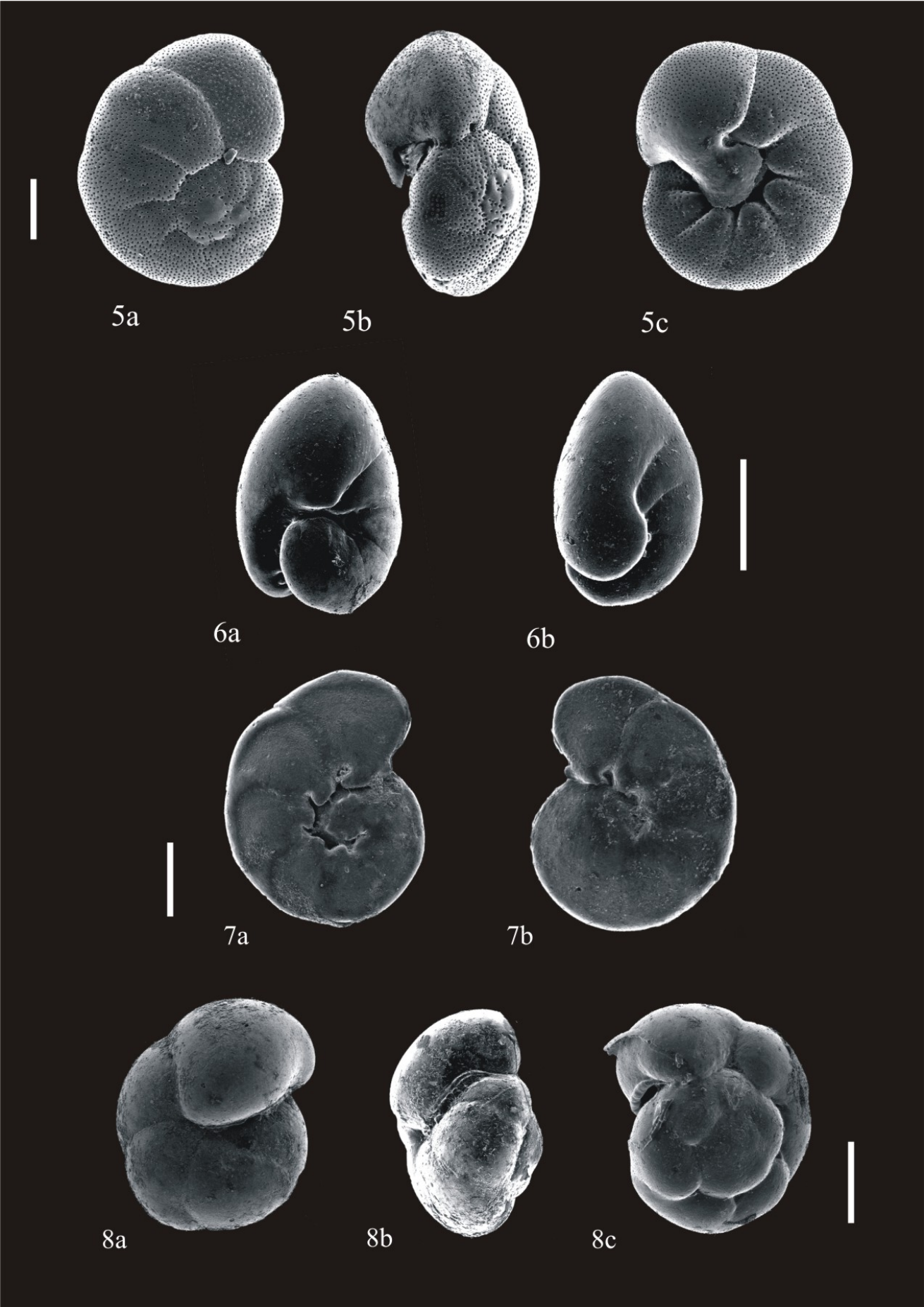
**Scale bar = 100  $\mu$ m**



**Plate 2-2**

5. *Valvulineria bradyana* (Fornasini, 1900), station 10 (80 m), 5a: dorsal side, 5b: apertural view, 5c: ventral side.
  
6. *Nonionella turgida* (Williamson, 1858), station 10 (80 m), 6a: apertural view, 6b: ventral side.
  
7. *Hyalinea balthica* (Schröter, 1783), station 10 (80 m), 7a, side view, 7b: side view.
  
8. *Gyroidinoides soldanii* (d'Orbigny, 1826), station 10 (80 m), 7a, ventral view, 7b: apertural view, 7c dorsal view.

**Scale bar = 100  $\mu$ m**



**Plate 2-3**

9. *Bulimina marginata* (d'Orbigny, 1826), station 24 (95 m).

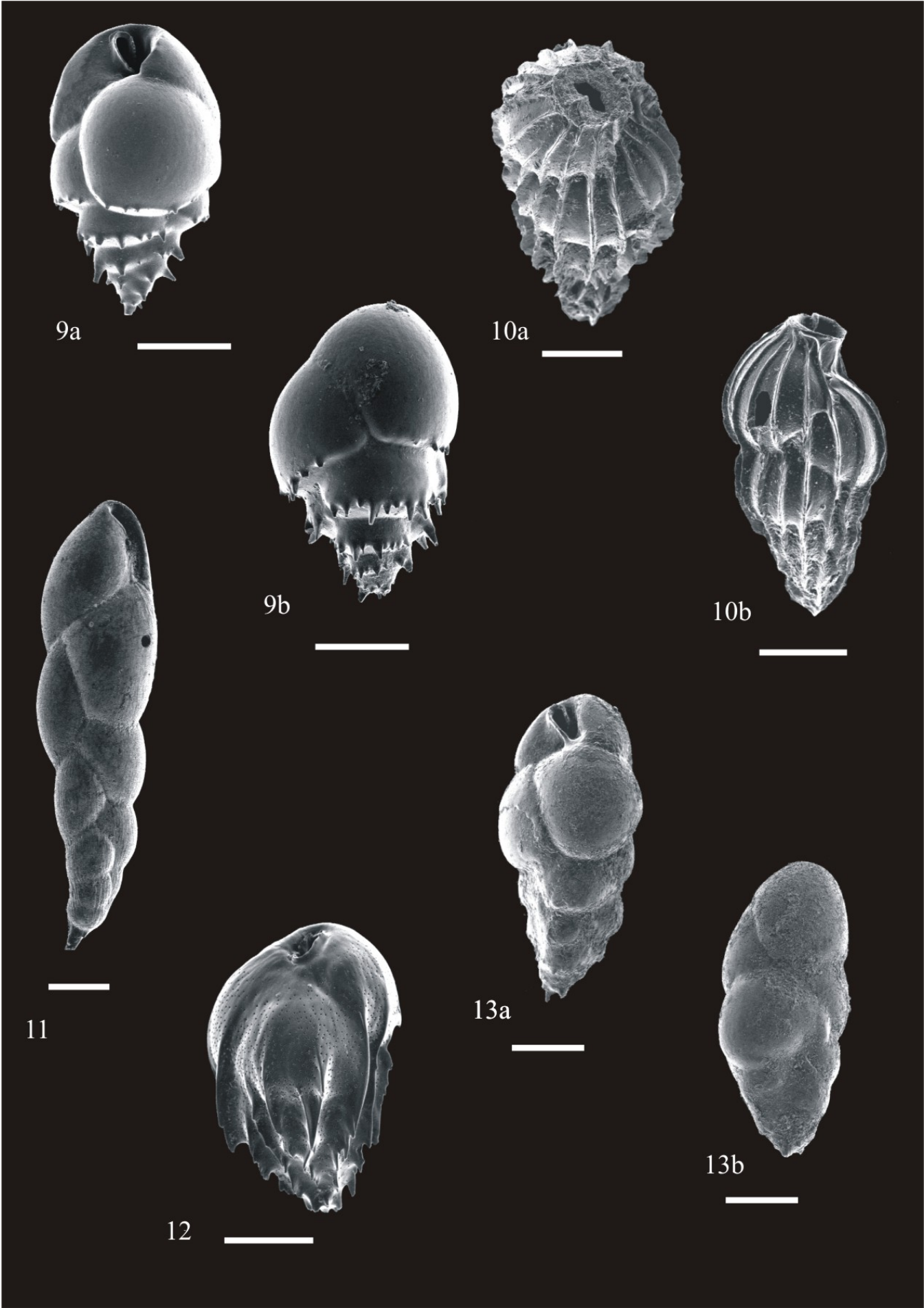
10. *Saidovina karreriana* (Brady, 1881), station 10 (80 m).

11. *Fursenkoina complanata* (Egger, 1893), station 10 (80 m).

12. *Bulimina costata* (d'Orbigny, 1852), station 24 (95 m).

13. *Bulimina aculeata* (d'Orbigny, 1826), station 10 (80 m).

**Scale bar = 100  $\mu$ m**

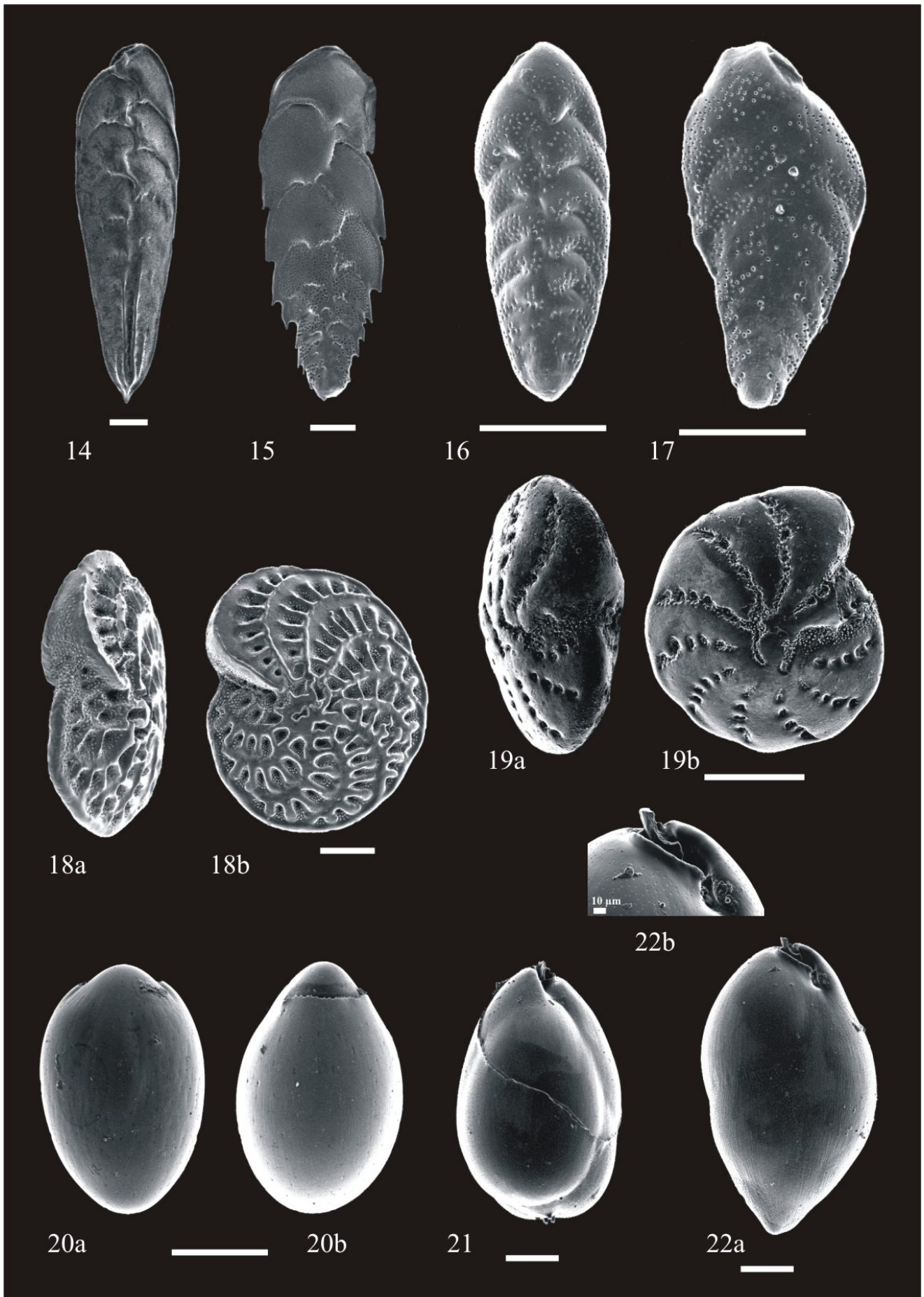




**Plate 2-4**

14. *Bolivina subaenariensis* (Cushman, 1922), station 10 (80 m).
15. *Bolivina alata* (Seguenza, 1862), station 24 (95 m).
16. *Bolivina dilatata* (Reuss, 1850), station 12 (58m).
17. *Bolivina spathulata* (Williamson, 1848), station 12 (58m).
18. *Elphidium crispum* forma *macellum* (Fichtel & Moll, 1798), station 23 (90 m), 18a: apertural view, 18b: side view.
19. *Elphidium advenum* (Cushman, 1922), station 10 (80m), 19a: apertural view, 19b: side view.
20. *Chilostomella ovoidea* (Reuss, 1850), station 24 (95m).
21. *Globobulimina pyrula* var. *pseudospinescens* (Emiliani, 1949), station 19 (98m).
22. *Globobulimina affinis* (d'Orbigny, 1839), station 19 (98m).

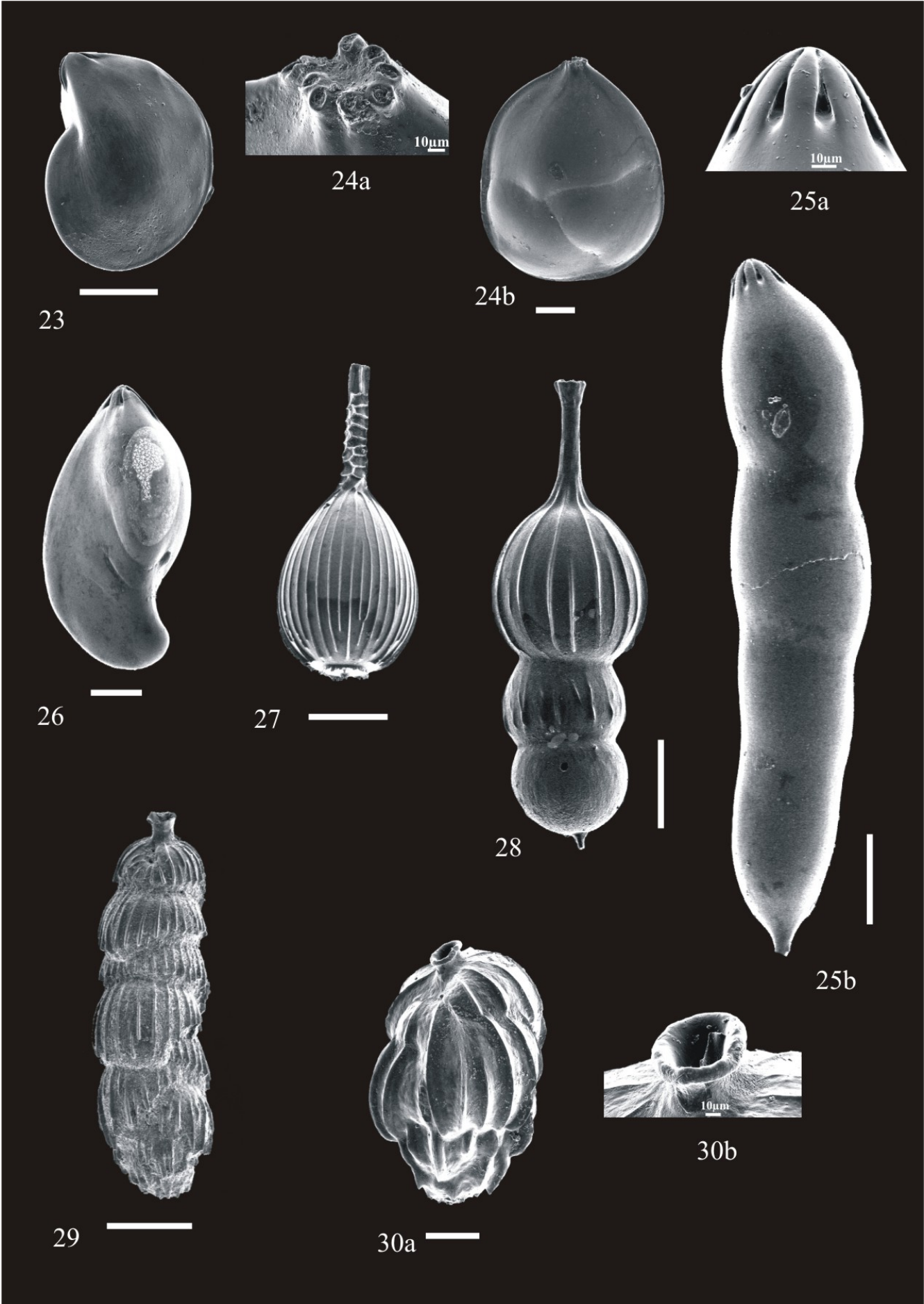
**Scale bar = 100 µm**



**Plate 2-5**

23. *Lenticulina atlantica* (Barker, 1960), station 15 (89m).
24. *Lenticulina peregrina* (Schwager, 1866), station 23 (90m). 24a: magnification of the aperture, 24b: side view.
25. *Dentalina bradyensis* (Dervieux 1894), station 19 (98m), 25a: magnification of the aperture.
26. *Astacolus insolitus* (Schwager, 1866), station 19 (98m).
27. *Lagena* sp., station 19 (98m).
28. *Amphicoryna scalaris* (Batsch, 1791), station 10 (80 m).
29. *Rectuvigerina phlegeri* (Le Calvez, 1958), station 10 (80 m).
30. *Uvigerina mediterranea* (Hofker, 1932), station 23 (90 m), 30b: magnification of the aperture.

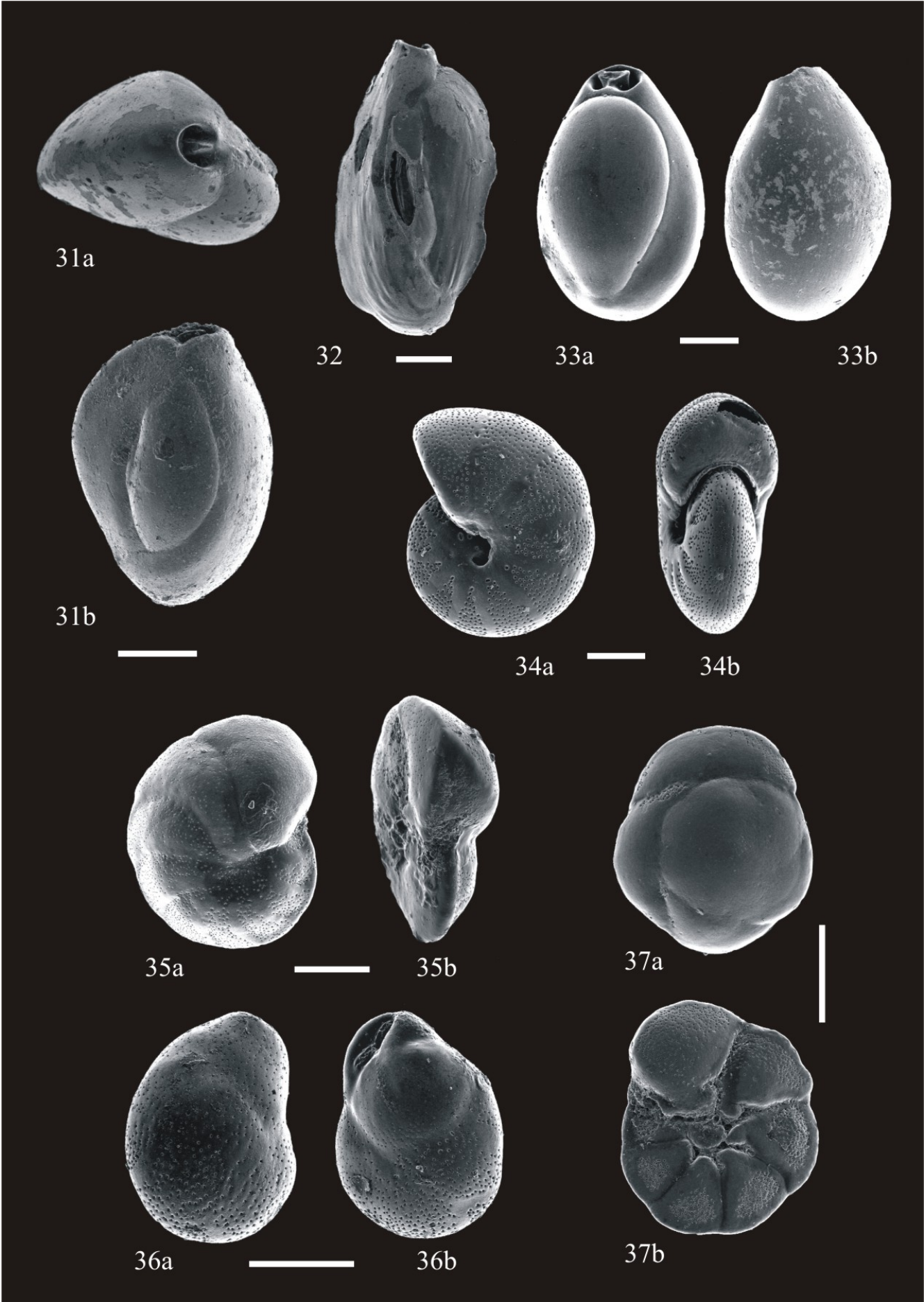
**Scale bar = 100  $\mu$ m**



**Plate 2-6**

31. *Quinqueloculina seminula* forma *longa* (Linné, 1758), station 10 (80 m), 31a: apertural view.
32. *Adelosina longirostra* (d'Orbigny, 1826), station 7 (65 m).
33. *Pyrgo subsphaerica* (d'Orbigny, 1826), station 7 (65 m).
34. *Melonis barleeanus* (Williamson 1858), station 23 (90 m), 34a: side view, 34b: apertural view.
35. *Hanzawaia boueana* (d'Orbigny, 1846), station 10 (80 m), 35a: ventral view, 35b: apertural view.
36. *Cassidulina oblonga* (Reuss 1850), station 10 (80 m).
37. *Gavelinopsis praegeri* (Heran-Allen & Earland, 1913), station 17 (73 m), 37a: dorsal view, 37b: ventral view.

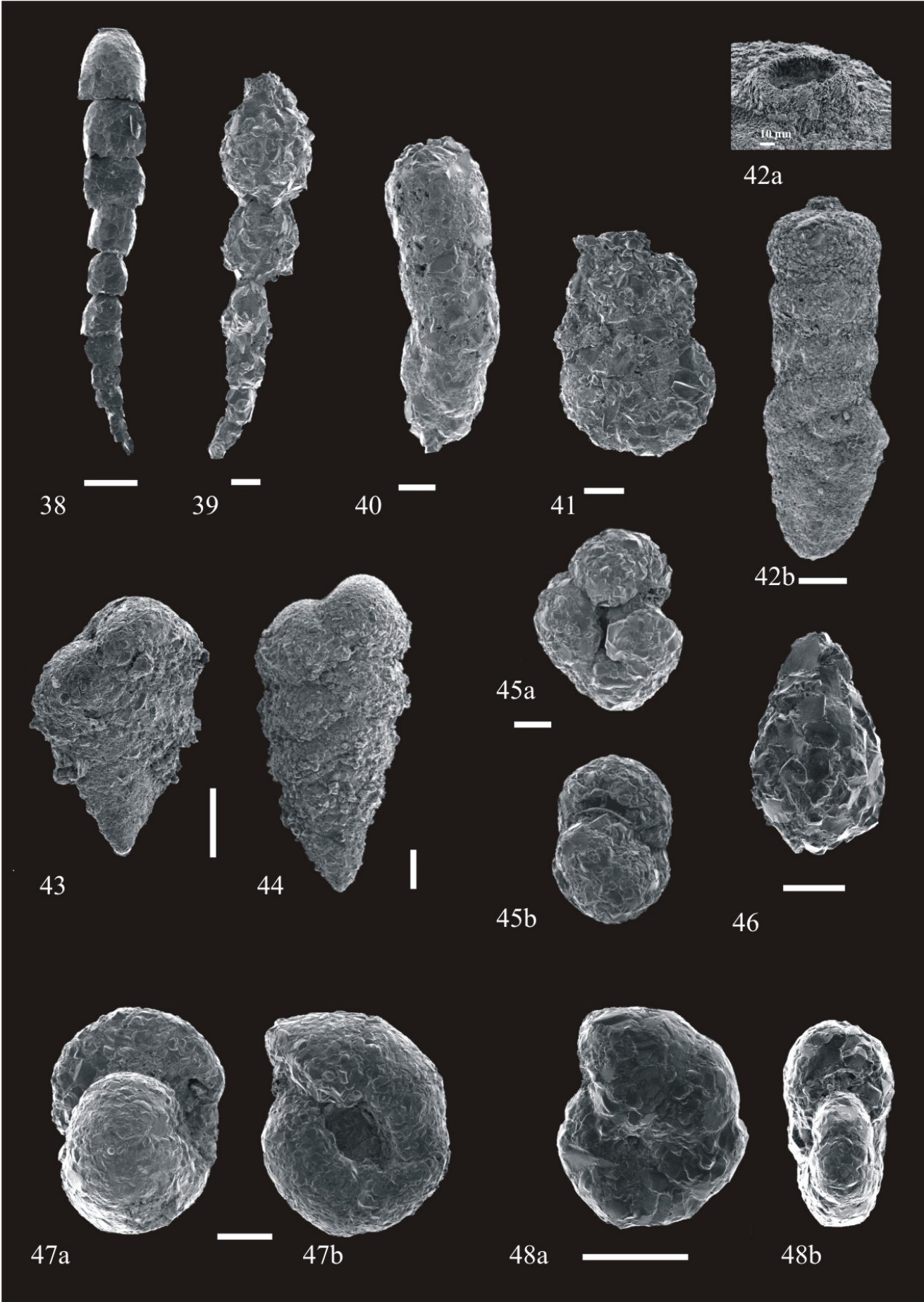
**Scale bar = 100 µm**



**Plate 2-7**

38. *Reophax scottii* (Chaster, 1892), station 10 (80 m).
39. *Reophax scorpiurus* (de Montfort, 1808), station 23 (90 m).
40. *Clavulina cylindrica* (d'Orbigny, 1852), station 6 (40 m).
41. *Eratidus foliaceus* (Brady, 1881), station 24 (95 m).
42. *Bigenerina nodosaria* (d'Orbigny, 1826), station 23 (90 m), 42a: the magnification of the aperture.
43. 44. *Textularia agglutinans* (d'Orbigny, 1839), station 10 (80 m).
45. *Recurvoides trochaminiformis* (Höglund 1947), station 23 (90 m), 45a: side view, 45b: apertural view.
46. *Lagenamma diffflugiformis* (Brady, 1879), station 24 (95 m).
47. *Cribrostomoides subglobosus* (Cushman, 1910), station 24 (95 m), 47a: apertural view, 47b: side view.
48. *Cribrostomoides jeffreysii* (Williamson, 1858), station 2 (40m), 48a: side view, 48b: apertural view.

**Scale bar = 100  $\mu$ m**







## **CHAPITRE 3. MICROHABITAT SELECTION OF BENTHIC FORAMINIFERA IN THE RHÔNE PRODELTA**

<b>RÉSUMÉ</b> .....	145
<b>3.1 ABSTRACT</b> .....	148
<b>3.2 INTRODUCTION</b> .....	148
<b>3.3 ENVIRONMENTAL SETTINGS</b> .....	151
<b>3.4 MATERIAL AND METHODS</b> .....	152
<b>3.5 RESULTS</b> .....	154
<b>3.5.1 Living foraminiferal density and composition</b> .....	154
<b>3.5.2 Vertical distribution of living foraminifera</b> .....	156
3.5.2.1 Overall vertical distribution of individual taxa.....	159
3.5.2.2 Vertical distribution of the main taxa at each station.....	163
<b>3.6 DISCUSSION</b> .....	169
<b>3.7 CONCLUSIONS</b> .....	175
<b>3.8 REFERENCES</b> .....	175



## RÉSUMÉ

Le microhabitat et la composition de la faune vivante des foraminifères benthiques dans les sédiments du prodelta du Rhône sont directement influencés par les apports du fleuve du Rhône. Dans ce type d'environnement marin peu profond, le microhabitat des espèces n'est pas bien délimité. Ceci est probablement dû à la faible pénétration d'oxygène dans le sédiment. Néanmoins, dans le prodelta du Rhône, nous avons pu mettre en évidence deux types d'espèces ; les espèces « préférentiellement superficielles » ayant un fort maximum de densité dans le niveau superficiel du sédiment et des espèces « potentiellement/préférentiellement endopéliques », également avec une forte densité à la surface du sédiment, mais continuant à avoir des fortes densités dans la zone anoxique du sédiment. En effet, dans la zone fortement influencée par les apports de fleuve, située à proximité de l'embouchure ainsi que dans la direction sud-ouest du panache du fleuve, la faune se compose principalement d'espèces « potentiellement/préférentiellement endopéliques » qui sont apparemment mieux adaptées à une matière organique continentale de qualité généralement réfractaire et à une très faible pénétration d'oxygène dans le sédiment. Cette faune est en général composée d'espèces tolérantes à un fort stress environnemental (e.g. *Nonionella turgida*, *Nonion scaphum*, *Rectuvigerina phlegeri* et *Valvulineria bradyana*). A l'opposé, les faunes des stations étant à l'abri de l'influence du fleuve se situant au sud et à l'Est de l'embouchure sont dominées par des espèces qui colonisent le centimètre supérieur du sédiment correspondant en général à la partie oxic de la colonne sédimentaire. La faune est principalement dominée par les espèces « préférentiellement superficielles » (e.g. *Cassidulina carinata*, *Bulimina aculeata*) connues dans la littérature pour réagir rapidement au dépôt de matière organique labile. Les corrélations entre ces deux types de faunes et les deux facteurs environnementaux prédominants ont révélé que la distribution verticale des faunes de foraminifères vivants dans le prodelta du Rhône semble être essentiellement gouvernée par la qualité de la matière organique et, avec une moindre importance, par la pénétration d'oxygène dans le sédiment.

**Mots clés:** Foraminifères benthiques ; distribution verticale ; microhabitat ; ALD ; panache du fleuve ; oxygène ; carbone organique ; Golfe du Lion ; le fleuve du Rhône.



## CHAPITRE 3. MICROHABITAT SELECTION OF BENTHIC FORAMINIFERA IN THE RHÔNE PRODELTA

M. Mojtahid \* and F. Jorissen \*

\* Laboratoire des Bio-Indicateurs Actuels et Fossiles (BIAF) UPRES EA 2644, Université d'Angers. 2, Boulevard Lavoisier, 49045 Angers Cedex, France, and Laboratoire d'Étude des Bio-Indicateurs Marins (LEBIM). Ker Chalon, 85350 Ile D'Yeu, France.

Ce chapitre correspond à un article en cours de préparation pour la revue *Marine Micropaleontology*.

**Keywords:** Benthic foraminifera; microhabitat; vertical distribution; Rhône River; ALD; river plume; organic carbon; Gulf of Lions; Rhône river.

### 3.1 ABSTRACT

The microhabitat and the composition of the living benthic foraminiferal faunas in the sediments deposited in the Rhône prodelta are directly influenced by the Rhône river input. In this shallow-water environment, the vertical distribution of the species is not well delimited, probably due to the low oxygen penetration into the sediment. Nevertheless, in the Rhône prodelta, we could highlight two types of species; “predominantly superficial” taxa showing a very clear population maximum in the topmost sediment layer and “potentially/predominantly infaunal taxa” that are also very frequent in the topmost sediment but also show considerable densities in the anoxic layer deep in the sediment. In the area which is strongly influenced by river input, located near the river mouth and in the southwestern direction, following the river plume, the fauna is composed mainly by “potentially/predominantly infaunal” species which are completely adapted to a higher contribution of continental organic matter, generally of a more refractory quality, and to the low oxygen penetration into the sediment. This fauna is in general composed of species that are tolerant to a strong environmental stress (e.g. *Nonionella turgida*, *Nonion scaphum*, *Rectuvigerina phlegeri* and *Valvulineria bradyana*). On the other hand, the stations that are less influenced by the river input, located south and east of the river mouth are composed of species which colonize the upper centimetre of the sediment corresponding in general to the oxic part of the sedimentary column. The dominant species are mainly “predominantly superficial” taxa (e.g. *Cassidulina carinata*, *Bulimina aculeata*) known in the literature to react quickly to the deposit of labile organic matter. The correlations between these two types of faunas and the two prevalent environmental factors suggests that the vertical distribution of living foraminifera in the Rhône prodelta is primarily controlled by the quality of the organic matter and only to a lesser degree by the oxygen penetration into the sediment.

### 3.2 INTRODUCTION

Benthic foraminifera do not live exclusively at the sediment-water interface, but can be found alive at considerable depths in the sediment, in some cases down to 10 cm (e.g. *Basov and Khusid, 1983, Corliss, 1985, Mackensen and Douglas, 1989; Corliss and Emerson, 1990; Corliss, 1991; Barmawidjaja et al., 1992; Rathburn and Corliss, 1994; Kitazato, 1994;*

*Rathburn et al., 1996; Ohga and Kitazato, 1997; De Stigter et al., 1998; Jorissen et al., 1998; Kitazato et al., 2000; Schmiedl et al., 2000; Fontanier et al., 2002; Licari et al., 2003*). At the sediment water interface, the sea water is usually well oxygenated (sometimes saturated in oxygen) and high quality organic matter is often available. Deeper in the sediment, conditions progressively change: often oxygen concentration rapidly decreases, to attain zero at several centimetres or millimetres depth, except in oxic halos around metazoan burrows. In the deeper, hypoxic (< 2 ml/l) to anoxic layers, toxic substances (e.g. H<sub>2</sub>S) may be present. Furthermore, the remaining organic matter, which has not been consumed by the macro and meiofauna, may be mostly refractory with a low nutritional value (*Caralp, 1989, Aller, 1994; Jorissen, 1999; Zegouagh et al., 1999*). In marine benthic environments, the exported organic matter flux, and the oxygenation and redox conditions at the bottom and in the interstitial waters are generally considered as the major parameters controlling the density, composition and microhabitat of benthic foraminiferal faunas (e.g. *Altenbach, 1988; Altenbach et Sartnthein, 1989; Lutze and Thiel, 1989; Mackensen and Douglas, 1989; Rathburn and Corliss, 1994; Jorissen et al., 1995, Rathburn et al., 1996; Fariduddin and Loubere, 1997; Jorissen, 1999; Schmiedl et al., 2000; Morigi et al., 2001*). In many continental shelf and margin environments, only the top centimetres or millimetres of the sediment contain oxygen (e.g. *Jorgensen and Revsbech, 1989*). A much deeper oxygen penetration may be found in coarse-grained, high energy, shallow water environments, or in very oligotrophic deep-sea areas (e.g. *Rutgers van der Loeff, 1990*). Also macrofaunal burrows can locally create oxic environments deeper in the sediment (*Aller and Aller, 1986; Meyers et al., 1987, 1988*). During the last two decades, a number of studies revealed that benthic foraminifera inhabit a succession of different microhabitats at and below the sediment surface (e.g. *Corliss, 1985; Lutze and Thiel, 1989; Mackensen and Douglas, 1989; Corliss and Emerson, 1990; Loubere, 1991*). According to the TROX-model (*Jorissen et al., 1995*), proposed for open marine benthic foraminiferal faunas, epifaunal and superficial infaunal foraminifera profit from well oxygenated conditions and from rather labile organic matter whereas deep infaunal foraminifera may survive in oxygenated micro-environments, but may also be resistant to extremely low oxygen conditions, or even to anoxia, as reported from numerous deep sea environments (e.g. *Bernhard and Reimers, 1991, Bernhard, 1992, Moodley and Hess, 1992, Bernhard et al., 1997*). These deep infaunal taxa would be able to feed on low quality food particles, eventually profiting from a partial bacterial conversion into more labile components. In anoxic environments, foraminifera survive, either by being facultative anaerobes (*Bernhard, 1993; Risgaard-Peterson et al., 2006*) or by having endosymbionts (*Bernhard,*



1993, 2003). Most species are able to change their microhabitat in response to food supply and to dissolved oxygen concentration in the bottom and pore waters (*Linke and Lutze, 1993; Jorissen et al., 1995*). In food-limited environments that are commonly characterised by well oxygenated bottom waters, both foraminiferal standing stock and diversity are rather low and the fauna mainly comprises superficially living epifaunal and shallow infaunal species. In mesotrophic environments, standing stocks are moderately high and faunal diversity is at a maximum. The corresponding faunal assemblages comprise a variety of epifaunal, shallow, intermediate and deep infaunal species. Finally, in eutrophic and oxygen limited environments, a low-diversity fauna with high standing stocks prevail, mainly comprising deep infaunal species that are adapted to dysoxic conditions (*Jorissen et al., 1995*). In such environments, the vertical species succession is often strongly compressed, and taxa which elsewhere occupy deep infaunal niches may be found close to, or at the sediment surface. This distribution of benthic microhabitats has been observed for deep-sea benthic foraminifera. In most shallow-water environments, there is no such clear distinction between shallow, intermediate and deep infaunal taxa. This may be due to intensive macrofaunal bioturbation down to a great depth, or, in fine-grained sediments, due to a very shallow oxygen penetration. For most species, a maximum number of stained foraminifera is found in the uppermost centimetre. However, in these shallow-water environments, often three types of distributional patterns can be recognised (Fig. 3-1):

- 1) Taxa which show a very strong maximum in the topmost centimetre.
- 2) Taxa which are found in about equal numbers down to several centimetres depth.
- 3) Taxa which live exclusively at and or below the limit of oxygen penetration.

These three types have been previously described by *Barmawidjaja et al. (1992)* in the Adriatic Sea. In this paper, we will use the terms 1) predominantly superficial taxa, 2) potentially infaunal taxa and 3) predominantly infaunal taxa for these three groups (Fig. 3-1). However, in our study area, most infaunal taxa tend to show an intermediate distributional pattern between the second and the third distributional pattern. In almost most cases, the topmost sediment layer contains already significant quantities of the infaunal taxon. We will therefore often use the term “potentially/predominantly infaunal” to describe species that can be found in significant amounts deeper in the sediment.

In this study, we describe the vertical distribution of living benthic foraminifera from twenty three stations in the Rhône prodelta (Gulf of Lions, western Mediterranean Sea) with water depths from 20 to 98 m. The main target of our study is to gain a better understanding

of the complex linkage between biological and physicochemical parameters and the resulting species composition and microhabitat structure of the foraminiferal fauna in a eutrophic environment.

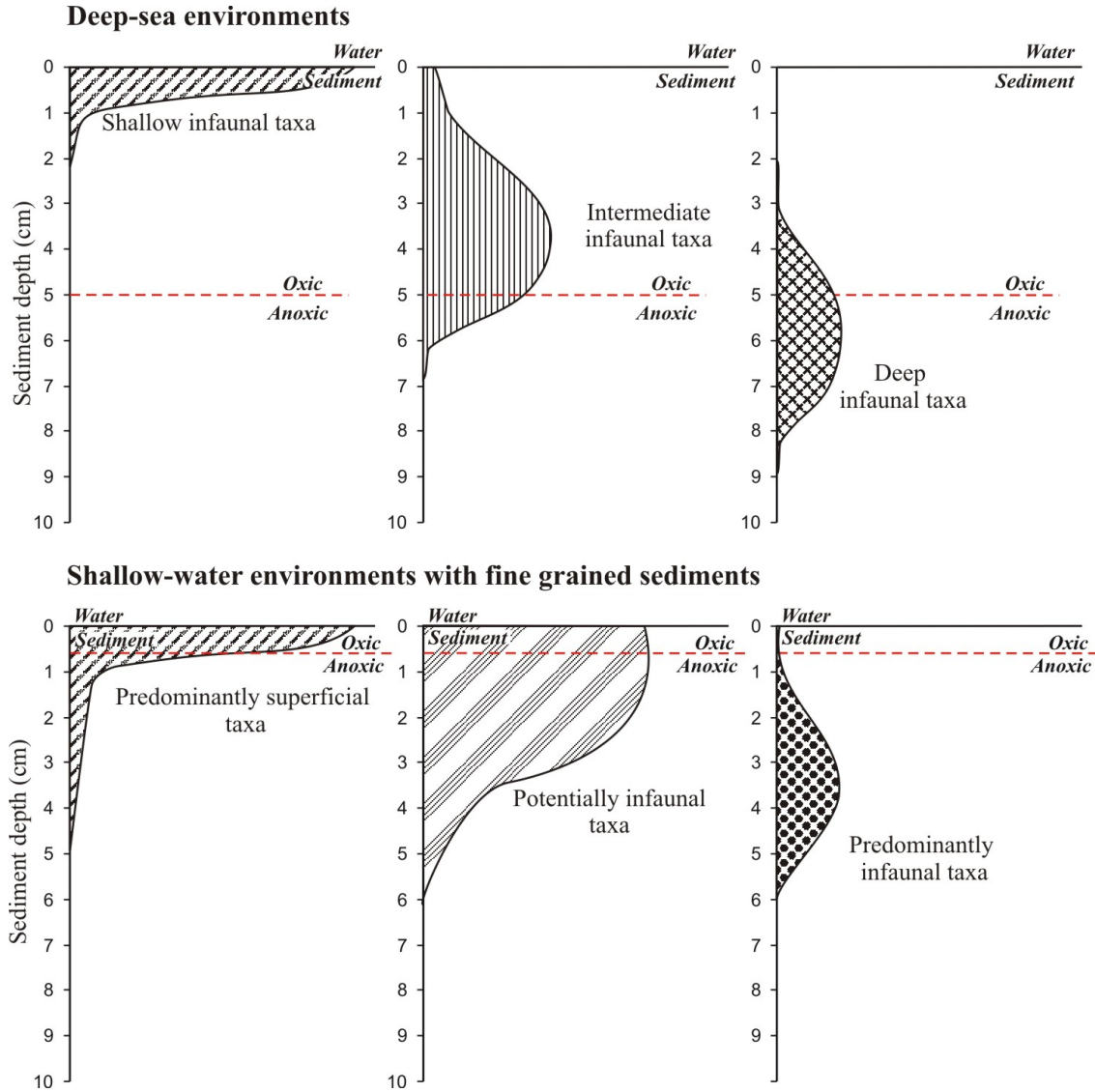


Figure 3-1. Schematic representation of the difference between foraminiferal microhabitats in deep-sea environments and shallow-water environments.

### 3.3 ENVIRONMENTAL SETTINGS

The Gulf of Lions is located in the Northwestern Mediterranean Sea and represents a prograding margin with a wide, crescent-shaped shelf and a continental slope that is incised by numerous canyons, descending down to the abyssal areas of the Algero-Balearic Basin

(Monaco *et al.*, 1990). Along the shelf, terrigenous material is discharged by the Rhône and by some smaller rivers. Got and Aloisi (1990) have estimated that approximately 70 % of the introduced particles are sedimented on the shelf and 30 % are exported to the slope or distributed by a number of canyons into the deep sea basin. The investigated sites of this study are located in the Rhône prodelta. The sedimentation and particle distribution in this area is mainly controlled by the hydrodynamic environment and the wind regimes. The oceanographic circulation is dominated by the cyclonic Liguro-Provencal Current (LPC), which follows the continental margin from the coast of the Provence to the Catalanian Sea (Lacombe and Tchernia, 1972; Millot, 1990). Northerly (Mistral) and northwesterly (Tramontane) winds, and a S–SE wind (Marin) are predominant. The Mistral and Tramontane are more frequent in winter and spring and induce distinctive and opposite circulation cells on the shelf favouring the intrusion of slope waters in the eastern and central parts of the shelf and the export of shelf water at its southwestern end (Estournel *et al.*, 2003; Petrenko *et al.*, 2005) (see satellite image on Fig. 3-2). In the Rhône prodelta, the organic matter originates from different sources, including continental sources and marine biological production (Gadel *et al.*, 1990; Monaco *et al.*, 1990; Buscail and Germain, 1997). During autumn and winter the inflow of terrestrial organic matter is increased due to river runoff. Primary production is highly seasonal and mainly triggered by the input of nutrients of the Rhône River, the shoaling of the mixed layer, and the availability of sunlight. Therefore, elevated phytoplankton concentrations are particularly observed during spring (March through early May) and are highest in the eastern part of the Gulf of Lions (Cruzado and Velasquez, 1990; Morel and André, 1991; Arnone, 1994; Lévy *et al.*, 1999).

### 3.4 MATERIAL AND METHODS

During a cruise of the French research vessel *Tethys II*, sediment cores of 15 cm internal diameter were collected in June 2005 at twenty three sites in the Rhône prodelta in the northeastern Gulf of Lions (western Mediterranean Sea) (Fig. 3-2). Sediments were collected using a Bowers and Connelly Mark VI multicorer between 20 and 98 m water depths. For the analysis of their foraminiferal content, the sampled cores were sliced onboard until 5 centimetres depth. For stations 1, 3, 4, 7, 9, 13, 14, 15, 17, 19 and 22, the cores were sliced into 0.5 cm levels down to 2 cm depth and then in 1 cm levels down to 5 cm depth. For

the other stations, the cores were sliced into four intervals: 0-0.5, 0.5-1, 1-2 and 2-5 cm. All samples were preserved in 95 % ethanol with 1 g/l Rose Bengal. In the laboratory, the collected samples were sieved over 63 and 150  $\mu\text{m}$  meshes. For the fraction larger than 150  $\mu\text{m}$ , living foraminifera from all levels (until 5 cm depth) were hand-sorted under a binocular microscope under wet conditions (50 % ethanol). If necessary, samples were dried, split with an Ottomicrosplitter and a minimum of 200 to 300 specimens were picked. All picked foraminifera were determined using commonly used taxonomic reference works (e.g. Parker, 1964; Loeblich and Tappan, 1964; Jones, 1994, etc) and taxonomic studies treating similar eutrophicated shelf environments (e.g. Jorissen, 1988; Barmawidjaja, 1991; Schiebel, 1992). At 10 of the 23 sampling stations (1, 3, 4, 5, 6, 13, 14, 16, 17, 22), in-situ measurements of oxygen were performed using microelectrodes (e.g. Lansard et al., 2003; Rabouille et al., 2003) fixed on an autonomous Lander profiler with a vertical resolution of 100  $\mu\text{m}$  (Unisense®, Science Park Aarhus, Gustav Wieds Vej 10, DK-8000 Aarhus C, Denmark; www.unisense.com). In-situ oxygen measurements were calibrated using an optode that measures the dissolved oxygen in the water above the sediment surface. This optode is also fixed on the in-situ profiler, near the microelectrodes. For  $C_{\text{org}}$ , N and  $\delta^{13}\text{C}$  analyses, cores were sliced onboard into 1 cm layers down to 5 cm sediment depth. Each subsample was conserved in a hermetic bag and frozen. In the laboratory, the sediments were dried at 50°C; cracked using an agate mortar. The samples were treated with diluted hydrochloric to remove carbonates.  $C_{\text{org}}$  and N were measured using a CHN elementary analyser and  $\delta^{13}\text{C}$  was measured using a GC-IRMS mass spectrometer.

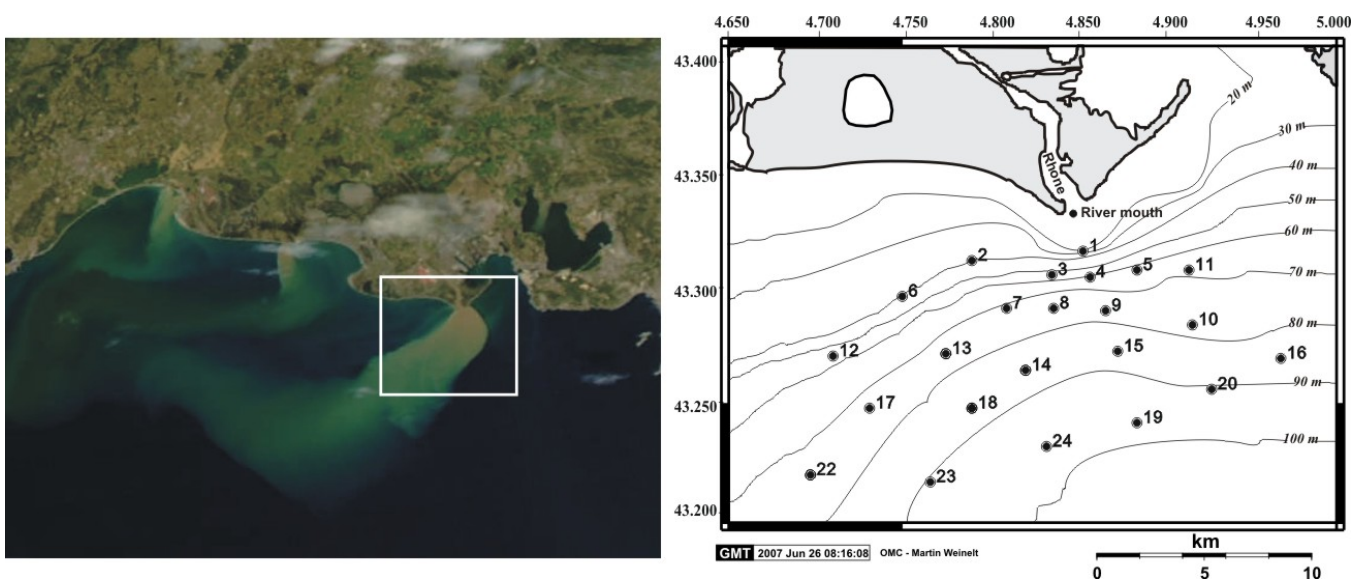


Figure 3-2. On the left; satellite image of the eastern part of the Gulf of Lions showing the spreading of the river plume in southwestern direction; on the right: location of the 23 sampling stations and bathymetry.

To describe the vertical distribution of the foraminifera of the > 150 µm fraction, the average living depth (ALD<sub>5</sub>) of individual species and of the total fauna in the top 5 cm of the sediment was calculated according to *Jorissen et al. (1995)*:

$$ALD_5 = \sum_{i=0,5} (n_i \times D_i) / N$$

where “5” is the lower boundary of the deepest sample interval “i”, “n” is the total number of specimens in interval “i”, “Di” the midpoint of sample interval “i”, and “N” is the total number of individuals for all levels.

For each station, the Shannon Wiener index (H) of biodiversity was calculated according to:

$$H = -\sum_{i=1}^s p_i \ln p_i$$

in which S is the number of species and p is the relative frequency of the ith species.

## 3.5 RESULTS

### 3.5.1 Living foraminiferal density and composition

The standing stock of stained foraminifera (> 150 µm fraction) found in the 5 cm deep sediment cores is varying from 39 to about 3300 specimens for a surface of 177 cm<sup>2</sup> (a total sediment volume of 883 cm<sup>3</sup> has been studied) corresponding to a density from about 22 to 1880 individuals below a 100 cm<sup>2</sup> sediment surface (Fig. 3-3d). The total standing stock is generally increasing with a larger distance from the river mouth (Fig. 3-3d), to the south, east and west. In the > 150 µm fraction, three principal foraminiferal assemblages occur:

1) A first assemblage is mainly present close to the river mouth (stations 1, 3, 4 and 5) where it accounts for 40 to 90 % of the total fauna, and densities and diversity are low. This assemblage is dominated by the species *Nonionella turgida* (18 % on average in the stations close to the river mouth), *Quinqueloculina seminula* forma *longa* (7 %), *Ammonia beccarii* forma *inflata* (7 %), *Eggerella scabra* (17 %), *Reophax scottii* (19 %) and *Elphidium macellum* (2 %).

2) The second assemblage (60 % to 75 %) dominates the stations which are under the influence of the river plume (2, 6, 7, 8, 12, 13, 14 and 18). It is mainly composed of the species *Nonion scaphum* (42 % on average in the stations under the river plume) and *Valvulineria bradyana* (15 %) accompanied by *Rectuvigerina phlegeri* (5 %).

# Microhabitat selection of benthic foraminifera in the Rhône prodelta

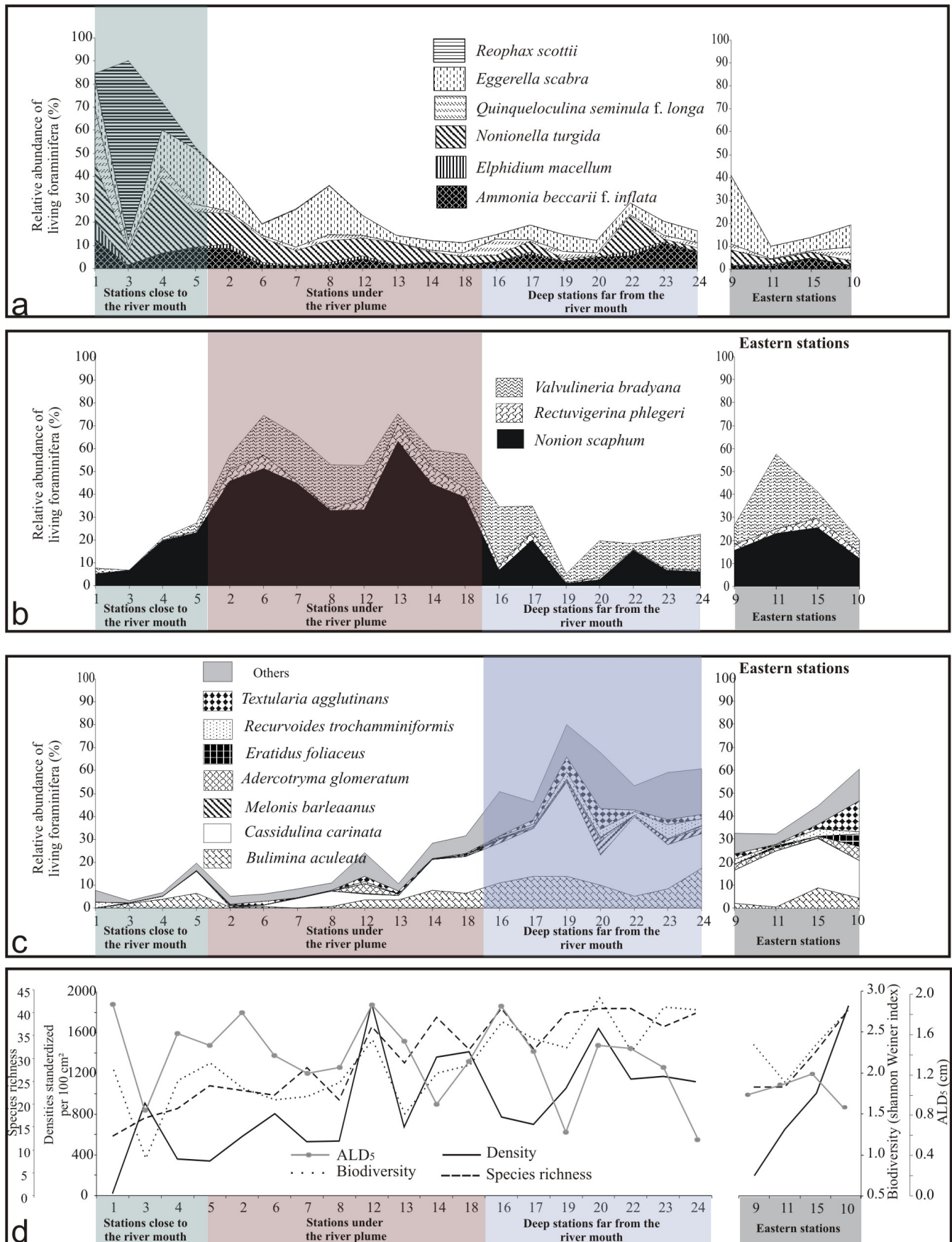


Figure 3-3. Relative abundance of the dominant taxa (> 150  $\mu\text{m}$  fraction,  $\geq 5\%$  in at least one of the stations): 3-3 a, taxa typical of the stations close to the river mouth; 3-3 b, taxa typical of stations under the river plume; 3-3 c, taxa typical of distal stations. 3-3d: total density (standardized for 100  $\text{cm}^2$  sediment surface), species richness (number of species), biodiversity (Shannon Wiener index) and ALD<sub>5</sub>.

3) The third assemblage occupies the deepest stations that are most distal with respect to the river outflow (16, 17, 19, 20, 22, 23 and 24) where it accounts for 50 % to 80 % of the fauna. The fauna is mainly composed of the species *Cassidulina carinata* (23.0 % on average in this distal area), *Bulimina aculeata* (11 %) and *Melonis barleeanus* (2 %), in some stations (especially to the east), accompanied by the agglutinated taxa *Textularia agglutinans* (5 %), *Recurvoides trochaminiformis* (3 %) and *Adercotryma glomeratum* (2 %).

The foraminiferal assemblages at the eastern stations are probably less influenced by river outflow. At stations 9 and 11, a mixture of the three foraminiferal assemblages is present whereas at stations 15 and 10, the fauna is dominated by the third assemblage, typical of the more distal stations (Fig. 3-3).

### 3.5.2 Vertical distribution of living foraminifera

Table 3-1 summarizes the depth in the sediment of the maximum abundances for the main species. White circles represent species that show maxima in the oxic layer whereas black circles show those that have maxima below the principal redox front. Some species show maxima in both oxic and anoxic sediments. These are represented with half white-half black circles. The average living depths (ALD<sub>5</sub>) of foraminiferal species are indicated in table 3-2, and in figure 3-3d, an indication of the ALD<sub>5</sub> for each core is given.

For all cores taken together, an average of 34.4 % (arithmetic mean of the percentage found at all individual stations) of foraminifera lives in the first half centimetre, 56.5 % in the first centimetre and 77.8 % live in the first two centimetres of the sediment. About 45.0 % of the fauna lives below the zero oxygen level. Consequently, the weighed ALD<sub>5</sub> (average living depth) of the total fauna for all stations is about 1.3 cm whereas the averaged oxygen penetration into the sediment is about 0.4 cm. Maximum weighed ALD<sub>5</sub> values are found at stations 1 and 16 (ALD<sub>5</sub> ~ 1.9). The shallowest microhabitat depth is observed at stations 19 and 24 (ALD<sub>5</sub> ~ 0.6) (Table 3-2). We can notice that the difference between the maximum and the minimum ALD<sub>5</sub> values is not very important in the Rhône prodelta. In fact, this descriptor was originally proposed to describe the vertical distribution of foraminifera in deep-sea environments. In shallow-water environments, this vertical distribution is compressed, mainly due to the low oxygen penetration into the sediment. For this reason, together with the average living depth (Table 3-2), we will use the depth of the maxima of living foraminiferal abundance (Table 3-1) to describe the vertical distributional pattern in the Rhône prodelta.

Microhabitat selection of benthic foraminifera in the Rhône prodelta

Taxa	Stations close to the river mouth				Stations under the river plume				Deep stations far from the river mouth				Eastern stations				Average weighted ALD <sub>5</sub>							
	1	3	4	5	2	6	7	8	12	13	14	18	16	17	19	20		22	23	24	9	11	15	10
<i>Ammonia beccarii</i> f. <i>inflata</i>		○	○	○	●	○		○	○	○	○	○	●	●	○	○	○	○	○	○	○	○	○	1.5
<i>Amphicoryna scalaris</i>																○							○	0.5
<i>Bolivina alata</i>													○		○	○	○	○	○					1.1
<i>Bolivina subaenariensis</i>											○		○		○	○	○	○	○		○			0.9
<i>Bulimina aculeata</i>		○	○	○					○	○	○	○	○	○	○	○	○	○	○		○	○		1.3
<i>Bulimina costata</i>																○		○						0.9
<i>Bulimina marginata</i>									○	○	○	○	○	○	○	○	○	○	○		○	○	○	1.6
<i>Cassidulina carinata</i>				○		○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	0.8
<i>Chilostomella ovoidea</i>															○	○		○						1.6
<i>Elphidium advenum</i>					○								○				○							3.0
<i>Elphidium macellum</i>					○	○			○		○		○					○						1.7
<i>Gavelinopsis praegeri</i>									○															2.8
<i>Globobulimina affinis</i>											○	○	○	○	○	○	○	○	○					2.2
<i>Hanzawaia boucana</i>																							○	0.3
<i>Hyalinea balthica</i>											○	○	○	○	○	○	○	○	○		○		○	1.6
<i>Lenticulina peregrina</i>																		○						0.9
<i>Melonis barleanus</i>									○				○			○		○	○					1.2
<i>Nonion scaphum</i>		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	1.5
<i>Nonionella turgida</i>	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	1.7
<i>Pseudoepionides falsobeccarii</i>									○			○	○			○	○	○	○				○	1.4
<i>Rectuvigerina phlegeri</i>					○	○			○	○	○	○	○	○		○	○	○	○	○	○	○	○	1.0
<i>Uvigerina mediterranea</i>															○	○		○	○					0.7
<i>Valvulineria bradyana</i>				○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	1.0
<i>Adelosina longirostra</i>									○	○													○	1.5
<i>Pyrgo subsphaerica</i>																							○	1.7
<i>Quinqueloculina badensis</i>																							○	1.5
<i>Quinqueloculina grata</i>																							○	1.2
<i>Quinqueloculina seminula</i> f. <i>longa</i>		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○				○	1.3
<i>Quinqueloculina</i> sp.1																							○	0.8
<i>Adercotryma glomeratum</i>									○						○	○		○		○	○	○		1.3
<i>Bigenerina nodosaria</i>															○	○	○	○	○					1.7
<i>Clavulina cylindrica</i>						○	○		○	○	○	○	○			○		○		○	○	○		0.9
<i>Cribrostomoides jeffreysii</i>																		○					○	0.5
<i>Cribrostomoides subglobosus</i>																○		○						1.8
<i>Eggerella scabra</i>		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	1.7
<i>Eratidus foliaceus</i>																○					○		○	1.2
<i>Lagenammina difflugiformis</i>									○		○		○	○	○	○	○	○	○			○		1.4
<i>Recurvoides trochamminiformis</i>									○					○	○	○	○	○	○		○	○	○	1.0
<i>Reophax scorpiurus</i>													○		○	○								1.7
<i>Reophax scottii</i>		○	○																					0.6
<i>Textularia agglutinans</i>						○			○	○	○	○	○	○	○	○	○	○	○		○	○		1.3
ALD <sub>5</sub> of the cores	1.9	0.9	1.6	1.5	1.8	1.4	1.2	1.3	1.9	1.5	0.9	1.3	1.9	1.4	0.6	1.5	1.5	1.3	0.6	1.0	1.1	1.2	0.9	

Table 3-1. Summary of the depth in the sediment of maximum abundances for living foraminiferal species (main species in gray) at all stations. White circles indicate a maximum density in the oxic layer whereas black circles indicate a maximum density in the anoxic layer. Half white-half black circles indicate a maximum density in the oxic and the anoxic layers. Weighted ALD<sub>5</sub> are indicated for each species and each station.



Taxa	Stations close to the river mouth					Stations characteristic of the river plume								Deep stations far from the river mouth								Eastern stations					A.W. ALD <sub>5</sub> species				
	1	3	4	5	A.W. ALD <sub>5</sub>	2	6	7	8	12	13	14	18	A.W. ALD <sub>5</sub>	16	17	19	20	22	23	24	A.W. ALD <sub>5</sub>	9	11	15	10		A.W. ALD <sub>5</sub>			
	<i>Ammonia beccarii</i> f. <i>inflata</i>	1.9 (22)	1.6 (40)	0.8 (53)		1.3	2.8 (87)	1.7 (23)	1.6 (14)	1.5 (140)	3.2 (16)	1.5 (61)	1.7 (37)		1.9	1.7 (40)	2.5 (74)	1.8 (54)	1.7 (145)	1.4 (111)	1.1 (234)	0.5 (145)				0.9 (16)		1.5 (87)	1.2 (46)	1.3	1.5
<i>Amphicoryna scalaris</i>																		0.8 (20)			0.3				0.3				0.3	0.5	
<i>Bolivina alata</i>																1.6 (43)		0.6 (12)	1.6 (61)		1.0 (77)	0.6								1.1	
<i>Bolivina subaenariensis</i>												0.7 (16)		0.7		1.5 (24)		0.4 (14)	1.2 (27)		0.9 (23)	0.6			0.9 (12)			0.9	0.9		
<i>Bulimina aculeata</i>	2.1 (32)	1.5 (24)	1.9 (38)		1.9					1.4 (119)	2.3 (43)	1.1 (189)	1.3 (159)	1.3	1.9 (153)	1.7 (173)	0.9 (261)	1.8 (295)	1.7 (102)	1.2 (179)	0.5 (355)				1.5 (163)	0.9 (143)		1.2	1.3		
<i>Bulimina costata</i>																		0.7 (14)		1.1 (30)									0.9	0.9	
<i>Bulimina marginata</i>										2.6 (42)	2.4 (11)	2.0 (15)	0.8 (17)	2.1	1.7 (13)		1.3 (25)		2.1 (25)	2.0 (22)					1.3 (10)	0.7 (62)		0.7	1.6		
<i>Cassidulina carinata</i>			1.1 (58)		1.1			1.0 (39)	1.1 (64)	0.9 (82)	0.9 (24)	0.5 (322)	0.6 (406)	0.7	1.3 (246)	1.3 (258)	0.5 (769)	0.9 (394)	1.0 (707)	1.1 (410)	0.4 (312)			0.6 (50)	0.5 (278)	0.8 (383)	0.5 (543)	0.6	0.8		
<i>Chilostomella ovoidea</i>																		1.3 (47)	2.6 (25)		2.6 (19)	0.7 (34)							1.6	1.6	
<i>Elphidium advenum</i>						3.2 (19)								3.2		3.4 (11)				2.5 (19)									2.9	3.0	
<i>Elphidium macellum</i>						2.7 (22)	2.2 (12)			1.3 (43)		1.3 (11)		1.8		3.2 (15)				1.2 (39)	1.3 (12)									1.7	1.7
<i>Gavelinopsis praeegeri</i>									2.8 (16)					2.8																2.8	2.8
<i>Globobulimina affinis</i>												1.1 (11)	2.5 (31)	2.1	2.9 (45)		1.6 (24)	2.8 (66)		1.9 (14)	0.7 (27)								2.3	2.2	
<i>Hanzawaia boueana</i>																					0.3 (13)								0.3	0.3	
<i>Hyalinea balthica</i>												2.8 (19)		2.8	1.4 (22)	2.4 (17)	0.5 (51)	2.4 (86)	1.4 (34)	1.6 (30)	0.5 (36)				2.9 (19)	0.6 (12)		2.1	1.6		
<i>Lenticulina peregrina</i>																					0.9 (11)								0.9	0.9	
<i>Melonis barleeanus</i>										1.1 (12)				1.1	1.8 (23)			1.4 (179)		1.1 (54)	0.5 (42)								1.2	1.2	
<i>Nonion scaphum</i>	1.8 (107)	1.6 (125)	1.2 (139)		1.7	1.5 (469)	1.7 (726)	1.2 (417)	1.1 (311)	2.4 (1104)	1.4 (755)	1.0 (1074)	1.5 (971)	1.5	2.1 (97)	1.0 (250)	1.1 (21)	1.9 (76)	1.9 (313)	2.1 (143)	1.1 (127)			0.6 (54)	1.7 (264)	1.4 (460)	1.0 (397)	1.3	1.5		
<i>Nonionella turgida</i>	1.8 (10)	1.6 (99)	1.2 (209)	1.6 (92)	1.4	1.3 (137)	1.4 (154)	1.7 (58)	1.1 (91)	2.5 (249)	1.4 (115)	1.3 (108)	1.7 (93)	1.7	2.3 (41)	1.2 (58)	1.3 (22)	1.7 (18)	2.2 (311)	1.9 (30)	1.1 (33)			0.6 (23)	2.2 (25)	1.7 (46)	1.2 (71)	1.4	1.7		
<i>Pseudoeponides falsobeccarii</i>										0.9 (23)		2.3 (18)		1.5	1.0 (19)		2.3 (52)	1.1 (42)	1.1 (75)										0.8 (29)	0.8	1.4
<i>Rectuvigerina phlegeri</i>						1.4 (50)	0.8 (84)			0.8 (178)	1.3 (94)	0.8 (178)	1.0 (105)	0.9	2.6 (33)	1.3 (41)		1.2 (25)		0.6 (17)	0.7 (13)				1.2 (24)	1.1 (72)	0.8 (92)	1.0	1.0		
<i>Uvigerina mediterranea</i>																	0.6 (12)	1.0 (38)		1.1 (31)	0.3 (43)								0.7	0.7	
<i>Valvulineria bradyana</i>		1.0 (22)			1.0	0.8 (63)	0.5 (246)	1.0 (188)	0.9 (184)	1.2 (470)	0.8 (49)	0.5 (176)	1.0 (361)	0.9	2.0 (357)	0.7 (141)	0.5 (74)	1.3 (483)	1.5 (49)	0.9 (272)	0.7 (326)			0.7 (29)	0.9 (378)	0.9 (209)	0.7 (172)	0.9	1.0		
<i>Adelosina longirostra</i>										1.1 (14)	1.5 (28)			1.4															1.7 (34)	1.7	1.5
<i>Pyrgo subphaerica</i>																													1.7 (11)	1.7	1.7
<i>Quinqueloculina badenensis</i>																													1.5 (32)	1.5	1.5
<i>Quinqueloculina grata</i>																													1.2 (46)	1.2	1.2
<i>Quinqueloculina seminula</i> f. <i>longa</i>	1.1 (22)	1.4 (29)	2.0 (20)		1.5	1.4 (10)	1.4 (14)	0.9 (14)	1.3 (24)	1.4 (42)		0.7 (15)	1.7 (35)	1.3	2.5 (100)		0.5 (56)	1.7 (36)	1.2 (14)	1.0 (32)	0.5 (44)						1.0 (195)	1.0	1.3		
<i>Quinqueloculina</i> sp.1																												0.8 (50)	0.8	0.8	
<i>Adercotryma glomeratum</i>										2.4 (138)				2.4			1.0 (17)	0.8 (31)			0.5 (25)				2.9 (14)	1.7 (13)	0.5 (203)	0.7	1.3		
<i>Bigenerina nodosaria</i>																0.4 (14)	2.0 (122)		2.1 (16)	0.4 (22)									1.7	1.7	
<i>Clavulina cylindrica</i>						0.7 (20)	0.6 (12)			0.8 (74)		0.4 (68)	1.6 (26)	0.7	1.4 (20)			1.6 (45)		1.2 (50)	0.6 (14)				1.1 (22)	0.6 (37)	0.8 (94)	0.8	0.9		
<i>Cribrostomoides jeffreysii</i>																					0.8 (13)							0.3 (16)	0.3	0.5	
<i>Cribrostomoides subglobosus</i>																		1.8 (39)		1.7 (18)									1.8	1.8	
<i>Eggerella scabra</i>	2.2 (51)	2.8 (100)	1.6 (143)		2.1	2.9 (133)	2.0 (69)	1.6 (153)	2.0 (202)	2.2 (294)	3.1 (39)	1.2 (99)	2.2 (117)	2.1	1.5 (24)	2.4 (77)	0.5 (139)	1.6 (163)	1.1 (99)	1.7 (133)	0.6 (108)			1.5 (104)	1.3 (60)	1.2 (107)	1.0 (323)	1.1	1.7		
<i>Eratidus foliaceus</i>																		3.5 (16)							0.3 (14)	1.1 (171)		1.1	1.2		
<i>Lagenammina difflugiformis</i>										1.4 (114)		2.4 (29)		1.6	2.7 (11)	1.4 (24)	0.9 (19)	1.5 (53)	1.1 (37)		0.6 (38)					2.0 (10)		2.0	1.4		
<i>Recurvoides trochaminiformis</i>										0.3 (37)				0.3		2.1 (15)	0.4 (60)	0.9 (98)	1.7 (36)	1.3 (131)	0.5 (62)				1.1 (60)	0.8 (38)		1.0	1.0		
<i>Reophax scoriurus</i>															3.5 (13)		0.3 (16)	1.6 (21)											1.7	1.7	
<i>Reophax scottii</i>	0.6 (1245)	1.3 (78)			0.6																									0.6	0.6
<i>Textularia agglutinans</i>										2.3 (24)		2.6 (75)	2.6 (13)	1.8 (15)	2.5	2.5 (24)	0.5 (118)	1.2 (270)	0.9 (13)	2.2 (48)	0.5 (37)				1.8 (32)	1.2 (440)		1.2	1.3		
ALD5 of the cores	1.9	0.9	1.6	1.5	1.2	1.8	1.4	1.2	1.3	1.9	1.5	0.9	1.3	1.4	1.9	1.4	0.6	1.5	1.5	1.3	0.6	1.2	1.0	1.1	1.2	0.9	1.0	1.3			

Table 3-2. Average living depth (ALD<sub>5</sub>) of foraminiferal species and (in parentheses) the number of individuals on which the calculation is based. Only occurrences of  $\geq 10$  individuals are shown. The grey boxes represent dominant taxa with a relative proportion  $\geq 5\%$  at least at one of the stations.

### 3.5.2.1 Overall vertical distribution of individual taxa

For the 16 quantitatively most important species, the vertical variation in standing stocks is depicted in figure 3-4. The comparison of the 16 profiles shows that there is no clear cut distinction between exclusively infaunal and exclusively surficial taxa and that the vertical distribution of the main foraminiferal species is very similar in the whole area. However, when looking in more detail, we can notice some differences. It is possible to distinguish two vertical distributional patterns:

1) Some taxa generally show a strong maximum in the first half centimetre (Fig. 3-4 a-d, n-o; Table 3-1) followed by a rapidly decrease downward. This first half centimetre usually corresponds to the oxygenated layer of the sediment.

2) Other taxa are already found in important numbers in the first half centimetre but have in nearly all cores, a maximum density in the anoxic layer (Fig. 3-4 f-i; Table 3-1).

A number of taxa show an intermediate vertical distribution between these two extreme cases (Fig. 3-4 e, j-m, p). In fact, the species *M. barleeanus* does not show a constant vertical distribution pattern in the five stations where it occurs with a percentage above 5.0 %. Nevertheless, we can notice that at station 20 (water depth 92 m) where it occurs with a high density, this species shows a strong maximum in the 0.5-1 cm level, below the zero oxygen level. In the literature, this species is known to have an intermediate to deep infaunal microhabitat (e.g. Fontanier et al., 2003, 2005, 2006, Ernst and Van der Zwaan, 2004). The taxa *Q. seminula* f. *longa*, *A. glomeratum*, *E. scabra*, *E. foliaceus* and *T. agglutinans* are generally very abundant in the topmost half centimetre but in some stations they can be found with considerable densities deep in the sediment. We can also observe a total absence of exclusively infaunal taxa; all our taxa are already found in significant quantities in the topmost sediment layer. On the basis of these vertical distributional patterns, we can therefore regroup the 16 main species into two major categories:

1) Predominantly superficial taxa that present a strong maximum in the oxygenated layer (e.g. *A. beccarii* f. *inflata*, *B. aculeata*, *C. carinata*, *E. macellum*, *Q. seminula* f. *longa*, *A. glomeratum*, *E. scabra*, *E. foliaceus*, *R. trochaminiformis*, *R. scottii* and *T. agglutinans*).

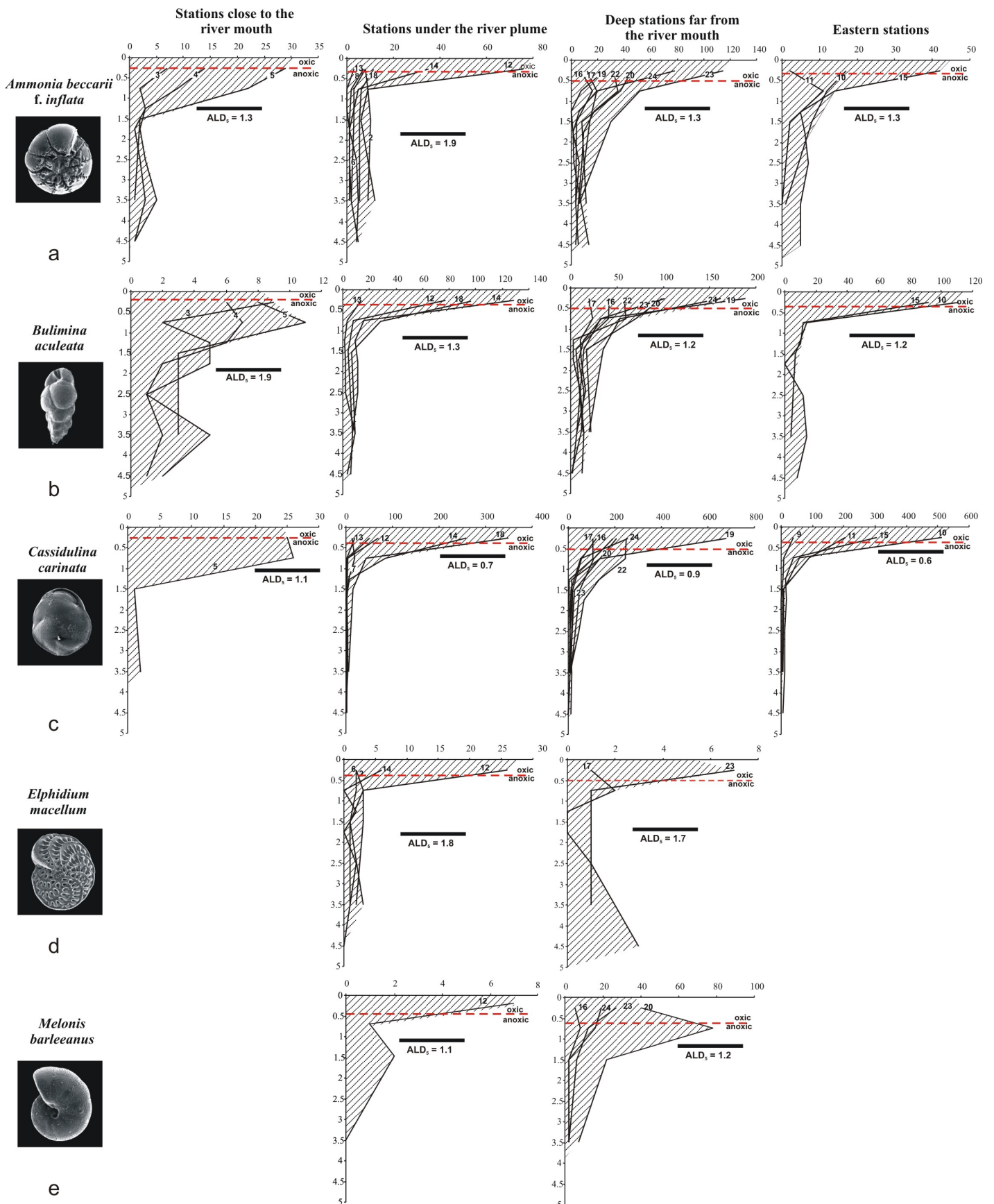


Figure 3-4. Vertical distribution of the main species occurring with more than 5 % in at least one sample (x-coordinate: number of individuals standardized for 100 cc sediment volume, y-coordinate: sediment depth in cm) and the weighted  $ALD_5$ , for each taxon at stations close to the river mouth, stations under the river plume, deep and eastern stations. The red line represents the oxygen penetration limit according to contours calculated by Surfer software on the basis of measurements performed at 10 stations.

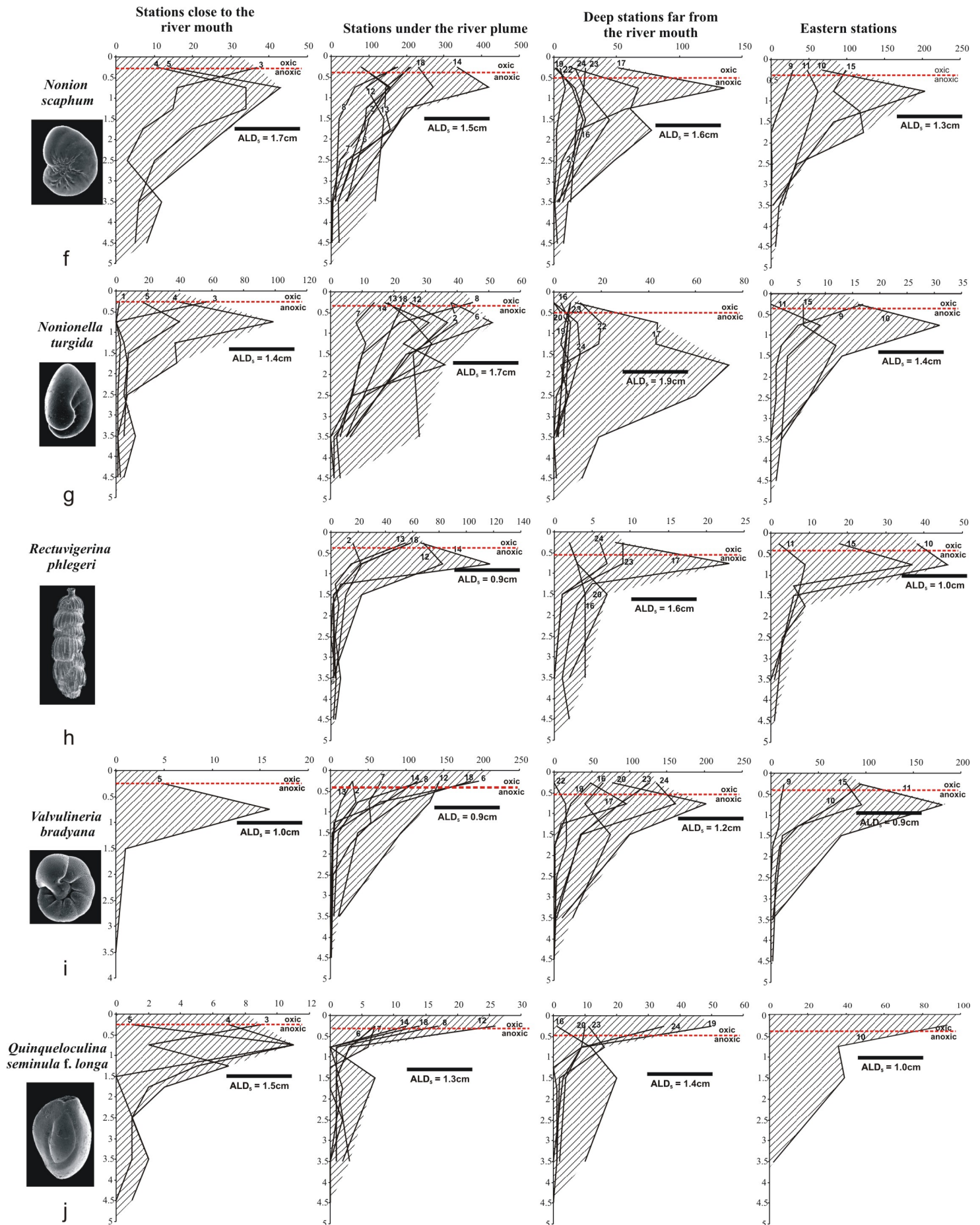


Figure 3-4. Continued.

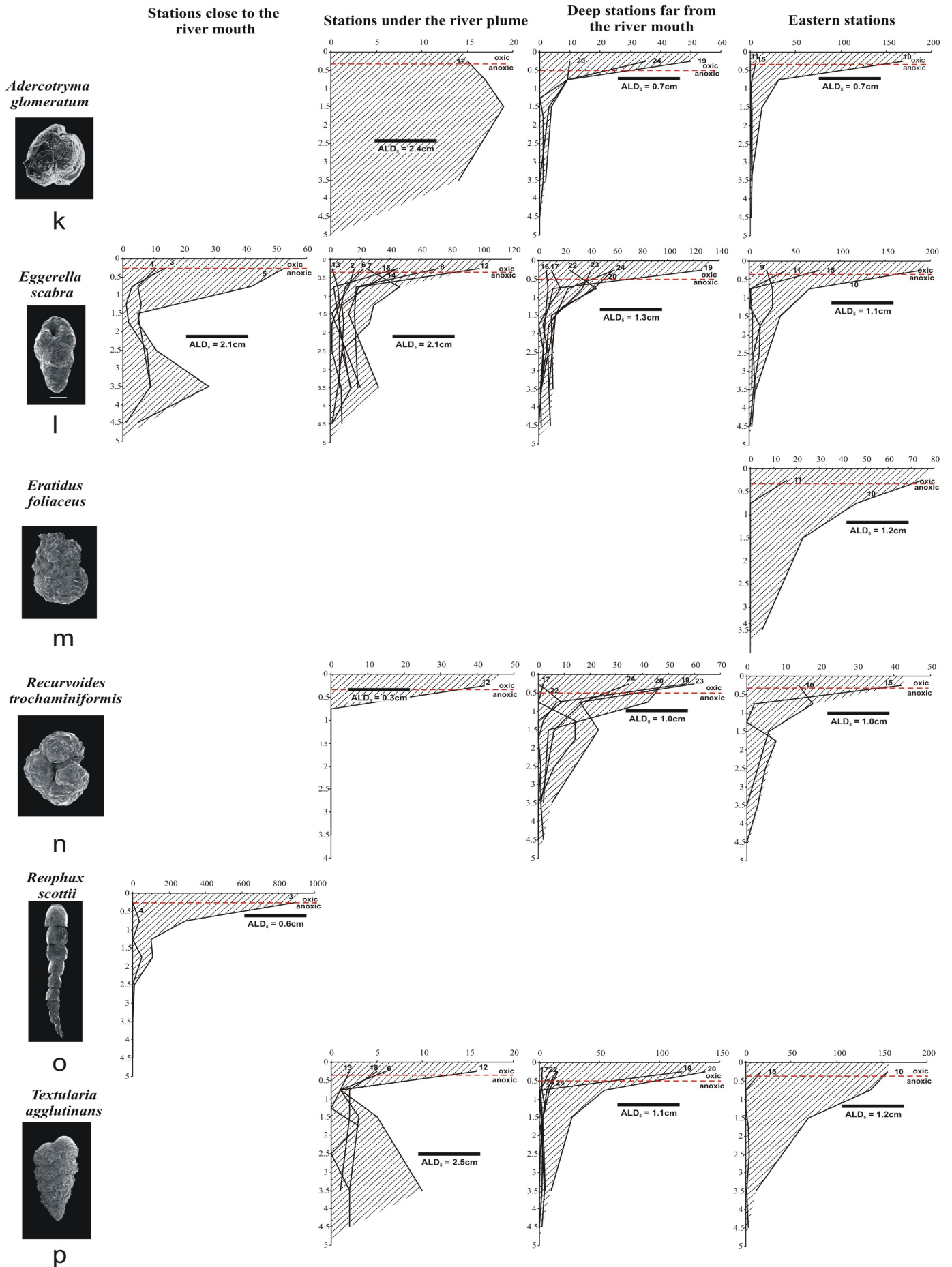


Figure 3-4. Continued.

2) Potentially/predominantly infaunal taxa that generally present a strong maximum in deeper sediment levels, most times, under the limit of oxygen penetration (e.g. *N. scaphum*, *N. turgida*, *R. phlegeri*, *V. bradyana* and *M. barleeanus*).

At stations near the river mouth, in most cases, the low densities of the foraminifera do not allow to distinguish a clear vertical distribution of the species. However, we can notice that at stations influenced by the river plume, most species (especially potentially/predominantly infaunal taxa) show maximal values in the oxic layer whereas in the other zones, much more species show maximum abundances in the anoxic part of the sediment (Table 3-1; Fig. 3.4). In fact, the species *N. scaphum*, *N. turgida*, *R. phlegeri* and *V. bradyana* all show a slightly shallower microhabitat at stations under the influence of the river plume (respectively,  $ALD_5 \sim 1.5, 1.7, 0.9, 0.9$ ) than at deep distal stations sheltered from the influence of the river outflow (respectively,  $ALD_5 \sim 1.6, 1.9, 1.6, 1.2$ ).

### 3.5.2.2 Vertical distribution of the main taxa at each station

In figures 3-5, 3-6, 3-7 and 3-8, the vertical distribution of the main species (> 5 %) is presented for each station.

Figure 3-5 represents the vertical distribution of the main species at stations 1, 3, 4, 5, situated close to the river mouth. These stations are characterised by the lowest oxygen penetration ( $\sim 2.5$  mm on average) and a weighed  $ALD_5$  of 1.2 cm (Table 3-2). Stations 1 and 3 present a poor fauna with the exception of the species *R. scottii* that is present at station 3 with more than 700 individuals per 100 cc. Therefore, we can not distinguish a clear vertical distribution of the living fauna at these two stations, except for *R. scottii* that shows a net preference for the surface layer. The species *Q. seminula* f. *longa* and *E. macellum* are only present at station 1 (considering only percentages higher than 5 %). At station 4, four main species are present: *A. beccarii* f. *inflata*, *N. scaphum*, *N. turgida* and *E. scabra*. At this station, *A. beccarii* f. *inflata* shows a predominantly superficial habitat whereas *N. scaphum*, *N. turgida* and *E. scabra* show maximal densities below the limit of oxygen penetration. At station 5, *A. beccarii* f. *inflata*, *N. scaphum* and *N. turgida* show the same vertical distributional pattern as found at station 4 whereas *E. scabra* seems to prefer the uppermost layer at this station. The species *C. carinata* and *B. aculeata* are also present at this station and show mainly a surficial distribution.

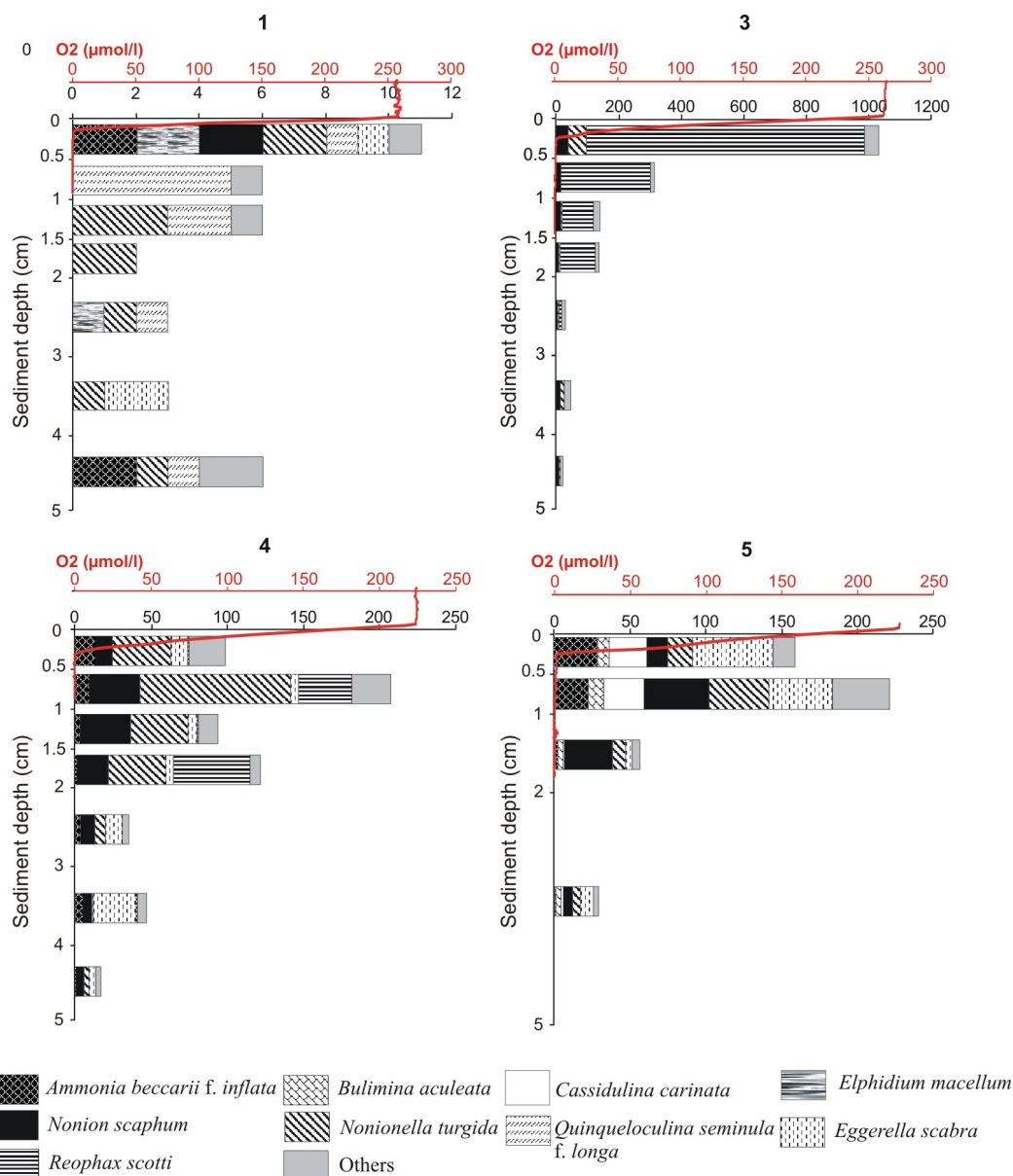


Figure 3-5. Living foraminiferal distribution (number of individuals > 150 μm fraction found at each sampled level, standardized for 100 cm<sup>3</sup> sediment volume) for the stations close to the river mouth (1, 3, 4, 5) and oxygen profiles (μmol/l). For each core, only the species that occur with more than 5 % are represented.

Figure 3-6 represents the vertical distribution of the main species at stations 2, 6, 7, 8, 12, 13, 14 and 18 that are situated southwest of the river mouth, in the direction of the spreading of the river plume. These stations are characterised by an intermediate oxygen penetration (~ 3.5 mm on average) and by an average living depth for the total fauna of 1.4 cm (Table 3-2). At most of these stations, *N. scaphum*, *V. bradyana*, *R. phlegeri* and *N. turgida* are systematically present in considerable densities deep in the sediment. At some stations (2, 7, 13, 14 and 18), maximal abundances are present under the limit of oxygen

penetration, especially for the species *N. scaphum* and *N. turgida*. Since significant quantities are already present in the topmost sediment level, the label potentially/predominantly infauna appears most suitable to describe the vertical distribution of these taxa. On the contrary, *C. carinata* and *B. aculeata* show a clear superficial distribution at stations where they are present (8, 14, 18). *E. scabra* has a predominantly superficial distribution at stations 8 and 12 whereas at stations 2 and 7, this species still occur in significant densities in the anoxic layer of the sediment.

Figure 3-7 represents the vertical distribution of the main species at the deepest stations 16, 17, 19, 20, 22, 23 and 24 that are situated in a more distal position with respect to river influence. These stations are characterized by the deepest oxygen penetration in the Rhône prodelta (~ 5 mm on average) and by a rather shallow average living depth of the total fauna (ALD<sub>5</sub> ~ 1.2 cm) (Table 3-2). The fauna of this zone is mainly composed of the species *C. carinata*, *B. aculeata*, accompanied in some stations by the hyaline species *A. beccarii* f. *inflata*, *N. scaphum*, *N. turgida*, *V. bradyana*, *Q. seminula* f. *longa* and *M. barleeanus* and by the agglutinated species *E. scabra*, *T. agglutinans* and *R. trochaminiformis*. In this distal area, the species *C. carinata*, *B. aculeata*, *A. beccarii* f. *inflata*, *Q. seminula* f. *longa*, *E. scabra*, *T. agglutinans* and *R. trochaminiformis* show all a clear preference for the uppermost oxygenated layer. Therefore, the label “predominantly superficial fauna” appears most appropriate to describe their vertical distribution. On the other hand, the other species (*N. scaphum*, *N. turgida*, *V. bradyana*) show systematically infaunal maxima at stations where they occur (16, 17, 20, 22, 24) (Table 3-1). They appear to live deeper in the sediment compared to their distribution at stations located under the river plume.

Figure 3-8 represents the vertical distribution of the main species at the eastern stations (9, 10, 11 and 15) that are less influenced by river outflow. These stations are characterized by an intermediate oxygen penetration (~ 4.0 mm on average) and by a shallow average living depth (ALD<sub>5</sub> ~ 1.0 cm) (Table 3-2). At these stations, and similarly to the fauna composing the deep distal stations, the species *C. carinata*, *B. aculeata*, *Q. seminula*, *E. scabra*, *T. agglutinans*, *R. trochaminiformis* and *E. foliaceus* show all a clear predominantly shallow microhabitat with the exception of *E. scabra* at station 9 that shows an infaunal maximum. *N. scaphum* and *V. bradyana* show in general an infaunal maximum with exception of station 9 close to river mouth where they live closer to the sediment surface and where they show, together with *N. turgida*, a maximal density in the uppermost sediment.



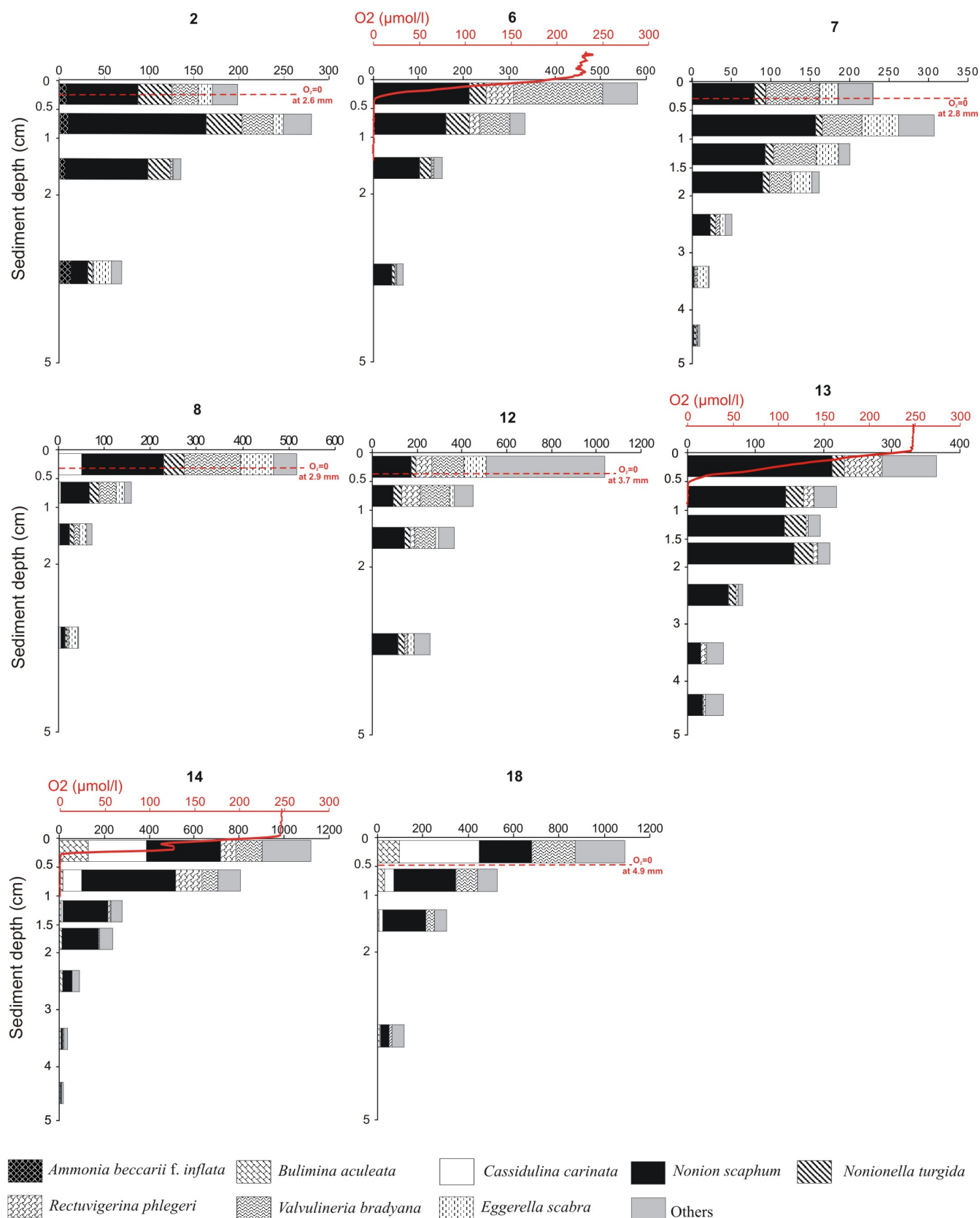


Figure 3-6. Living foraminiferal distribution (number of individuals > 150 µm fraction found at each sampled level, standardized for 100 cm<sup>3</sup> sediment volume) for the stations located under the river plume (2, 6, 7, 8, 12, 13, 14 and 18) and oxygen profiles (µmol/l). For each core, all species that occur with more than 5 % are represented. The red dashed lines represent the oxygen penetration limit according to contours calculated by Surfer software on the basis of measurements performed at 10 stations.

## Microhabitat selection of benthic foraminifera in the Rhône prodelta

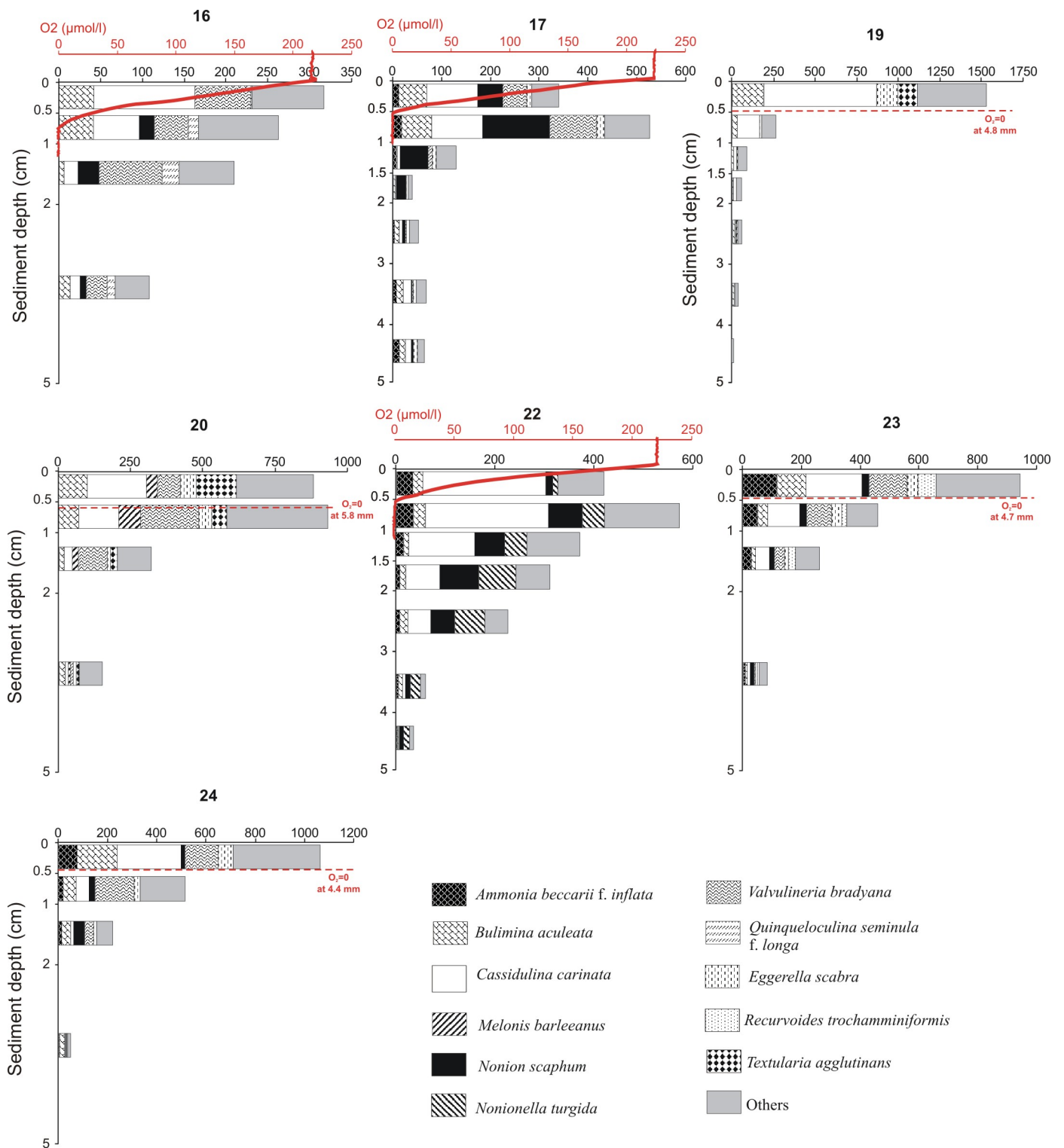


Figure 3-7. Living foraminiferal distribution (number of individuals > 150  $\mu\text{m}$  fraction found at each sampled level, standardized for 100  $\text{cm}^3$  sediment volume) for the deep stations (16, 17, 19, 20, 22, 23 and 24) and oxygen profiles ( $\mu\text{mol/l}$ ). For each core, all species that occur with more than 5 % are represented. The red dashed lines represent the oxygen penetration limit according to contours calculated by Surfer software on the basis of measurements performed at 10 stations.

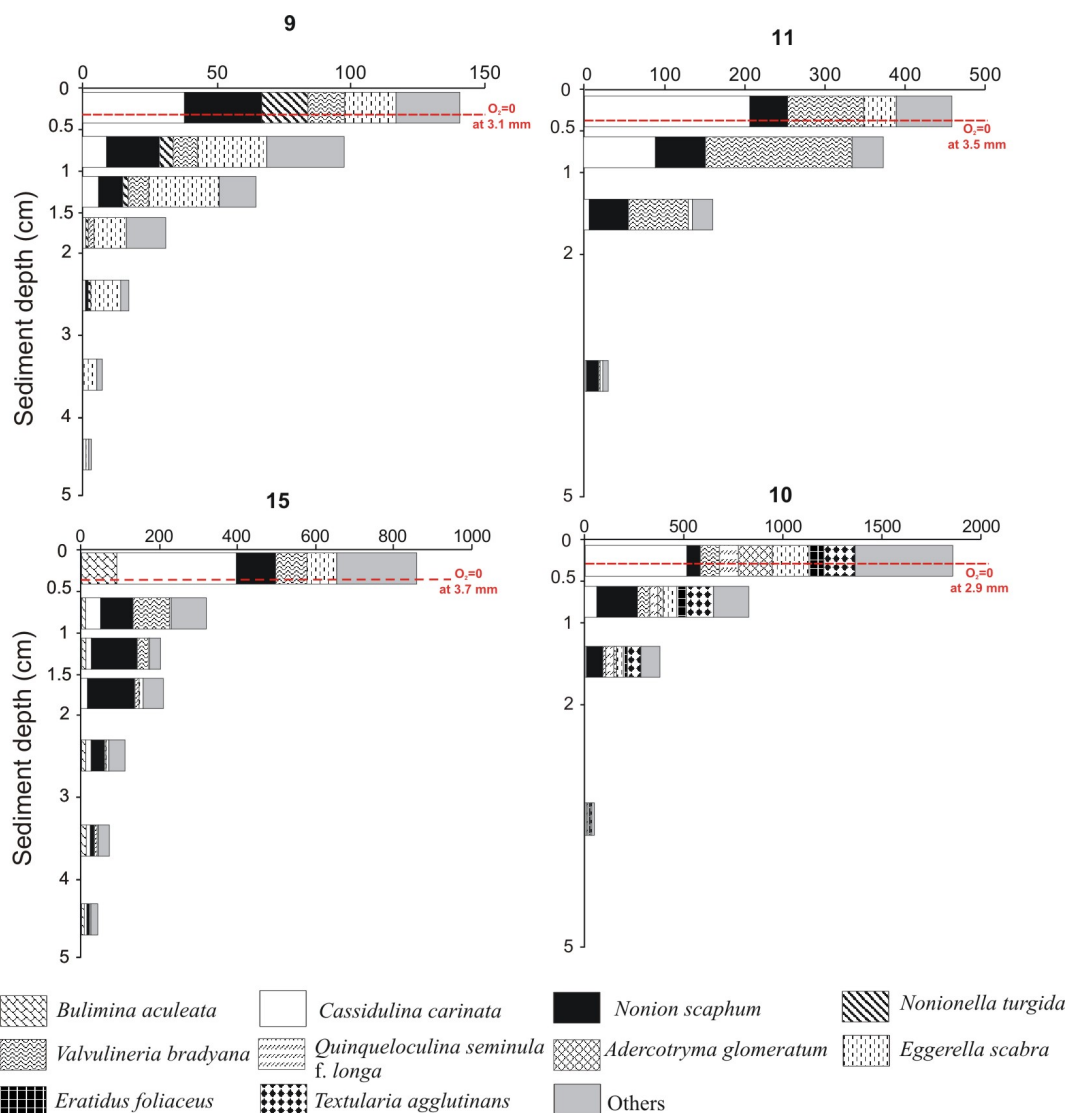


Figure 3-8. Living foraminiferal distribution (number of individuals > 150  $\mu\text{m}$  fraction found at each sampled level, standardized for 100  $\text{cm}^3$  sediment volume) for the eastern stations (9, 11, 10 and 15). For each core, all species that occur with more than 5 % are represented. The red line represents the oxygen penetration limit according to contouring calculated by Surfer software on the basis of measurements performed at 10 stations.

Figure 3-9 presents the spatial distribution of the cumulative percentages of the previously determined “predominantly superficial” taxa (*A. beccarii* f. *inflata*, *B. aculeata*, *C. carinata*, *E. macellum*, *Q. seminula* f. *longa*, *A. glomeratum*, *E. scabra*, *E. foliaceus*, *R. trochaminiformis*, *R. scottii* and *T. agglutinans*) and “potentially/predominantly infaunal” taxa (*N. scaphum*, *N. turgida*, *R. phlegeri*, *V. bradyana* and *M. barleaanus*). We can observe that the “potentially/predominantly infaunal” taxa become strongly dominant in the southwestern stations that are under the influence of the river plume. The “predominantly superficial” taxa dominate at the deeper and eastern stations that are less influenced by river input, and also at

station 3 that is in the immediate vicinity of the river mouth. However, the fauna at station 3 is very peculiar because of the very strong dominance of *R. scotti* which occupies a predominantly superficial niche at this station.

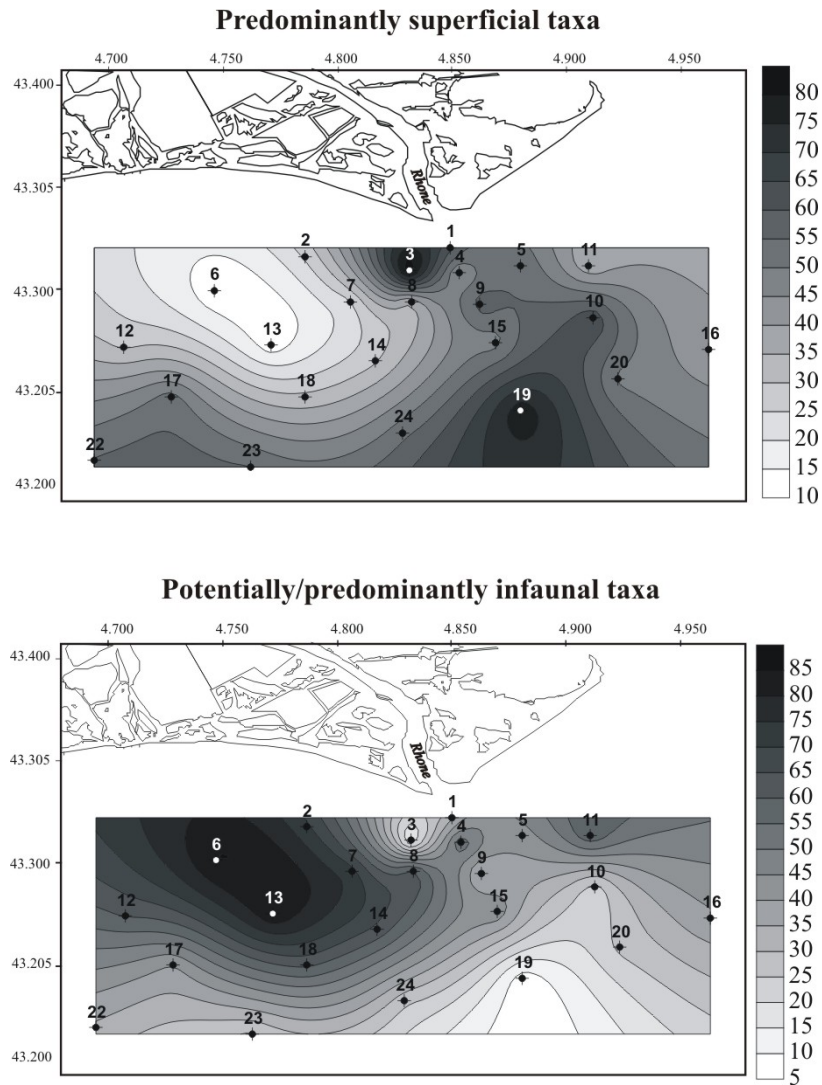


Figure 3-9. Geo-referenced contour maps of spatial distribution of the cumulative percentages of the "predominantly superficial" taxa and the "potentially/predominantly infaunal" taxa using a grid based contour program, Surfer for Windows (Golden Software; version 6.02).

### 3.6 DISCUSSION

Our data on the vertical distribution of benthic foraminiferal faunas in the Rhône prodelta show surprisingly few geographical variability. At all sites, there is a strong

maximum of foraminifera living close to the surface, and densities drop rapidly in the first centimetres to attain zero at 2 to 5 cm depth. When we compare the vertical distribution of individual species, we can observe, that also here differences are rather limited. Almost all taxa show maximal densities at the surface, and the main difference is the rapidity of the downward density decrease. When looking in more detail, the existing data on vertical distributions of individual taxa in the Rhône prodelta reveals that two main distributional patterns may be recognized. The first type of profile shows a very clear maximum in the topmost 0.5 cm thick interval that usually corresponds to the oxygenated layer of the cores. However, in our continental shelf environment, abundant species are never completely limited to this topmost interval, and are always found in significant numbers at the levels below. *Buzas (1974) and Buzas et al. (1993)* argue that in such environments with fine-grained sediments, even taxa living exclusively at the topmost level are mostly probably infauna. In order to underline their preference for the topmost sediment layer, we labelled those species as “predominantly superficial” taxa. Species with the second type of vertical distribution show comparable densities in several successive intervals with or without a clear maximum in the anoxic layer of the sedimentary column. *Jorissen (1999)* suggests that this type of distribution is very common in shallow-water environments, perhaps because the sediment is intensely burrowed to a considerable depth and much rarer in deep-sea environments, where pore-water characteristics change rapidly over a short depth interval. This distributional profile should be typical for taxa which do not have a clear preference for the topmost sediment layer (or which do not successfully compete there with other taxa), and which tolerate the conditions found deeper in the sediment (*Jorissen, 1999*). For these species, we choose the term “potentially/predominantly infaunal” taxa. Differences between these two main distributional patterns are generally clear in the Rhône prodelta faunas, but the reader should keep in mind that species with intermediate patterns exist and that for a single species, different patterns may be found at different stations.

In the Rhône prodelta, three major ecological biofacies can be distinguished thanks to the foraminiferal distribution:

- 1) A first zone, located near the river mouth, presents a minimal oxygen penetration into the sediment (~ 2.5 mm) and important input of predominantly continental organic matter ( $C_{org} \sim 2\%$ ). At station 1, the very few living foraminiferal specimens do not allow to distinguish any vertical distribution. At station 3, the predominant taxon *R. scottii* present a

superficial niche. This species is accompanied in much lower densities by two main “potentially/predominantly infaunal” taxa (*N. turgida* and *N. scaphum*). Stations 4 and 5 are inhabited by few individuals of predominantly superficial taxa (*A. beccarii*, *Q. seminula*, *E. scabra*) and considerable numbers of potentially/predominantly infaunal taxa *N. turgida* and *N. scaphum*. At station 5, the superficial species *B. aculeata* and *C. carinata* are also present in significant numbers. It should be noticed that the species *E. scabra* does not show a clear microhabitat preference, but shows an intermediate pattern with a surface maximum at stations 5 and a second maximum deeper in the sediment at stations 1 and 4. All these taxa occur with considerable densities deeper in the sediment. They seem therefore to tolerate also the conditions occurring in the anoxic layers. In fact, they have all been described in the literature as stress-resistant taxa. *N. turgida* was described by *Barmawidjaja et al. (1995)* as a stress-tolerant taxa and conclude, in a study of changes in foraminiferal assemblages influenced by the supply of human-derived nutrients to the northern Adriatic Sea, that the increasing nutrient load and consequent stress led to the increase in abundance of this species. *E. scabra* is a continental shelf species (e.g. *Murray, 1991; Barmawidjaja et al., 1992*) that lives in various microhabitats from the oxygenated sediment surface to the deepest anoxic layers (e.g. *Barmawidjaja et al., 1992; Jorissen et al., 1992; Ernst et al., 2002, 2005; Duijnste et al., 2003, 2004*). It appears therefore to be tolerant for strongly hypoxic conditions. For instance, *E. scabra* is common in the Adriatic Sea, in areas where important amounts of degraded organic matter cause oxygen depletion (*Donnici and Serandrei-Barbero, 2002*). *E. scabra* also occurs in estuarine areas (e.g. *Murray, 1991*), in association with *Elphidium excavatum*, in environments impacted by important anthropogenic discharges (e.g. *Debenay et al., 1996*). *A. beccarii* is a euryhaline species, and is widely distributed in intertidal and subtidal zones (*Alve and Murray, 1999*). It survives under a wide range of values of dissolved oxygen (*Moodley and Hess, 1992*), salinity, and temperature (*Murray, 1991*) as well as in heavily polluted waters (*Alve, 1995*). *Thomas et al. (2000)* suggested that an abundance of *A. beccarii* might be associated with high sewage inputs. However, in the literature, there is considerable confusion between *A. beccarii*, a fully marine species and *Ammonia parkinsoniana/tepida* that can also be found in shallow settings. The *inflata* morphotype of *A. beccarii* has been described earlier by *Jorissen (1988)* in front of the Po River in the Adriatic Sea between about 20 to 50 m water depth in an area under the influence of the input of nutrients by runoff. In the Ria de Arosa (Galicia, Spain; *Van Voorthuysen, 1973*), this morphotype appears on clayey bottoms, which are food-enriched as result of upwelling near to the Galician coast.

2) The second biofacies consists of stations under the influence of the river plume. In this area, the substrate is characterized by low oxygen penetration into the sediment ( $\sim 3.5$  mm in average) and an important concentration of organic matter (Corg  $\sim 1.4$  %) with a significant continental contribution. The living assemblage is strongly dominated by three “potentially/predominantly infaunal” species (*N. scaphum*, *R. phlegeri* and *V. bradyana*). The ALD<sub>5</sub> of all stations located under the river plume is 1.4 cm on average, which is deeper than at the most distal stations. In the literature, *N. scaphum* is often described as an opportunistic species. It has been suggested that this infaunally living taxon migrates to the sediment surface in response to an increased organic matter input to the seafloor (Langezaal *et al.*, 2004, Langezaal *et al.*, 2006, Fontanier *et al.*, 2003). *N. scaphum* has also been described in the upwelling system off Portugal (Levy *et al.*, 1993). *R. phlegeri* prefers sediments close to the Tagus River plume in the western Iberian margin (in Bartels-Jónsdóttir *et al.*, 2006). In a previous study performed on foraminiferal fauna in the occidental Mediterranean Sea, Bizon and Bizon (1984) found *R. phlegeri* in a range of 40 to 100 m with a strong abundance in the southwestern part of the Rhône prodelta. Jorissen (1987) describes a minimum water depth of 40 m for *V. bradyana*, in combination with stressed conditions. Morigi *et al.* (2005) suggest that increased percentages of this species could eventually reflect a human impact on the marine environment, such as increased organic matter input associated with industrial development. In such cases, this taxon could move to superficial sediments, and take over the niches of less resistant taxa (Morigi *et al.*, 2005). In our samples, a similar tendency can be observed; *V. bradyana*, that has its maximum in the uppermost layer of the sediment at the stations under the influence of the river plume, lives deeper in the sediment, in the anoxic layer, at the more distal stations (Table 3.1, Fig. 3.4).

3) The third biofacies is present at stations that are less influenced by river input (deepest and eastern stations). These stations are characterised by a higher oxygen penetration ( $\sim 5.0$  mm on average) and low amounts of organic carbon (Corg  $\sim 0.8$  %), probably mostly of marine (more labile) origin. The ALD<sub>5</sub> of this zone is the shallowest in the Rhône prodelta (1.2 cm for the deepest stations and 1.0 cm for the eastern stations). This shallower living depth is due to the strong dominance of the “predominantly superficial” taxa (*C. carinata*, *B. aculeata*, *A. glomeratum*, *R. trochaminiformis*, *E. foliaceus*, *T. agglutinans*) that have a preference for the uppermost oxygenated sediment layer. The most abundant species *C.*

*carinata* is known in the literature to respond quickly to labile organic matter input by a reproductive event (Fontanier *et al.*, 2003).

To summarize, the stations under the influence of river input are rich in “potentially/predominantly infaunal” taxa. A dominance of infaunal taxa is a common phenomenon in high productivity and/or low oxygen settings (Sen Gupta and Machain-Castillo, 1993). The strong dominance of “potentially/predominantly infaunal” species in the stations influenced by river runoff suggests that, in this area, they are more competitive than “predominantly superficial” taxa. Since the oxygen concentration at the sediment water interface is relatively elevated at all stations (210 – 260  $\mu\text{mol/l}$ ), this infaunal dominance can not be explained by a disappearance of more surficial taxa due to a low oxygen content. The fact that all “predominantly superficial” taxa systematically also appear in deeper anoxic sediment layers, strongly suggests that the oxygen concentration does not entirely explain their preference for the sediment surface. We suggest that the segregation between superficial and potentially/predominantly infaunal taxa is mainly determined by their different tolerance with respect to food quality. At stations under the influence of river input, low quality terrestrial organic carbon will prevail whereas labile marine organic matter will be relatively rare. As a consequence, infaunal taxa, that have a higher tolerance for this low quality food, strongly dominate the assemblage. At stations that are less influenced by river input, predominantly superficial taxa dominate. We suggest that high densities of these taxa are a response to a higher quality of labile organic matter of marine origin at a more distal position from the river. However, bacterial breakdown of more low quality organic carbon deeper in the sediment, which is a relatively slow process, continues to supply food to the less frequent infaunal taxa deeper in the sediment. At most of these distal stations, maximal densities are found in the first half centimetre of the sediment.

In order to elucidate the factors controlling the vertical distributional patterns, we plotted the cumulative percentages of the two described microhabitat categories together with the oxygen penetration in the sediment and with the C/N ratio and  $\delta^{13}\text{C}$ , that both translate the organic matter quality (Fig. 3-10). In this graph, we did not represent station 1 that is inhabited by only a few individuals, and station 3, that is very peculiar since the fauna is largely dominated by *R. scottii* that occurs almost only at this station. In figure 3-10, we can observe that there is indeed a fair positive correlation between the cumulative percentages of the “potentially/predominantly infaunal” taxa with increasing C/N ratio and decreasing  $\delta^{13}\text{C}$  values, ( $r^2 = 0.58$  and  $0.45$  respectively) that indicate a more important terrestrial component



of organic carbon. Alternately, a negative correlation of the cumulative percentages of the “predominantly superficial” taxa can be seen with increasing C/N ratio and decreasing  $\delta^{13}\text{C}$  values ( $r^2 = 0.52$  and  $0.40$  respectively). There is only a very weak correlation between these faunas and the oxygen penetration in the sediment. We conclude therefore that the quality of the organic matter is the major factor controlling the vertical distribution of the living foraminifera in the Rhône prodelta and that oxygen concentration of the sediment has at best a minor contribution.

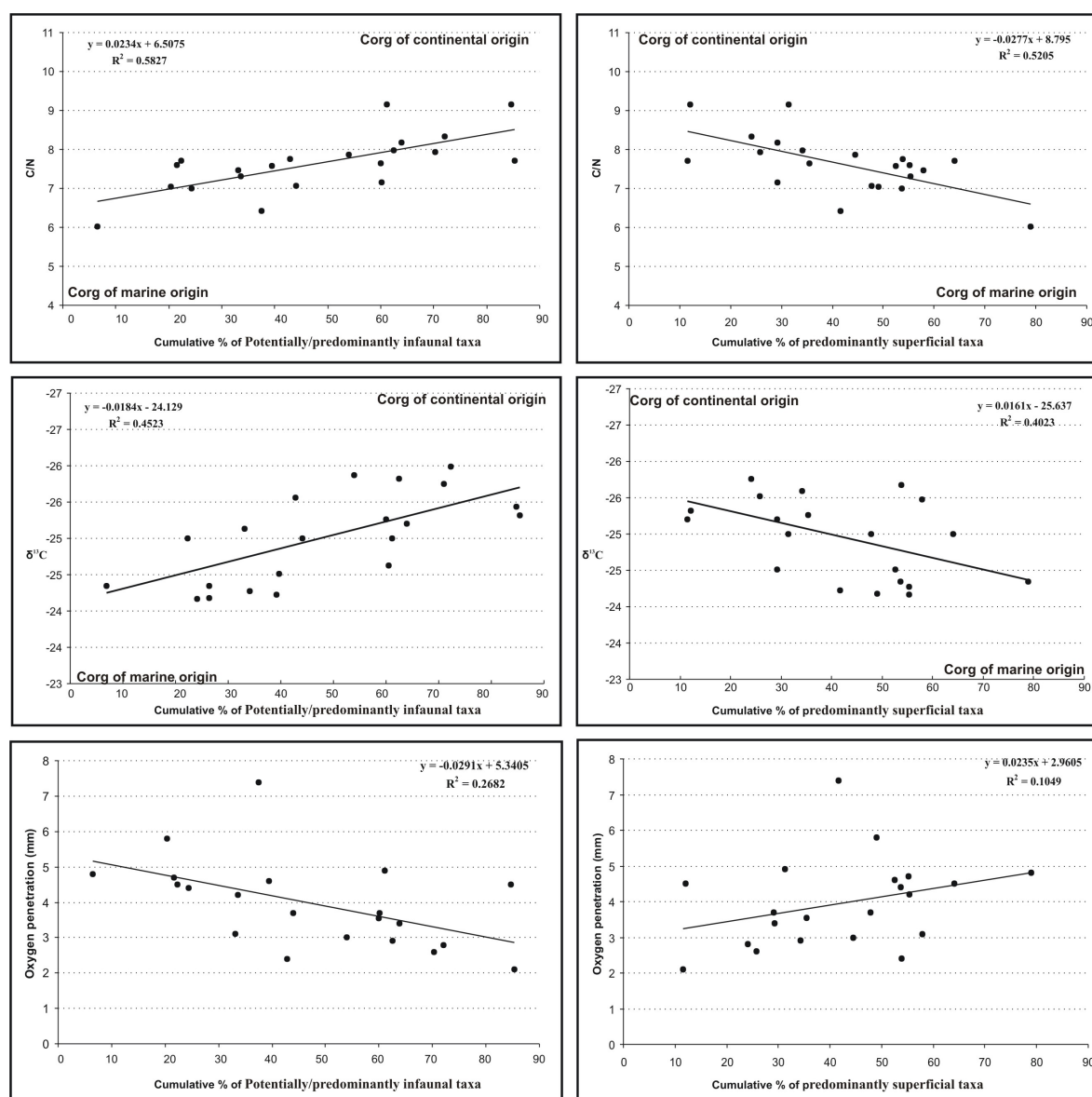


Figure 3-10. Graphs representing the correlation between the cumulative percentages of the “predominantly superficial” taxa and the “potentially/predominantly infaunal” taxa with C/N ratio,  $\delta^{13}\text{C}$  and the oxygen penetration into the sediment. Oxygen penetration depth: based on clustering by Surfer software on the basis of the measurements performed at 10 stations.

### 3.7 CONCLUSIONS

- In shallow-marine environments, it appears to be impossible to divide benthic foraminiferal microhabitats into shallow infaunal, intermediate infaunal and deep infaunal taxa as it is usually done in deep-sea environments. In the Rhône prodelta, most foraminifera live in the topmost centimetre of the sediment. However, we could distinguish between two vertical distributional patterns. We labelled a group that occurs with a strong maximum in the oxygenated layer of the sediment as “predominantly superficial taxa” and a group which is found deeper in the sediment in considerable densities as “potentially/predominantly infaunal” taxa.

- At stations that are subjected to Rhône River input, the foraminiferal assemblages are dominated by “potentially/predominantly infaunal” taxa which seem to profit from the important input of organic matter with a significant proportion of more refractory component. These species tolerate the anoxic conditions that occur deeper in the sediment.

- The stations that are less influenced by river input are characterised by the dominance of “predominantly superficial” species that profit from more labile organic matter of marine origin. These species live mainly in the oxygenated layer of the sediment.

- The correlation between the proportion of these two faunas and the environmental factors strongly suggests that the vertical distribution of foraminifera in the Rhône prodelta is mainly controlled by the quality of organic matter, whereas oxygen penetration into the sediment has at best a marginal influence.

### 3.8 REFERENCES

Aller, R.C., 1994. The sedimentary Mn cycle in Long Island Sound: its role as intermediate oxidant and the influence of bioturbation, O<sub>2</sub> and C<sub>org</sub> flux on diagenetic reaction balances. *Journal of Marine Research*, 52, 259-295.

Aller, J. Y., Aller, R. C., 1986. Evidence for localized enhancement of biological activity associated with tube and burrow structure in deep-sea sediments at the HEBBLE site, western north Atlantic. *Deep-Sea Research*, 33, 755-790.

Altenbach, A. V. 1988. Deep-sea benthic foraminifera and flux rate of organic carbon (Résumé - Abstract). in "Benthos' 1986". Revue de Paléobiologie Volume Spécial, 2, Partie 2: 719-720.

Altenbach, A.V. and Sarntheim, M., 1989. Productivity Record in Benthic Foraminifera. In: W.H. Berger, V.S. Smetacek and G. Wefer (eds.) Productivity of the Ocean: Present and Past., p. 255-269. John Wiley and Sons Limited.

Alve, E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. *Journal of Foraminiferal Research*, 25, 190-203.

Alve, E., Murray, J.W., 1999. Marginal marine environments of the Skagerrak and Kattegat, a baseline study of living (stained) benthic foraminiferal ecology. *Palaeogeography, Palaeoclimatology, Palaeoceanography*, 146, 171-193.

Arnone, R., 1994. The temporal and spatial variability of chlorophyll in the western Mediterranean. Seasonal and Interannual Variability of the Western Mediterranean Sea, La Violette, P.E. (Ed.). *Coastal Estuarine Studies*, 46, 195-225.

Barmawidjaja, D.M., 1991. Studies in living and fossil foraminifers from seasonally productive regions. *Geologica Ultraiectina*, 82, 221 pp.

Barmawidjaja, D.M., Jorissen, F.J., Puskaric, S. and Van der Zwaan, G.J., 1992. Microhabitat selection by benthic foraminifera in the Northern Adriatic Sea. *Journal of Foraminiferal Research*, 22, 297-317.

Barmawidjaja, D.M., Van Der Zwaan, G.J., Jorissen, F.J., Puskaric, S., 1995. 150 years of eutrophication in the northern Adriatic Sea, evidence from a benthic foraminiferal record. *Marine Geology*, 122, 367-384.

Bartels-Jónsdóttir, H.B., Knudsen, K. L., Abrantes, F., Lebreiro, S., Eiríksson, J., 2006. Climate variability during the last 2000 years in the Tagus Prodelta, western Iberian Margin: Benthic foraminifera and stable isotopes. *Marine Micropaleontology*, 59, 83-103.

Basov, I.A., Khusid, T.A., 1983. Biomass of benthic foraminifera in the sediments of the Sea of Okhotsk. *Oceanology*, 33, 489-495.

Bernhard, J.M., 1992. Benthic foraminiferal distribution and biomass related to porewater oxygen content: central California continental slope and rise. *Deep-Sea Research*, 39, 585-605.

Bernhard, J.M., 1993. Experimental and field evidence of Antarctic foraminiferal tolerance to anoxia and hydrogen sulfide. *Marine Micropaleontology*, 20, 203-213.

Bernhard, J.M., 2003. Potential symbionts in bathyal foraminifera. *Science*, 299, 861.

Bernhard, J.M. and Reimers, C.E., 1991. Benthic foraminiferal population fluctuations related to anoxia: Santa Barbara Basin. *Biogeochemistry*, 15, 127-149.

Bernhard, J.M., Sen Gupta, B.K. and Bonne, P.F., 1997. Benthic foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations: Santa Barbara Basin, U.S. Pacific continental margin. *Journal of Foraminiferal Research*, 27, 301-310.

Bizon, G. and Bizon, J.J., 1984. Distribution des foraminifères sur le plateau continental au large du Rhône. In: Bizon, J. J. & Burollet, P. F. (eds) *Ecologie des microorganismes en Méditerranée occidentale 'ECOMED'*, Association Française des Techniciens du Pétrole, Paris, 84-94.

Buscail, R., Germain, C., 1997. Present-day organic matter sedimentation on the NW Mediterranean margin: Importance of off-shelf export. *Limnology and Oceanography*, 42 (2), 217-229.

Buzas, M.A., 1974. Vertical distribution of *Ammobaculites* in the Rhode river, Maryland. *Journal of foraminiferal research*, 4, 144-147.

Buzas, M.A., Culver, S.J. and Jorissen, F.J., 1993. A statistical analyses evaluation of the microhabitats of living (stained) infaunal benthic foraminifera. *Marine micropaleontology*, 20, 311-320.

Caralp, M.H., 1989. Abundance of *Bulimina exilis* and *Melonis barleeanum*: Relationship to the quality of marine organic matter. *Geo-Marine Letters*, 9, 37-43.

Corliss, B.H., 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*, 314, 435-438.

Corliss, B.H., 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. *Marine Micropaleontology*, 17, 195-236.

Corliss, B.H. and Emerson, S., 1990. Distribution of Rose Bengal stained deep-sea benthic foraminifera from the Nova Scotian continental margin and Gulf of Maine. *Deep Sea Research*, 37, 381-400.

Cruzado, A., Velasquez, Z.R., 1990. Nutrients and phytoplankton in the Gulf of Lions, northwestern Mediterranean. *Continental and Shelf Research*, 10 (9-11), 931-942.

Debenay, J.P. Beck-Eichler, B., Fernandez-Gonzalez, M., Mathieu, R., Bonetti, C., Duleba, W., 1996. Les foraminifères paraliques des côtes d'Afrique et d'Amérique du Sud, de part et d'autre de l'Atlantique, comparaison et discussion. In, S. Jardiné, I. Klazis and J.-P. Debenay (Editors), *Géologie de l'Afrique et de l'Atlantique sud. Compte rendu des colloques de géologie d'Angers*. Elf-Aquitaine Edition, Pau, Angers, pp. 463-471.

De Stigter, H.C., Jorissen, F.J., Van der Zwaan, G.J., 1998. Bathymetric distribution and microhabitat partitioning of live (Rose Bengal stained) benthic foraminifera along a shelf to deep-sea transect in the southern Adriatic Sea. *Journal of Foraminiferal Research*, 28, 40-65.

Donnici, S. and Serandrei-Barbero, R., 2002. The benthic foraminiferal communities of the North Adriatic continental shelf. *Marine Micropaleontology*, 44, 93-123.

Duijnste, I., Ernst, S.R., Van Der Zwaan, G.J., 2003. Effect of anoxia on the vertical migration of benthic foraminifera. *Marine Ecology Progress Series*, 246, 85-94.

Duijnste, I., De Lugt, I., Vonk Noordegraaf, H. and Van Der Zwaan B., 2004. Temporal variability of foraminiferal densities in the northern Adriatic Sea. *Marine Micropaleontology*, 50, 125-148.

Ernst S., Duijnste, I. and Van Der Zwaan, B., 2002. The dynamics of the benthic foraminiferal microhabitat, recovery after experimental disturbance. *Marine Micropaleontology*, 46, 343-361.

Ernst, S. and van der Zwaan, B., 2004. Effects of experimentally induced raised levels of organic flux and oxygen depletion on a continental slope benthic foraminiferal community. *Deep Sea Research Part I: Oceanographic Research Papers*, 51, 1709-1739.

Ernst, S., Bours R., Duijnste I., and Van Der Zwaan, B., 2005. Experimental effects of an organic matter pulse and oxygen depletion on a benthic foraminiferal shelf community. *Journal. of Foraminiferal Research*, 35, 177-197.

Estournel, C., Durrieu de Madron, X., Marsaleix, P., Auclair, F., Julliand, C., Vehil, R., 2003. Observations and modelisation of the winter coastal oceanic circulation in the Gulf of Lions under wind conditions influenced by the continental orography (FETCH experiment). *Journal of Geophysical Research*, 108 (C3), 8059.

Gadel, F., Puigbó, A., Alcañiz, J.M., Charrière, B., Serve, L., 1990. Tracers and constituents indicating the nature of organic fluxes, their origin and the effect of environmental conditions. *Continental and Shelf Research*, 10 (9-11), 1039-1062.

Got, H., Aloisi, J.C., 1990. Holocene sedimentation on the Gulf of Lions margin: a quantitative approach. *Continental and Shelf Research*, 10 (9-11), 841-855.

Fariduddin, M., and Loubere, P., 1997. The surface ocean productivity response of deeper water benthic foraminifera in the Atlantic Ocean. *Marine Micropaleontology*, 32, 289-310.

Fontanier, C., Jorissen, F.J., Licari, L., Alexandre, A., Anschutz, P., Carbonel, P., 2002. Live benthic foraminiferal faunas from the Bay of Biscay: faunal density, composition, and microhabitats: *Deep-Sea Research I*, 49, 751-785.

Fontanier, C., Jorissen, F. J., Chaillou, G., David, C., Anschutz, P., Lafon, V., 2003. Seasonal and interannual variability of benthic foraminiferal faunas at 550m depth in the Bay of Biscay. *Deep Sea Research Part I*, 50, 457-494.

Fontanier, C. Jorissen, F.J., Chaillou, G., Anschutz, P., Gremare, A. and Griveaud, C., 2005. Live foraminiferal faunas from a 2800 m deep lower canyon station from the Bay of Biscay: Faunal response to focusing of refractory organic matter. *Deep Sea Research Part I: Oceanographic Research Papers*, 52, 1189-1227.

Fontanier, C., Jorissen, F., Anschutz, P. and Chaillou, G., 2006. Seasonal variability of benthic foraminiferal faunas at 1000 M depth in the Bay of Biscay. *Journal of Foraminiferal Research*, 36, 61-76.

Jones, R.W., 1994. *The Challenger foraminifera*. Oxford University Press, 142 pp.

Jorgensen, B. B., and Revsbech, N. P., 1989. Oxygen uptake, bacterial distribution, and carbon-nitrogen-sulfur cycling in sediments from the Baltic Sea-North Sea transition. *Ophelia*, 31, 29-49.

Jorissen, F.J., 1987. The distribution of benthic foraminifera in the Adriatic Sea. *Marine Micropaleontology*, 12, 21-48.

Jorissen, F.J., 1988. Benthic foraminifera from the Adriatic Sea; Principles of phenotypic variation. *Utrecht Micropaleontology Bulletin*, 37, 176 pp.

Jorissen, F.J., 1999. Benthic foraminiferal microhabitats. In: Sen Gupta B.K. (editor), *Modern foraminifera*. Kluwer Academic Publishers, pp. 161-179.

Jorissen, F.J., Barmawidjaja, D.M., Puskaric, S. and van der Zwaan, G.J., 1992. Vertical distribution of benthic foraminifera in the northern Adriatic Sea, The relation with the organic flux. *Marine Micropaleontology* 19, 131-146.

Jorissen, F.J., De Stigter, H.C., Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology* 26, 3-15.

Jorissen, F.J., Wittling I., Peypouquet J.P., Rabouille C., Relexans, J.C., 1998. Live benthic foraminiferal faunas off Cap Blanc, NW Africa: community structure and microhabitats. *Deep-Sea Research I*, 45, 2157-2188.

Kitazato, H. 1994. Foraminiferal microhabitats in four marine environments around Japan. *Marine Micropaleontology*, 24, 29-41.

Kitazato, H., Shirayama Y., Nakatsuka T., Fujiwara S., Shimanaga M., Kato Y., Okada Y., Kanda J., Yamaoka A., Masukawa T., Suzuki, K., 2000. Seasonal phytodetritus deposition and responses of bathyal benthic foraminiferal populations in Sagami Bay, Japan: preliminary results from "Project Sagami 1996-1999". *Marine Micropaleontology*, 40, 135-149.

Lacombe, H., Tchernia, P., 1972. Caractères hydrologiques et circulation des eaux en Méditerranée. In: Stanley, D.J. (Ed.). *The Mediterranean Sea: A Natural Sedimentation Laboratory*, Dowden, Hutchinson and Ross, Stroudsburg, pp. 25-36.

Langezaal, A.M., van Bergen, P.F. and van der Zwaan, G.J., 2004. The recovery of benthic foraminifera and bacteria after disturbance: experimental evidence. *Journal of Experimental Marine Biology and Ecology*, 312, 137-170.

Langezaal, A.M., Jorissen, F.J., Braun, B., Chaillou, G., Fontanier, C., Anschutz, P., van der Zwaan, G.J., 2006. The influence of seasonal processes on geochemical profiles and foraminiferal assemblages on the outer shelf of the Bay of Biscay. *Continental Shelf Research*, 26, 1730-1755.

Lansard, B., Rabouille, C. and Massias, D., 2003. Variability in benthic oxygen fluxes during the winter-spring transition in coastal sediments: an estimation by in situ micro-electrodes and laboratory mini-electrodes. *Oceanologica Acta*, 26, p. 269-279.

Levy, A., Mathieu, R., Poignant, A., Rosset-Moulinier, M., Ubaldo, M.d.L. and Ambroise, D., 1993. Recent foraminifera from the continental margin of Portugal. *Micropaleontology*, 39, 75-87.

Lévy, M., Mémery, L., Madec, G., 1999. The onset of the spring bloom in the MEDOC area: mesoscale spatial variability. *Deep Sea Research I*, 46, 1137-1160.

Licari, L. N., Schumacher, S., Wenzhöfer, F., Zabel, M., Mackensen, A., 2003. Communities and microhabitats of living benthic foraminifera from the tropical East Atlantic: impact of different productivity regimes: *Journal of Foraminiferal Research*, 33, 10-31.

Loeblich, A.R., and Tappan, H., 1964. *Foraminiferal genera and their classification*. Van Nostrand Reinhold Co., New York, 2 vol. 970+847 pp.

Loubere, P., 1991. Deep sea benthic foraminiferal assemblage response to a surface ocean productivity gradient: A test. *Paleoceanography*, 6, 193-204.

Lutze, G.F., and Thiel, H., 1989. Epibenthic foraminifera from elevated microhabitats: *Cibicoides wuellerstorfi* and *Planulina ariminensis*. *Journal of Foraminiferal Research*, 19, 153-158.

Linke, P., Lutze, G.F., 1993. Microhabitat preferences of benthic foraminifera — a static concept or a dynamic adaptation to optimize food acquisition?. *Marine Micropaleontology*, 20, 215-234.

Mackensen, A., Douglas, R.G., 1989. Down-core distribution of live and dead deep-water benthic foraminifera in box cores from the Weddell Sea and the California continental borderland. *Deep-Sea Research*, 36 (6), 879-900.

Meyers, M. B., Fossing, H., Powell, E. N., 1987. Microdistribution of interstitial meiofauna oxygen and -sulfide gradients, and the tubes of macro-infauna. *Marine Ecology Progress Series*, 35, 223-241.

Meyers, M. B., Powell, E. N., Fossing, H., 1988. Movement of oxybiotic and thiobiotic meiofauna in response to changes in pore-water oxygen and sulfide gradients around macro-infaunal tubes. *Marine biology*, 98, 395-414.

Millot, C., 1990. The Gulf of Lions' hydrodynamics. *Continental and Shelf Research*, 10 (9-11), 885-894.

Moodley, L. and Hess, C., 1992. Tolerance of Infaunal Benthic Foraminifera for Low and High Oxygen Concentrations. *Biology Bulletin*, 183, 94-98.

Monaco, A., Biscaye, A., Soyer, J., Pocklington, R., Heussner, S., 1990. Particle fluxes and ecosystem response on a continental margin: the 1985–1988 Mediterranean ECOMARGE experiment. *Continental and Shelf Research*, 10 (9-11), 809-839.

Morel, A., André, J.-M., 1991. Pigment distribution and primary production in the western Mediterranean as derived and modeled from Coastal Zone Scanner observations. *Journal of Geophysical Research*, 96, 12 685-12 698.

Morigi, C., Jorissen, F.J., Gervais, A., Guichard, S. and Borsetti, A.M., 2001. Benthic foraminiferal faunas in surface sediments off NW Africa: relationship with the organic flux to the ocean floor. *Journal of Foraminiferal Research*, 31, 350-368.

Morigi, C., Jorissen, F.J., Fraticelli S., Horton, B. P., Principi, M., Sabbatini, A., Capotondi, L., Curzi, P. V. and Negri, A., 2005. Benthic foraminiferal evidence for the formation of the Holocene mud-belt and bathymetrical evolution in the central Adriatic Sea. *Marine Micropaleontology*, 57, 25-49.

Murray, J.W., 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman Scientific & Technical, Harlow, 397pp.

Ohga, T., Kitazato, H., 1997. Seasonal changes in bathyal foraminiferal populations in response to the flux of organic matter (Sagami Bay, Japan). *Terra Nova*, 9, 33-37.

Parker, F.L., 1964. Foraminifera from the experimental Mohole drilling near Guadalupe Island, Mexico: *Journal of Paleontology*, 38, 617-637.

Petrenko, A., Leredde, Y., Marsaleix, P., 2005. Circulation in a stratified and wind-forced Gulf of Lions, NW Mediterranean Sea: in situ and modelling data. *Continental Shelf Research*, 25, 7–27.

Rabouille, C., Denis, L., Dedieu, K., Stora, G., Lansard, B. and Grenz, C. 2003. Oxygen demand in coastal marine sediments: comparing in situ microelectrodes and laboratory core incubations. *Journal of Experimental Marine Biology and Ecology*, 285-286, 49-69.

Rathburn, A.E. and B.H. Corliss, 1994. The Ecology of Living (Stained) Benthic Foraminifera from the Sulu Sea. *Paleoceanography*, 9, (1): 87-150.

Rathburn, A.E., B.H. Corliss, K. D. Tappa, and K.C. Lohmann, 1996. Comparisons of the Ecology and Stable Isotopic Compositions of Living (Stained) Deep-Sea Benthic Foraminifera from the Sulu and South China Seas. *Deep-Sea Research*, 43, 1617-1646.

Risgaard-Petersen, N., Langezaal, A.M., Ingvarsen, S., Schmid, M.C., Jetten, M.S.M., Op den Camp, H.J.M et al., 2006. Evidence for complete denitrification in a benthic foraminifer. *Nature*, 443, 93–96.

Rutgers v. d. Loeff, M. M., 1990. Oxygen in Pore Waters of Deep- Sea Sediments. *Philosophical Transactions of the Royal Society of London*, A331, 69-84.

Schiebel, R., 1992. Rezente benthische Foraminiferen in Sedimenten des Schelfes und oberen Kontinentalhanges im Golf von Guinea (Westafrika). *Berichte Geologisch-Paläontologisches Institut und Museum Christian-Albrechts-Universität Kiel, Deutschland*, n° 51, 126 pp.

Schmiedl, G., de Bovée, F., Buscail, R., Charrière, B., Hemleben, C., Medernach, L., Picon, P., 2000. Trophic control of benthic foraminiferal abundance and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea. *Marine Micropaleontology*, 40, 167-188.

Sen Gupta, B.K. and Machain-Castillo, M.L., 1993. Benthic foraminifera in oxygen-poor habitats. *Marine Micropaleontology*, 20, 183-201.

Thomas, E., Gapotchenko, T., Varekamp, J.C., Mécay, E.L., Buchholz ten Brink, M.R., 2000. Benthic foraminifera and environmental changes in Long Island Sound. *Journal of Coastal Research*, 16, 641–655.

Van Voorthuysen, J.H. 1973. Foraminiferal ecology in the Ria de Arosa, Galicia, Spain. *Zoologische Verhandelingen*, 123, 1-68.

Zegouagh, Y., Derenne, S., Largeau, C., Bertrand, P., Sicre, M.A., Saliot, A., Rousseau B., 1999. Refractory organic matter in sediments from the North-West African upwelling system: abundance, chemical structure and origin. *Organic Geochemistry*, 30, 101-117.





## **CHAPITRE 4. COMPARISON BETWEEN DEAD AND LIVING BENTHIC FORAMINIFERAL FAUNAS IN THE RHÔNE PRODELTA**

<b>RÉSUMÉ</b> .....	185
<b>4.1 ABSTRACT</b> .....	188
<b>4.2 INTRODUCTION</b> .....	188
<b>4.3 MATERIAL AND METHODS</b> .....	191
<b>4.4 RESULTS</b> .....	194
<b>4.5 DISCUSSION</b> .....	204
<b>4.6 CONCLUSIONS</b> .....	207
<b>4.7 REFERENCES</b> .....	208
<b>APPENDICES</b> .....	211



## RÉSUMÉ

La comparaison entre les faunes mortes et les faunes vivantes des foraminifères benthiques dans le prodelta de Rhône suggère que les différences existant entre ces deux groupes sont déterminées, au moins partiellement, par les fluctuations épisodiques des décharges du fleuve du Rhône. Les faunes mortes ainsi que les faunes vivantes décrivent trois principaux biofaciès: 1) une zone située en face de l'embouchure, 2) une zone influencée par le panache du fleuve et 3) une zone plus ou moins abritée de l'influence de fleuve. La distribution spatiale des pourcentages cumulatifs de chaque assemblage des faunes vivantes et des faunes mortes, dominant ces trois biofaciès, suggère que la situation géographique moyenne dans le temps du panache du fleuve est peut être différente de sa localisation en Juin 2005 au moment où les faunes vivantes ont été échantillonnées. Les assemblages morts décrivent une extension vers l'ouest du panache du fleuve à sa sortie du Rhône, tandis que, au moment de l'échantillonnage, le panache prendrait une direction sud-ouest. Les faunes vivantes décrivent également une plus grande extension du panache qui pourrait être une conséquence de l'importante décharge fluviale enregistrée environ 2 mois avant les prélèvements. Deux espèces, *Nonion scaphum* et *Rectuvigerina phlegeri*, semblent répondre à cet apport épisodique important de matière organique, en présentant des abondances relatives beaucoup plus importantes dans les faunes vivantes que dans les faunes mortes. Nous proposons que ces espèces montrent une réponse fortement opportuniste au fort apport de matière organique provoquée par la décharge du fleuve. Cette étude suggère donc que des informations écologiques importantes pourraient être obtenues grâce à la comparaison des faunes vivantes et des faunes mortes des foraminifères benthiques dans le prodelta du Rhône.

**Mots clés:** Foraminifères benthiques; faunes mortes; faunes vivantes; espèces opportunistes; panache du fleuve; biofaciès.



## **CHAPITRE 4. COMPARISON BETWEEN DEAD AND LIVING BENTHIC FORAMINIFERAL FAUNAS IN THE RHÔNE PRODELTA**

M. Mojtahid \* and F. Jorissen \*

\* Laboratoire des Bio-Indicateurs Actuels et Fossiles (BIAF) UPRES EA 2644, Université d'Angers. 2, Boulevard Lavoisier, 49045 Angers Cedex, France, and Laboratoire d'Étude des Bio-Indicateurs Marins (LEBIM). Ker Chalon, 85350 Ile D'Yeu, France.

Ce chapitre correspond à un article en cours de préparation pour la revue *Journal of Foraminiferal Research*.

**Keywords:** Benthic foraminifera; dead faunas; living faunas; opportunistic species; river plume; biofacies.

## 4.1 ABSTRACT

A comparison of live and dead benthic foraminiferal faunas from the Rhône prodelta suggests that differences between living and dead foraminiferal faunas are, at least partially, determined by episodic fluctuations of the Rhône river discharge. Dead as well as living foraminiferal faunas are distributed in three major biofacies: 1) an area located in front of the river mouth, 2) an area influenced by the river plume and 3) an area more or less sheltered from the river influence. The spatial distribution of the cumulative percentages of each assemblage of dead and living faunas, dominating these three biofacies, suggests that the time-averaged geographic location of the river plume may be different from its location during sampling in June 2005 when the living faunas were sampled. The dead assemblages suggest that the river plume generally spreads in a western direction while, at the time of sampling, it extended in a southwestern direction. Moreover, the living faunas describe larger extension of the river plume that may be a consequence of the important discharge recorded about 2 months before the sampling time. Two species, *Nonion scaphum* and *Rectuvigerina phlegeri*, seem to respond to this episodically important input of organic matter, by presenting much higher relative abundances in the living faunas than in the dead faunas. We suggest that these species show a highly opportunistic response to the strong organic matter input caused by river outflow. This study proposes therefore that important ecological information in the Rhône prodelta can be gained from comparisons of living and dead foraminiferal faunas.

## 4.2 INTRODUCTION

The wide distribution of benthic foraminifera both in space and geological time, their rapid response to ecological change and their ability to secrete carbonatic shells that leave excellent record in the sediment make them probably the best microfossil group for studying benthic processes. For instance, subrecent foraminifera have been used to investigate environmental change over the last few hundred years (Murray, 1991). However, all applications of benthic foraminifera to interpret the geological record (stratigraphy, palaeoceanography, palaeoecology) and to monitor modern environments must be based on careful considerations of their ecology. Living assemblages are short-lived, and temporal changes in absolute and relative abundance of species occur in relation to seasonal or longer fluctuations of environmental parameters. In spite of their exceptionally good fossilization

potential, also benthic foraminiferal faunas are often strongly biased by taphonomical processes. Taphonomic processes may change the composition from living to dead fossil assemblage (Murray, 1991; Jorissen and Wittling, 1999). Because of their small size, foraminiferal tests are especially prone to processes responsible for differences between dead and living faunas, such as transport and dissolution. Along with a complex of strictly taphonomical processes, there are also a number of more biological factors that can cause large differences between the living fauna present at a certain site and the dead fauna, which ultimately is going to be fossilized there. Even without significant alteration by taphonomical processes, factors such as interspecific differences in turnover rate, seasonal differences in standing stock, and patchiness, can result in considerable differences between the time-averaged dead fauna and the living fauna at the same site. The careful study of the differences between living and dead faunas can give us clues about the population dynamics of individual species and seasonal fluctuations of the faunal composition and can help us to better understand the ecological strategies of key species and the functioning of the ecosystem as a whole (Murray, 1991; Jorissen and Wittling, 1999). Also, in areas with important seasonal variation (for instance, in organic flux or in bottom water oxygenation), a time-averaged mixture will be formed. Time-averaging also cancels out patchiness, which may be significant in the living fauna (Bernstein et al., 1978).

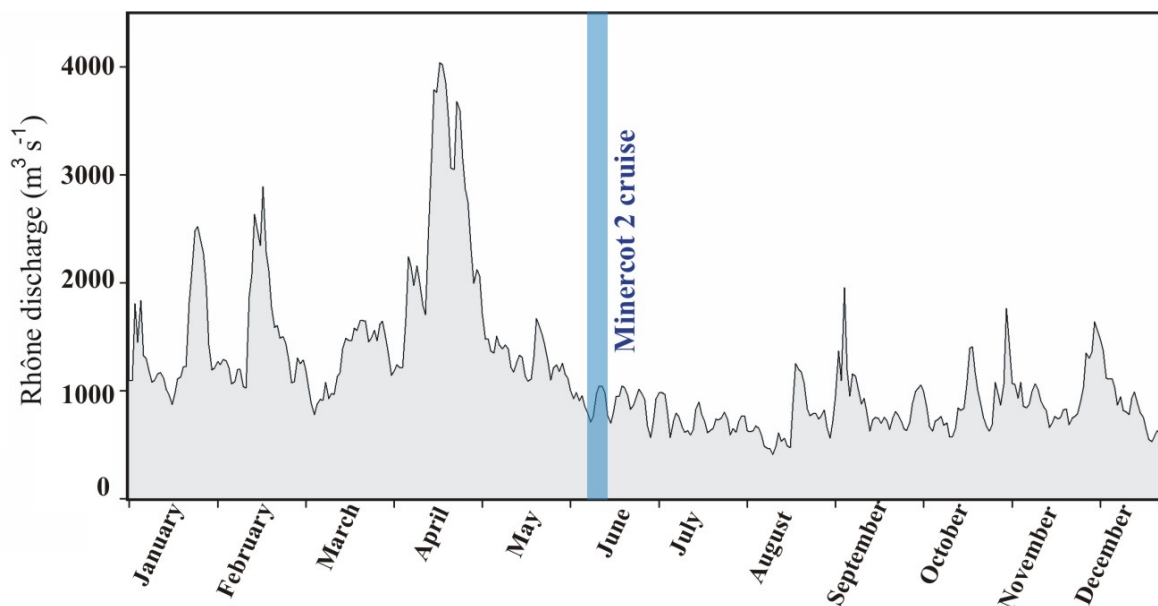


Figure 4-1. Mean daily Rhône river discharge recorded in 2005 by the Compagnie Nationale du Rhône in Beaucaire, located 65 km upstream from the river mouth. The MINERCOT 2 cruise (June 2005) is indicated by red line.



In the present study, we will compare living and dead benthic foraminiferal faunas from the Rhône prodelta. This area is under the direct influence of the Rhône river input. The river contribution in organic matter and nutrients is more or less important depending on the episodic river floods that are mainly related to the rainfall on the continent. Several authors have suggested that benthic foraminiferal faunas are to a large extent structured by the organic flux and its intermittency (e.g. *Gooday, 1988; Altenbach and Sarnthein, 1989; Lambshead and Gooday, 1990; Linke and Lutze, 1993; Jorissen et al., 1995*). In the Rhône prodelta, the organic matter originates from different sources including continental sources and marine biological production (*Gadel et al., 1990; Monaco et al., 1990; Buscail and Germain, 1997*). During autumn and winter, the inflow of detritic organic matter episodically increases due to abundant river runoff. Primary production is highly seasonal and is mainly triggered by the input of nutrients of the Rhône River, the shoaling of the mixed layer, and the availability of sunlight. Therefore, elevated phytoplankton concentrations and corresponding blooms are observed particularly during spring (March through early May) and are highest in the eastern part of the Gulf of Lions (*Cruzado and Velasquez, 1990; Morel and André, 1991; Arnone, 1994; Lévy et al., 1999*). During sampling in June 2005, the Rhône discharge was about  $1000 \text{ m}^3 \text{ s}^{-1}$ . Samples were taken approximately 2 months after the most important river discharge of 2005 ( $4000 \text{ m}^3 \text{ s}^{-1}$ ) (Fig. 4-1). The Rhône River discharges into the Gulf of Lions forms a visible plume of turbid waters that extends up to a distance of 100 Km. The direction of spreading of the river plume is mainly determined by the hydrodynamic environment (cyclonic Liguro-Provencal Current) and the wind regimes (Mistral and Tramontane). Due to the Rhône river supplies, a decreasing gradient of organic carbon and total nitrogen is present from the river mouth ( $C_{\text{org}} \sim 1.80 \text{ \% d.w.}$ ;  $N_{\text{tot}} \sim 0.21 \text{ \% d.w.}$ ) to the deepest stations ( $C_{\text{org}} \sim 0.80 \text{ \% d.w.}$ ;  $N_{\text{tot}} \sim 0.13 \text{ \% d.w.}$ ). The C/N ratio and the  $\delta^{13}\text{C}$  of the organic matter describe a change in the quality of the organic carbon with a clear tendency from a strong terrestrial signature close to the river mouth ( $C/N \sim 10.00$ ;  $\delta^{13}\text{C} \sim -27 \text{ ‰}$ ) gradually changing into a more marine signature towards the farthest stations ( $C/N \sim 6.00$ ;  $\delta^{13}\text{C} \sim -23 \text{ ‰}$ ). Because of the preferentially southwestern direction of the Rhône river plume during the time of sampling, the eastern part of the prodelta is more or less sheltered from river influence. This asymmetric distribution is clearly shown by the geographical distribution of organic carbon, the C/N ratio and the  $\delta^{13}\text{C}$  of the organic matter and also by oxygen penetration into the sediment which is a reflection of oxygen demand needed for organic matter recycling. This last parameter shows high values close to the river mouth (Diffusive  $\text{O}_2 \sim 28.00 \text{ mmol/m}^2/\text{d}$ ) where the oxygen penetration is minimal ( $\sim 1.50 \text{ mm}$ ) and gradually decreases towards the

farthest stations. The decrease in oxygen demand is stronger towards the eastern stations where minimal values are observed (Diffusive  $O_2 \sim 4.00 \text{ mmol/m}^2/\text{d}$ ), and where the thickness of the oxic zone is maximal ( $\sim 8.00 \text{ mm}$ ). We expected to find the same trend in bottom water oxygenation with low values near the river mouth gradually increasing towards the farthest stations. However, in the Rhône prodelta, the tendency is inverted. The high bottom-water oxygen concentrations close to the river mouth could be due to the strong hydrodynamics in this area. Consequently, benthic environments in this area are well oxygenated in spite of the important organic matter supply to this zone. At station 4 in the Rhône prodelta (Fig. 4-2), the measurement of the activity of the natural radionuclide  $^{210}\text{Pb}$ , that has a 22.3 yr half time, allows the estimation of a sedimentation rate of about  $0.6 \text{ cm/y}$ .

In the present chapter, we will show that a comparison of live and dead benthic foraminiferal assemblages can give important clues about the variations of the organic flux to the benthic ecosystem, and about the faunal response to this variation.

### 4.3 MATERIAL AND METHODS

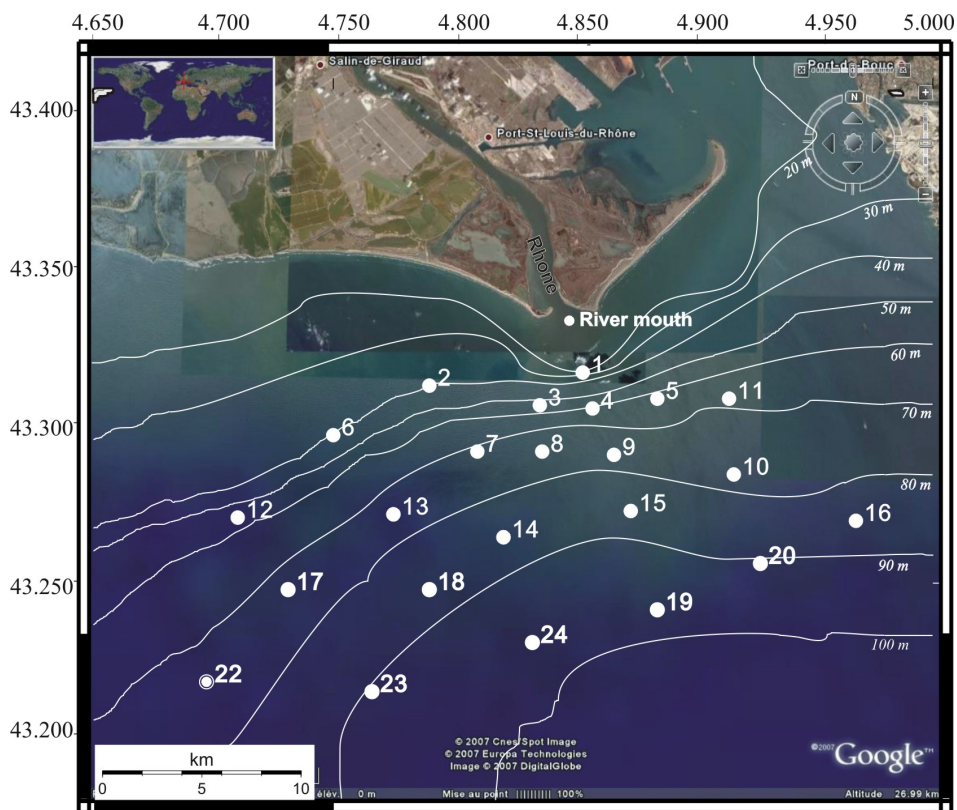


Figure 4-2. Sampling locations and water depths.

During a cruise of the French research vessel *Tethys II*, sediment cores of 15 cm internal diameter were collected in June 2005 at twenty three sites in the Rhône prodelta in the northeastern Gulf of Lions (western Mediterranean Sea) (Fig. 4-2). Sediments were collected using a Bowers and Connelly Mark VI multicorer between 20 and 98 m water depths. For the analysis of their foraminiferal content, the sampled cores were sliced onboard until 5 centimetres depth. For stations 1, 3, 4, 7, 9, 13, 14, 15, 17, 19 and 22, the cores were sliced into 0.5 cm levels down to 2 cm depth and then in 1 cm levels down to 5 cm depth. For the other stations, the cores were sliced into four intervals: 0-0.5, 0.5-1, 1-2 and 2-5 cm. All samples were preserved in 95 % ethanol with 1 g/l Rose Bengal. In the laboratory, the collected samples were sieved over sieves of 63 and 150  $\mu\text{m}$  openings. For the fraction larger than 150  $\mu\text{m}$ , living (stained) foraminifera from all levels (until 5 cm depth) were hand-sorted under a binocular microscope under wet conditions (50% ethanol). To gain more insight into the population dynamics, we investigated the dead (unstained) foraminifera in the 3-4 cm or 2-5 cm levels (depending on stations; see appendix 4-1) for the  $> 150 \mu\text{m}$  fraction at all stations (except 11 and 17 where the sediment for dead faunal analysis was lost). At this sediment depth we expected a strong decrease of taxa with rapidly decomposing tests (especially some arenaceous taxa), and also a more correct representation of deeper living infaunal species, that could be under-represented in superficial dead faunas (*Loubere, 1989*). If necessary, samples were split with an Otto-microsplitter, and a minimum of 200 to 300 specimens were collected. All foraminifera selected were determined using commonly used taxonomic reference works (e.g. *Parker, 1964; Loeblich and Tappan, 1964; Jones, 1994, etc.*) and taxonomic studies treating similar eutrophicated shelf environments (e.g. *Jorissen, 1988; Barmawidjaja, 1991; Schiebel, 1992*).

In order to better show spatial patterns of faunal variability, we applied a Principal Component Analysis (*StatSoft, Inc. (2004). STATISTICA (data analysis software system), version 7. www.statsoft.com.*) to the dead and living foraminiferal ( $> 150 \mu\text{m}$  fraction) percentage data. Cluster analyses were performed on the basis of non-standardized percentage data (*Davis, 1986*). Only taxa occurring with more than 5% in at least one sample were retained in these PCA and Cluster analyses. In order to enhance foraminiferal data visualization, geo-referenced contour maps of spatial distribution using a grid based contour program, Surfer for Windows (*Golden Software; version 6.02*), were performed. For each station, the Shannon Wiener index (H) was calculated according to:

$$H = -\sum_{i=1}^s pi \ln pi$$



## 4.4 RESULTS

The study of dead faunas provides a time-averaged picture that may inform us about the ecological environment that occurs in general in the Rhône prodelta. The composition of these subrecent faunas, present at several centimetres depth in the sediment can be studied thanks to the preservation of carbonatic foraminiferal shells after the death of the organism. The comparison between these subrecent fossil faunas and the living faunas allow us to determine how the recent distributional pattern is inscribed in the fossil faunas. It may also enable us to recognize opportunistic species. This knowledge will yield essential information about how the fossil faunas, in such river-induced prodelta environments, can be used to reconstruct the past conditions in these areas.

A principal component analyses has been performed on the basis of the percentage data for dead as well as for living foraminifera in the  $> 150 \mu\text{m}$  fraction of all taxa occurring with more than 5 % in at least one sample (dead foraminiferal analyses at stations 11 and 17 are not available) (Table 4-1). Station 1 is not represented in the dead faunal analyses due to the presence of only one individual of the species *Quinqueloculina seminula* forma *longa*. The results of this PCA are presented in table 4-3 and in figure 4-3. Axis 1 (Eigenvalue = 5.98), axis 2 (Eigenvalue = 3.45) and axis 3 (Eigenvalue = 2.47) account respectively for 35.2 %, 20.3 % and 14.5 % of the total variation in the dataset of the dead fauna whereas in the living fauna, axis 1 (Eigenvalue = 5.80), axis 2 (Eigenvalue = 3.58) and axis 3 (Eigenvalue = 2.42) account respectively for 30.5 %, 18.8 % and 12.7 % of the total variation in the dataset.

Dead fauna				Living fauna			
Axis number	Eigenvalue	% Total variance	Cumulative % of variance	Axis number	Eigenvalue	% Total variance	Cumulative % of variance
1	5.98	35.2	35.2	1	5.80	30.5	30.5
2	3.45	20.3	55.5	2	3.58	18.8	49.4
3	2.47	14.5	70.0	3	2.42	12.7	62.1
4	1.59	9.3	79.3	4	1.69	8.9	71.1
5	1.18	6.9	86.3	5	1.22	6.4	77.5
6	0.75	4.4	90.7	6	1.10	5.8	83.3
7	0.52	3.1	93.7	7	0.93	4.8	88.2
8	0.41	2.4	96.1	8	0.58	3.0	91.3
9	0.25	1.5	97.6	9	0.46	2.4	93.8
10	0.14	0.8	98.5	10	0.35	1.8	95.7

Table 4-3. Results of a Principal Component Analysis based on the percentages of dead and living foraminifera ( $> 5\%$ ) in the  $> 150 \mu\text{m}$  fraction.

Figures 4-3 (a) and (c) show the position of the species on the first two PCA axes for dead and living foraminifera; in figures 4-3 (b) and (d), the position of the samples on the axial plot.

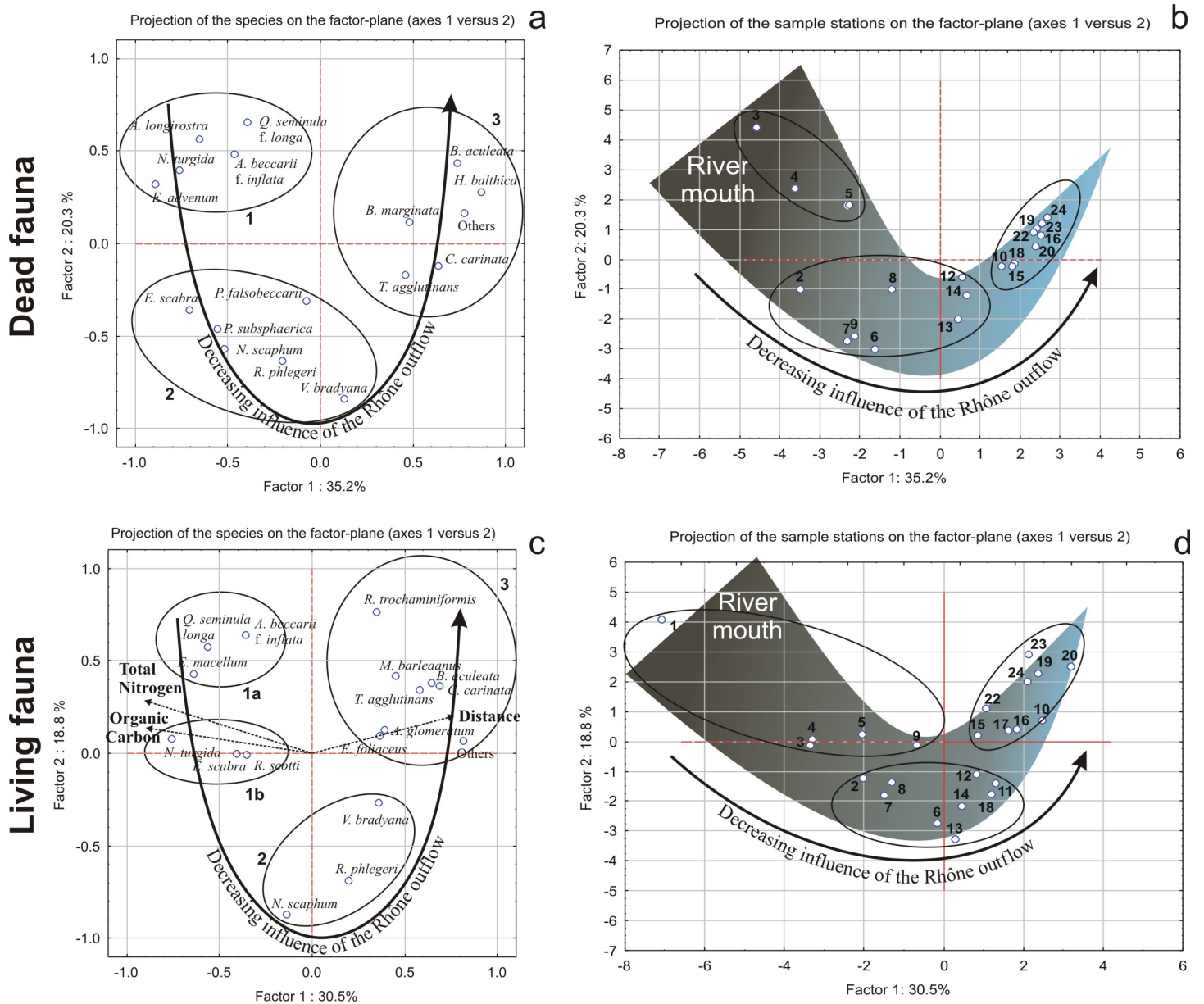


Figure 4-3. Principal Component Analysis. a. projection of the variables (dead foraminifera, taxa > 150  $\mu\text{m}$ ) on the first two PCA axes. Three assemblages are recognised; b. Score plot of 20 stations (dead foraminifera, taxa > 150  $\mu\text{m}$ ) on the first two PCA axes and indication of decreasing river influence. Station 1 is not represented because of the near absence of specimens (1 ind./100cm<sup>2</sup>); c. projection of the variables (living foraminifera, taxa > 150  $\mu\text{m}$ ) on the first two PCA axes. Four assemblages are recognised; d. Score plot of 23 stations (living foraminifera, taxa > 150  $\mu\text{m}$ ) on the first two PCA axes and indication of decreasing river influence.

Three major assemblages can be distinguished in the dead fauna. Assemblage 1, that has negative loadings on the first axis and positive loadings on the second PCA axis, is composed of *Ammonia beccarii* forma *inflata*, *Elphidium advenum*, *Nonionella turgida*, *Adelosina longirostra* and *Quinqueloculina seminula* forma *longa*. This assemblage is mainly present at stations 3, 4 and 5 that are located in the vicinity of the river mouth. Assemblage 2 composed of *Nonion scaphum*, *Pseudoepionides falsobeccarii*, *Rectuvigerina phlegeri*, *Valvulineria bradyana*, *Pyrgo subsphaerica* and *Eggerella scabra* has negative loadings on the second axis. This assemblage is mainly present at stations 2, 6, 7, 8, 9, 12, 13 and 14. Assemblage 3 that has positive loadings on the first axis is composed of *Bulimina aculeata*, *Bulimina marginata*, *Cassidulina carinata*, *Hyalinea balthica* and *Textularia agglutinans*. This assemblage dominates stations 10, 15, 16, 18, 19, 20, 22, 23 and 24.

Also in the living fauna, we can distinguish, according to the PCA analysis, three major assemblages with two sub-assemblages (1a and 1b). Assemblage 1a, that has negative loadings on the first PCA axis and positive loadings on the second PCA axis, is composed of the species *Ammonia beccarii* f. *inflata*, *Elphidium macellum* and *Quinqueloculina seminula* f. *longa*. This assemblage is mainly present at station 1. Assemblage 1b composed of *Nonionella turgida*, *Eggerella scabra* and *Reophax scottii* has negative loadings on the first PCA axis and is characteristic of stations 3, 4, 5 and 9, whereas assemblage 3 composed of the species *Bulimina aculeata*, *Cassidulina carinata*, *Melonis barleeanus*, *Adercotryma glomeratum*, *Eratidus foliaceus*, *Reophax trochaminiformis* and *Textularia agglutinans* has a positive contribution to both axes. This assemblage dominates the foraminiferal fauna at stations 10, 15, 16, 17, 19, 20, 22, 23 and 24. *Nonion scaphum*, *Rectuvigerina phlegeri* and *Valvulineria bradyana*, composing assemblage 2, have negative loadings on the second PCA axis. This assemblage is mainly present at stations 2, 6, 7, 8, 11, 12, 13, 14 and 18.

Both figures 4-3 (b) and (d), which represent the position of the samples on the axial plot for, respectively, dead and living foraminifera, show a typical horse shoe distribution (Hill and Gauch, 1980; Digby and Kempton, 1987). Both dead and living faunal distribution clearly reflects a decreasing influence of the Rhône outflow from the upper left to the lower centre, to the upper right of the axis plot.

On the basis of the PCA analyses performed on the percentages of the main species found in dead and living assemblages, we can group the stations into 3 major units. In the dead fauna, stations 3, 4 and 5 belong to a zone in the vicinity of the river mouth. Stations 2,

6, 7, 8, 9, 12, 13 and 14 are located under the river plume and stations 10, 15, 16, 18, 19, 20, 22, 23 are located in the area sheltered from the river influence (Fig. 4-4). In the living fauna, stations 1, 3, 4, 5 and 9 represents the most impacted sites, in the immediate vicinity of the river mouth. 2, 6, 7, 8, 11, 12, 13, 14 and 18 are stations under the influence of the river plume during time of sampling whereas stations 10, 15, 16, 17, 19, 20, 22, 23 and 24 are more sheltered from the river influence (Fig. 4-5). The percentages of the most common species in the dead and living faunas are presented, respectively, in figures 4-4 and 4-5:

While comparing dead and living foraminiferal composition, we can observe, that in general, the dead fauna contains the same species as the living assemblages. The three major biotopes described by the living foraminiferal repartition are also depicted by the dead foraminiferal distribution in the Rhône prodelta. Despite this overall similarity, some differences exist. We can notice the presence of the species *E. advenum* in the dead assemblages in front of the river mouth whereas in living assemblages, this species is nearly absent and is replaced (especially at station 1) by the species *E. macellum* (Table 4-1). The miliolids *Pyrgo subsphaerica* and *Adelosina longirostra* and the hyaline species *Pseudoeponides falsobeccarii* are nearly absent in the living faunas whereas they are well represented in the dead assemblage. The same observation can be made for the species *B. marginata* and *H. balthica* that are under-represented in the living assemblages. The agglutinated taxa *A. glomeratum*, *E. foliaceus*, *R. trochaminiformis* and *R. scottii* which are well-represented in the living fauna nearly disappear in the dead community probably as a consequence of their low fossilisation potential. Only the arenaceous taxa *E. scabra* and *T. agglutinans* are still well represented in the dead faunas (Figs. 4-4 and 4-5).

Another difference between dead and living assemblages appears when we look at the three biofacies determined by the foraminiferal distributional pattern in the Rhône prodelta. In general, the same foraminiferal assemblages are present at the same stations for both dead and foraminiferal faunas. When looking in more detail, we can see that the fauna at station 9, which is mainly composed of taxa inhabiting the area in the immediate vicinity of the river mouth, clusters with stations located under the river plume in dead assemblages. This is mainly due to the fact that, in living assemblages, station 9 does not contain high abundances of the species *N. scaphum*. Likewise, station 18 presents living faunal composition characteristic of the biofacies under the river plume influence while the dead foraminiferal assemblage at this station is more similar to faunas found at stations sheltered from the river influence (Figs. 4-4 and 4-5). This is mainly due to the fact that the living fauna at station 18 is dominated by *N. scaphum*, which is much poorer in the dead fauna.



### Dead foraminifera

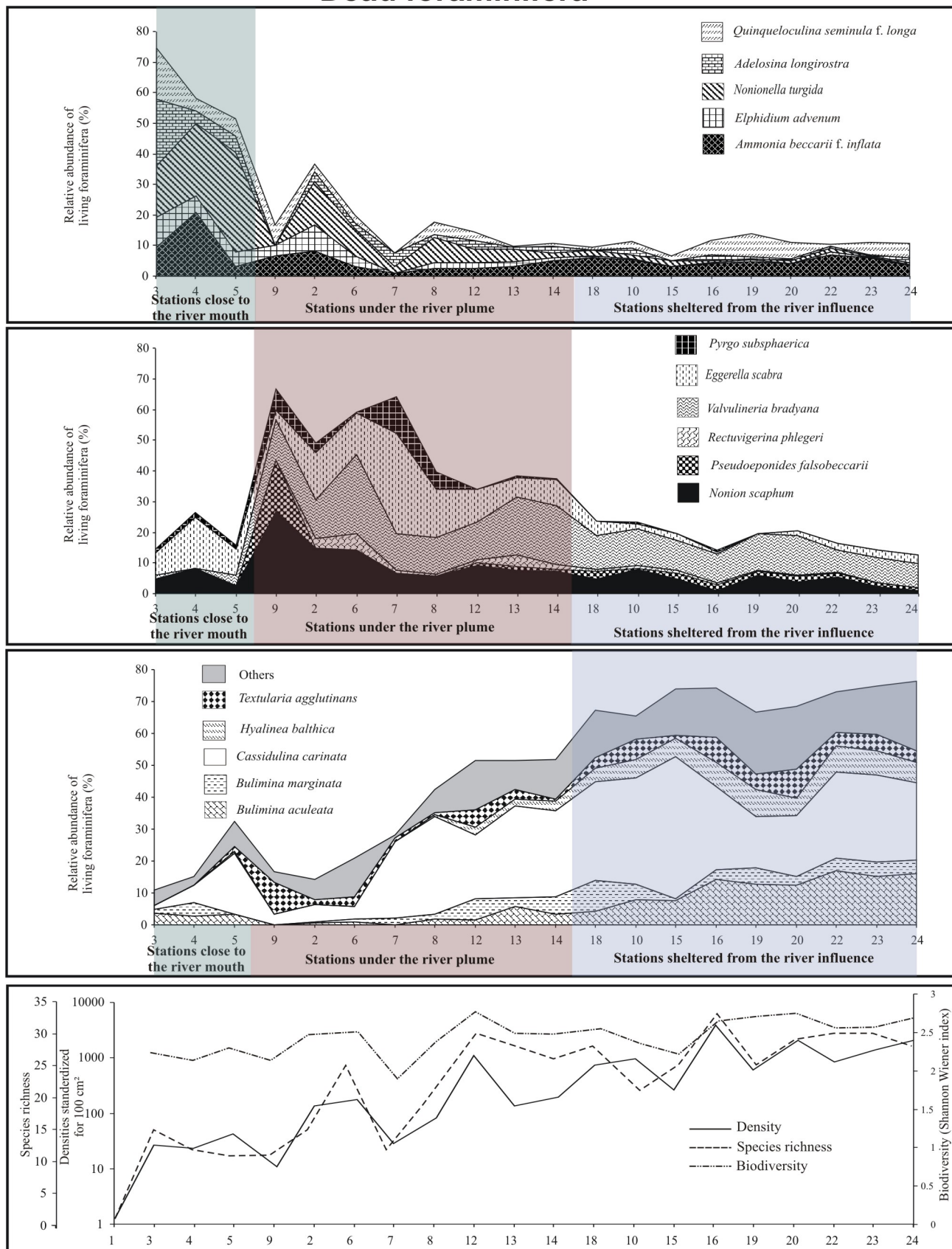


Figure 4-4. Dead foraminiferal relative abundance of the dominant taxa (> 150 μm fraction) with a relative proportion of ≥ 5% in at least one of the stations and total density (standardized for 100 cm<sup>2</sup> sediment surface), species richness (number of species) and biodiversity (Shannon Wiener index) values for 21 stations (The relative abundance at station 1 is not represented because of the near absence of specimens (1 ind./100cm<sup>2</sup>)).

### Living foraminifera

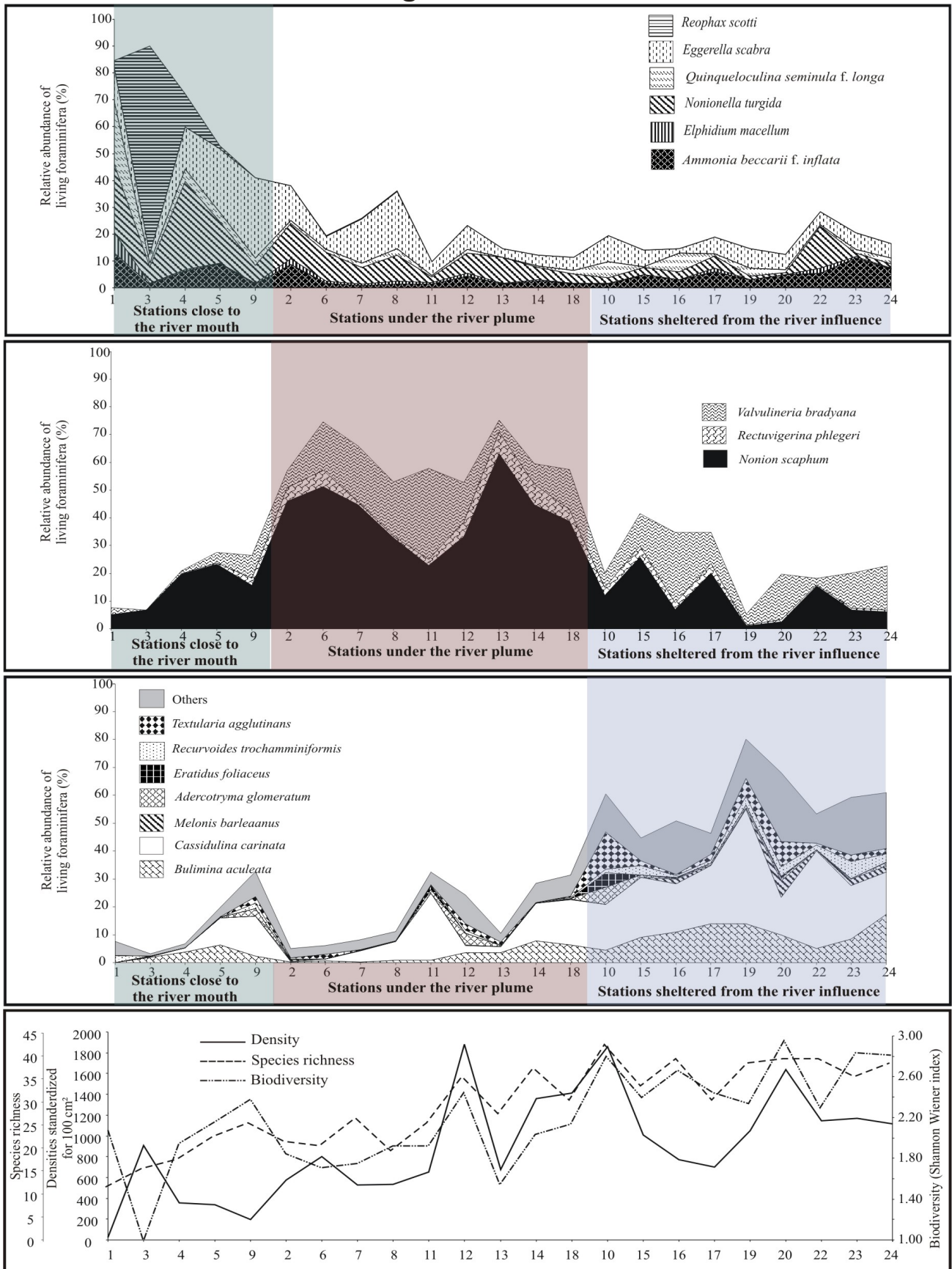


Figure 4-5. Living foraminiferal relative abundance of the dominant taxa (> 150  $\mu\text{m}$  fraction) with a relative proportion of  $\geq 5\%$  in at least one of the stations and total density (standardized for 100  $\text{cm}^2$  sediment surface), species richness (number of species) and biodiversity (Shannon Wiener index) values for the 23 stations.

To better illustrate these observations, we performed cluster analyses based on non standardized percentage data (Davis, 1986) of both dead and living assemblages (Fig. 4-6) and we plotted the cumulative percentages of each cluster on a geographical map in the aim to obtain the spatial distribution of each assemblage in the Rhône prodelta (Fig. 4-7). Indeed, when a cut-off level of 0.3 is applied, cluster shows 3 major foraminiferal assemblages for dead foraminifera and 4 for living foraminifera. It should be noticed that clusters IIIa and IIIb determined by the living assemblages are both found in the area of the Rhône prodelta that is sheltered from the river influence. Moreover, cluster IIIa concerns mainly only one station (10) situated in the eastern part of the Rhône prodelta. For these reasons, we choose to reassemble these two clusters in one major group that represents fauna from the area sheltered from the Rhône influence.

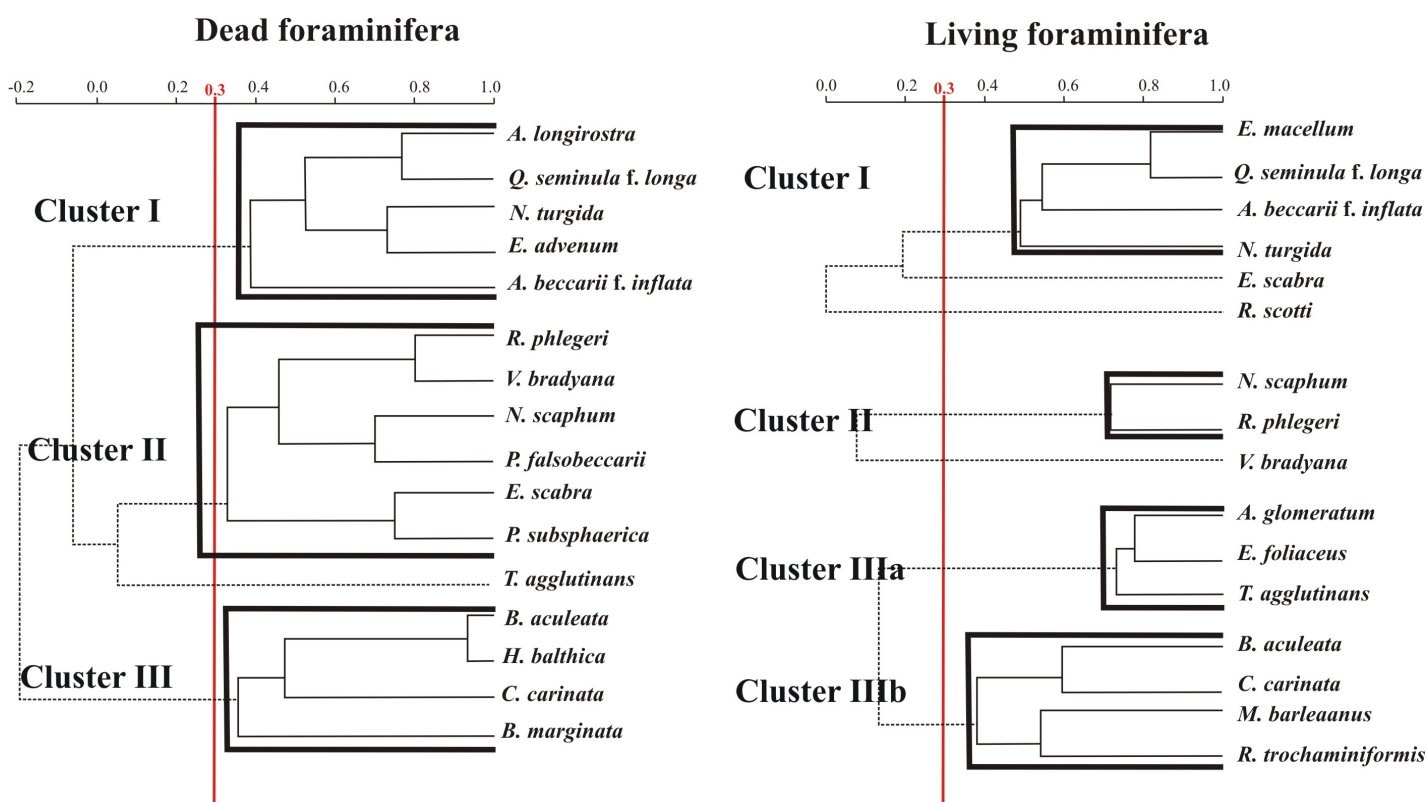


Figure 4-6. Clusters based on non-standardized percentage data of dead and living foraminifera in the  $> 150 \mu\text{m}$  fraction (Davis, 1986).

In the dead fauna: Cluster I (*A. beccarii f. inflata*, *E. advenum*, *N. turgida*, *Q. seminula f. longa* and *A. longirostra*), cluster II (*N. scaphum*, *P. falsobeccarii*, *R. phlegeri*, *V. bradyana*, *P. subsphaerica* and *E. scabra*) and cluster III (*B. aculeata*, *B. marginata*, *C. carinata* and *H. balthica*).

## Comparison dead/living foraminifera in the Rhône prodelta

In the living fauna: Cluster I (*A. beccarii* f. *inflata*, *E. macellum*, *N. turgida* and *Q. seminula* f. *longa*), cluster II (*N. scaphum* and *R. phlegeri*), cluster IIIa (*A. glomeratum*, *E. foliaceus* and *T. agglutinans*) and cluster IIIb (*B. aculeata*, *C. carinata*, *M. barleaanus* and *R. trochaminiformis*).

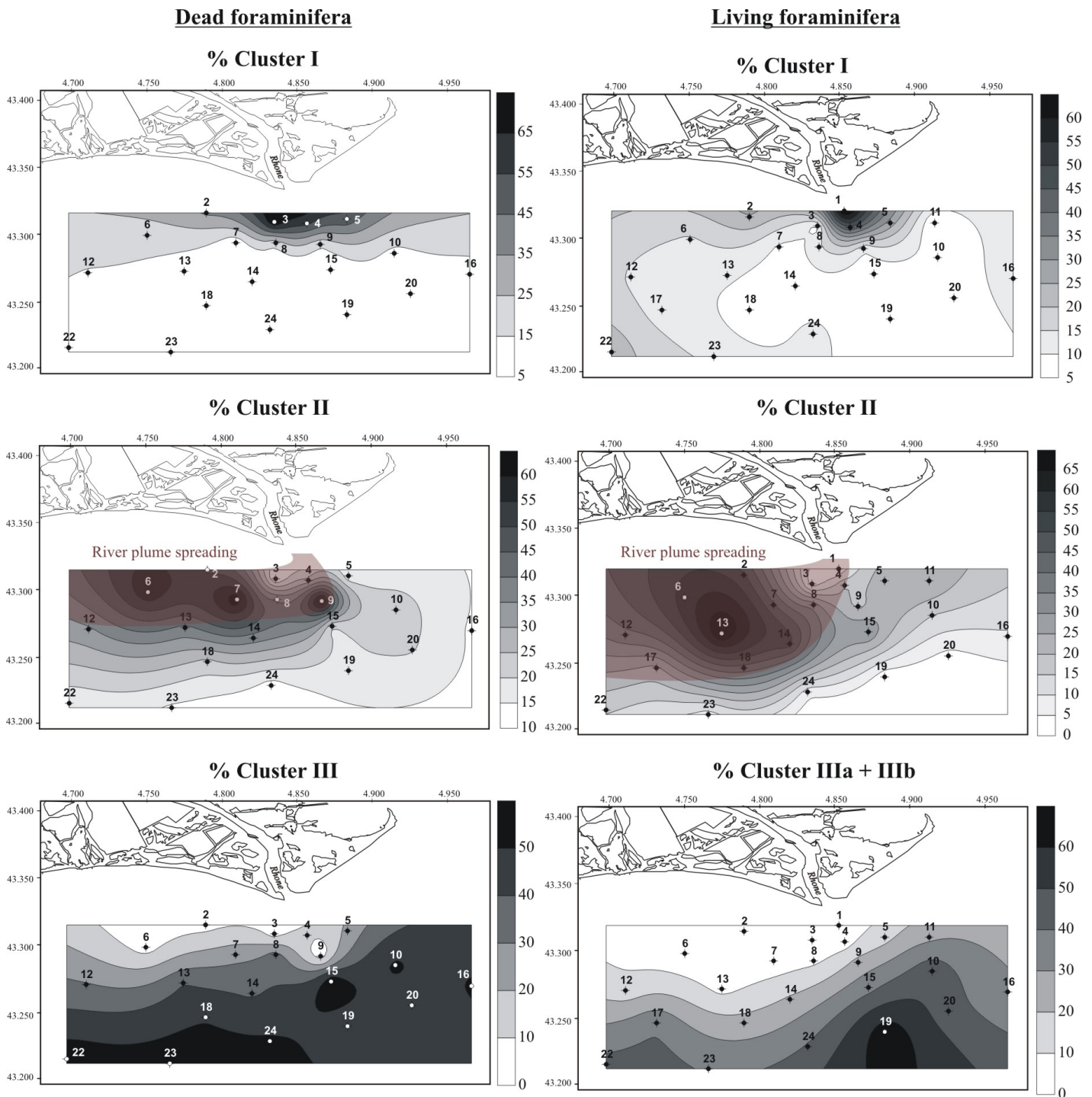


Figure 4-7. Spatial distribution of the foraminiferal assemblages of the > 150  $\mu\text{m}$  fraction recognised by cluster analyses in dead and living fauna.

The spatial distribution of the “three” determined foraminiferal groups for dead and living assemblages allows us to determine 3 major biofacies (Fig. 4-7). In general, both dead and living assemblages describe similar biotopes: 1) a biotope close to the river mouth, 2) an area influenced by the river plume and 3) an area sheltered from river influence. Since the sedimentation rate is very high in the Rhône prodelta (at station 4 ~ 0.6 cm/an), the dead fauna, which was analysed at about 4 cm sediment depth, may inform us about the environmental characteristics for some 5 to 10 years before the sampling collection. When comparing the spatial distribution of cluster II in dead and living assemblages, we can see that the dead fauna suggests that, on the average, the river plume has spread towards the west whereas the living foraminiferal fauna indicates a spreading of the river plume to the southwest (Fig. 4-7, Clusters II). We can also observe that, during the time of sampling, the river plume was farther extended to the south and west than the average situation, as shown by the dead foraminiferal cluster II. This may be a consequence of the important river discharge that occurred about 2 months before sampling (Fig. 4-1).

In the dead fauna, the foraminiferal assemblages at stations under the influence of the river plume present a high biodiversity (Shannon Wiener index ~ 3). This is mainly due to the presence in this area of 6 species, which are generally present in similar proportions (*N. scaphum*, *P. falsobeccarii*, *R. phlegeri*, *V. bradyana*, *E. scabra* and *P. subsphaerica*). Inversely, in the living assemblage that dominates the same area, the biodiversity is lower (Shannon Wiener index ~ 2), as a consequence of the strong dominance of the species *N. scaphum* (Figs. 4-4 and 4-5).

In order to better document the difference between dead and living foraminifera, especially for stations under the influence of the river plume, we calculated  $L/(L+D)$  (%Living/%(Living+Dead)) ratios for all species with a percentage larger than 5 % in either the living or dead fauna of one sample. The resulting values are presented in table 4-4. In order to correct for the taphonomical loss of some agglutinated taxa due to their rapid disintegration, we removed all non-fossilizable arenaceous taxa (*A. glomeratum*, *Clavulina cylindrica*, *Cribrostomoides* spp., *Eggerella advena*, *Eratidus foliaceus*, *Lagenammina difflugiformis*, *Reophax* spp.). Most of these species are characterized by weakly cemented tests that are easily degradable. In contrast, the arenaceous taxa *Bigenerina nodosaria*, *Eggerella scabra* and *Textularia agglutinans* are agglutinated with a stronger organic matrix and consequently they are more resistant to mechanical and chemical degradation within the sediment. Therefore, we calculated new percentages for the dead as well as for the living assemblages (Appendix 4-2). Taxa that are richer in dead fauna have values between 0.0 and

0.5, whereas taxa that are richer in the living fauna have values between 0.5 and 1.0. Values at station 1 can not be exploited because of the near absence of individuals in the dead fauna.

Stations	Stations close to river mouth					River plume area							Deepest stations										
	1	3	4	5		9	2	6	7	8	12	13	14	18	10	15	16	19	20	22	23	24	
<i>Ammonia beccarii</i> f. <i>inflata</i>	1.00	0.12	0.23	0.73		0.18	0.51						0.33	0.20	0.21			0.55	0.45	0.65	0.54		
<i>Bullimina aculeata</i>				0.66								0.39	0.71	0.60	0.36	0.54	0.43	0.52	0.44	0.23	0.35	0.53	
<i>Bullimina marginata</i>											0.16		0.10	0.06				0.06					
<i>Cassidulina carinata</i>			0.20	0.34		0.81	0.03				0.15	0.18	0.11	0.07	0.33	0.34	0.32	0.40	0.72	0.41	0.57	0.41	0.36
<i>Elphidium macellum</i>		0.04	0.08				0.18																
<i>Hyalinea balthica</i>	1.00												0.08										
<i>Melonis barlecanus</i>																							
<i>Nonion scaphum</i>	1.00	0.58	0.70	0.90		0.37	0.76	0.78	0.87	0.85	0.78	0.89	0.86	0.89	0.60	0.85	0.89	0.16		0.74	0.76	0.75	
<i>Nonionella turgida</i>	1.00	0.27	0.58	0.32		1.00	0.48	0.54	0.74	0.55	0.63	0.70									0.93		
<i>Pseudoepionides falsobeccarii</i>						0.09																	
<i>Rectuvigerina phlegeri</i>							0.63	0.53			0.83	0.67	0.82	0.56	0.31	0.55	0.73	0.25	0.56	0.25	0.61	0.67	
<i>Valvulineria bradyana</i>						0.39	0.33	0.40	0.63	0.62	0.54	0.18	0.28										
<i>Adelosina longirostra</i>		0.00		0.16																			
<i>Pyrgo subsphaerica</i>						0.26																	
<i>Quinqueloculina seminula</i> f. <i>longa</i>		0.08		0.36		0.28								0.73					0.60	0.29	0.18		
<i>Eggerella scabra</i>	1.00	0.31	0.49	0.74		0.90	0.46	0.27	0.33	0.57	0.45	0.34	0.33	0.85	0.74			1.00	0.80		0.71	0.67	
<i>Textularia agglutinans</i>						0.19					0.30			0.67				0.56	0.50		0.30		

Table 4-4.  $L/(L+D)$  (Living/(Living+Dead)) ratios of the most important fossilizable species. Only ratios of species occurring with more than 5% for each core are shown. Grey boxes represent values between 0.5 and 1.0 (higher % in living fauna) and black boxes represent values between 0.0 and 0.5 (higher % in dead fauna).

The major observations that can be made from table 4-4 are:

- As shown by their elevated L/(L+D) ratios (respectively, 0.75, 0.70 and 0.60 on average), the species *N. scaphum*, *N. turgida* and *R. phlegeri* have, in the whole area, higher percentages in the living assemblages.

- The species *C. carinata*, *H. balthica*, *B. marginata* and *Q. seminula* f. *longa* show higher percentages in the dead assemblages. This is documented by their low L/(L+D) ratios (respectively, 0.34, 0.18, 0.10, 0.36 on average).

- For the other species, percentages are more or less comparable in dead and living assemblages.

- The species *P. falsobeccarii*, *P. subsphaerica* and *E. scabra* that belong to the dead foraminiferal assemblage, which dominate stations under the influence of the river plume, are present in this area in higher densities in dead faunas. On the contrary, the species *N. scaphum* and *R. phlegeri*, which makes part of the same foraminiferal assemblage, are much richer in living fauna. This could indicate that the latter 2 species proliferate in response to the strong input of organic matter by the river plume and show therefore a highly opportunistic behaviour. The former species (*P. falsobeccarii*, *P. subsphaerica* and *E. scabra*), on the contrary, could make part of the fauna typical for periods with a lower river supply.

## 4.5 DISCUSSION

In most foraminiferal studies, especially those which aim to reconstruct palaeoenvironments, interpretations of benthic foraminiferal data are generally made by comparing the fossil assemblages with either modern dead assemblages or total (live plus dead) assemblages. In both cases this comparison is hampered by post-mortem changes that have differentially affected preservation (Murray, 1991). It is therefore important to establish the primary ecological controls by analysing the living assemblages. Various factors, including transport, dissolution and population dynamics, can influence the composition of the dead fauna (Murray, 1991; Loubere et al., 1993; Mackensen et al., 1995; Jorissen and Wittling, 1999), and may create fundamental differences between the dead and living fauna at the same site. Recently, it was demonstrated that these differences may also result from seasonal fluctuations in the downward flux of organic matter (e.g. Jorissen and Wittling, 1999; Gooday and Hughes, 2002). Different reproduction rates of opportunistic and non-opportunistic species may reflect seasonal variations of organic-matter flux, resulting in

greater numbers of opportunistic species with fast reproduction rates following seasonal pulses of food supply. The living fauna represents therefore a snapshot of actual environmental conditions, while the dead fauna represents a longer time-averaged period (Murray, 2006).

In the Rhône prodelta, the dead assemblages at about 4 cm sediment depth give a time-averaged faunal record for the last 5-10 years (probably a longer period towards the distal stations from the river mouth). In general, the comparison between dead and living fauna does not reveal significant differences in faunal composition. This may mean that the dead faunal composition is representative of the total fauna and that the calcareous faunal assemblages are well preserved and did not suffer from important taphonomic losses (Jorissen and Wittling, 1999). Indeed, calcareous taxa do not show any traces of dissolution. Easily dissolvable species such as most miliolid taxa (e.g. *Q. seminula* f. *longa*), are present in the dead faunas in fair numbers and, for some species (e.g. *A. longirostra* and *P. subsphaerica*), even with high densities. No signs of significant transport were found either; at all sites the 63-150  $\mu\text{m}$  fraction forms a significant part of the fauna. However, a first inspection of the specific composition of the dead fauna reveals the near absence of the agglutinated forms *A. glomeratum*, *E. foliaceus*, *R. trochaminiformis* and *R. scottii*. One of the most obvious explanations is their low preservational potential due to the fragile nature of their tests. Only the more resistant arenaceous taxa, *E. scabra* and *T. agglutinans*, are well represented in the dead assemblages. The other taxa, especially the hyaline species seem all to be well preserved. The species diversity of the dead foraminiferal fauna is higher and more stable than that of the living assemblages. This difference is normally interpreted as being due to the fact that dead assemblage represents an accumulation of the empty tests from successive living assemblages, i.e. it is time-averaged (Murray, 2006). The densities of the dead foraminiferal faunas increase towards the farthest stations, probably due the high sedimentation rate occurring near the river mouth, which dilutes the faunal signal.

The Principal Component and cluster analyses reveal the occurrence of three major biofacies in response to the ecological conditions resulting from the Rhône river input, in dead as well as in living fauna. The first assemblage in the dead faunas (*A. beccarii* f. *inflata*, *E. advenum*, *N. turgida*, *Q. seminula* f. *longa* and *A. longirostra*) and its equivalent in the living faunas (*A. beccarii* f. *inflata*, *E. macellum*, *N. turgida* and *Q. seminula* f. *longa*) dominate the biofacies located in front of the river mouth. These species seem to tolerate the stressful conditions present in this area rather well. Indeed, there are not many taxa which are able to live in an area subjected to brackish waters, high turbidity, important input of organic



matter mainly from continental signature (low quality) and very low oxygen penetration into the sediment. The second dead assemblage (*N. scaphum*, *P. falsobeccarii*, *R. phlegeri*, *V. bradyana*, *P. subsphaerica* and *E. scabra*) and its equivalent in the living fauna (*N. scaphum* and *R. phlegeri*) dominate the biofacies located under the river plume. This fauna seems to develop in response to the high organic input with a mainly continental signature that may be the major stressing factor in this area. The third assemblage in dead fauna (*B. aculeata*, *B. marginata*, *C. carinata* and *H. balthica*) and the third and fourth assemblages in the living faunas (*B. aculeata*, *C. carinata*, *M. barleaanus* and *R. trochaminiformis*, *A. glomeratum*, *E. foliaceus* and *T. agglutinans*) dominate mostly stations sheltered from the river influence. In these more distal areas, environmental stress appears to be less important and the faunas seem to respond to the presence of organic matter of mainly marine origin.

The spatial distributions of the cumulative percentages of each assemblage in dead and living faunas suggest that the time-averaged geographic location of the river plume is different from its location during sampling in June 2005. It appears that, in general, the river plume spreads preferentially into a western direction while, at the time of sampling, it extended in southwestern direction. Moreover, the living faunas describe wider extension of the river plume, to the deeper part of the Rhône prodelta. This may be the consequence of the important discharge recorded about 2 months before the time of sampling. On average, benthic foraminifera have a life cycle of 1 to 3 months (Murray, 1991). This time is even shorter for opportunistic taxa that can reproduce and arrive at an adult age in some cases, less than one month (Gustafsson and Nordberg, 2001).

In order to see where species respond to this punctual important input of continental organic matter, we calculated L/(L+D) ratios for the most frequent species. Generally, responsive species show a strong contrast between an absence (or a low density) in the original fauna and a high abundance in the living faunas. In the Rhône prodelta, two species (*N. scaphum* and *R. phlegeri*) show much higher percentages in living than in the dead assemblages. These species dominate the living foraminiferal assemblage at stations under the influence of the river plume. Moreover, the biodiversity of living faunas is much lower than that of the dead fauna in this area influenced by the river plume. Two months after the most important discharge of the Rhône River recorded in 2005, *N. scaphum* and *R. phlegeri* seem to have reacted quickly in response to this punctual important organic input; we infer that they show therefore a highly opportunistic response. In the literature, *N. scaphum* is known to occur in strongly suboxic and anoxic sediments. In these stressed environments, these species appear to have a competitive advantage over more superficially living taxa. They may

proliferate because of the input of large quantities of organic matter into the deeper sediment layers (Rathburn and Corliss, 1994) or migrate to the sediment surface in response to increased organic matter input to the seafloor (Langezaal *et al.*, 2006). *N. fabum* (= *N. scaphum* in our study) is reported to be characteristic of the upwelling system off Portugal (Levy *et al.*, 1995). In recent sediments of the Tagus prodelta in the western Iberian margin, *R. phlegeri* prefers sediments closer to the Tagus river plume (in Bartels-Jonsdottir *et al.*, 2006). Diz *et al.* (2006) describe this taxon as an opportunistic species that react quickly to the input of labile organic matter from the upwelling system in the Ria de Vigo (NW Spain).

To summarize, we can suggest that in general, when the river discharge is low (1000 m<sup>3</sup>/s), the river plume spreads in the western direction. On the contrary, during periods of important discharges, the extension of the river plume is more important in the southwestern direction. In these exceptional situations, *N. scaphum* and *R. phlegeri* are the first species to profit from this important supply of continental organic matter. These speculations should be confirmed by a study of satellite images during different periods of the year. It has therefore to be specified that the direction of spreading of the Rhône river plume depends, not only on the importance of the river discharges but also on the wind regimes that are predominant at these periods.

## 4.6 CONCLUSIONS

- In this paper we have tried to show that the study of the dead fauna is not only important to obtain a better knowledge of the average faunal composition of the foraminiferal community, but that it can also give additional ecological information.

- In the Rhône prodelta, the calcareous faunal assemblage is well preserved and does not suffer important taphonomic losses.

- The differences between living and dead foraminiferal faunas are mainly determined by a differential response of the species to the episodic fluctuations of the Rhône river discharges.

- The riverine input has a strong impact on benthic foraminiferal faunas; three major biofacies are recognised both for the dead and living foraminiferal faunas.

- The dead assemblages suggest that, on the average, the river plume is deviated preferentially into western direction. At the time of sampling, it extended towards a southwestern direction. This may be a consequence of the important discharge recorded about 2 months before the time of sampling.

- The comparison between the dead and the living foraminiferal faunas allows to recognise the opportunistic behaviour of the species *N. scaphum* and *R. phlegeri* that are much abundant in the living fauna at the stations under the influence of the river plume. These species seem to respond to the episodic discharge of the Rhône River.

## 4.7 REFERENCES

Altenbach, A.V. and Sarnheim, M., 1989. Productivity Record in Benthic Foraminifera. In: W.H. Berger, V.S. Smetacek and G. Wefer (eds.) Productivity of the Ocean: Present and Past., p. 255-269. John Wiley and Sons Limited.

Arnone, R., 1994. The temporal and spatial variability of chlorophyll in the western Mediterranean. Seasonal and Interannual Variability of the Western Mediterranean Sea, La Violette, P.E. (Ed.). Coastal Estuarine Studies, 46, 195–225.

Barmawidjaja, D.M., 1991. Studies in living and fossil foraminifers from seasonally productive regions. *Geologica Ultraiectina*, 82, 221 pp.

Bartels-Jónsdóttir, H.B., Knudsen, K. L., Abrantes, F., Lebreiro, S., Eiriksson, J., 2006. Climate variability during the last 2000 years in the Tagus Prodelta, western Iberian Margin: Benthic foraminifera and stable isotopes. *Marine Micropaleontology*, 59, 83-103.

Bernstein, B.B., Hessler, R., Smith, R., Jumars, P., 1978. Spatial dispersion of benthic foraminifera in the abyssal central North Pacific. *Limnology and Oceanography*, 23, 401-416.

Buscail, R., Germain, C., 1997. Present-day organic matter sedimentation on the NW Mediterranean margin: Importance of off-shelf export. *Limnology and Oceanography*, 42 (2), 217–229.

Cruzado, A., Velasquez, Z.R., 1990. Nutrients and phytoplankton in the Gulf of Lions, northwestern Mediterranean. *Continental and Shelf Research*, 10 (9–11), 931–942.

Davis, J.C. 1986. *Statistics and Data Analysis in Geology*, 2nd ed., John Wiley & Sons, New York, 289 pp.

Digby, P.G.N. and Kempton, R.A., 1987. *Multivariate analysis of ecological communities*. Chapman and Hall, London, 206 pp.

Diz, P., Francés, G. and Rosón, G., 2006. Effects of contrasting upwelling–downwelling on benthic foraminiferal distribution in the Ría de Vigo (NW Spain). *Journal of Marine Systems*, 60, 1-18.

Gadel, F., Puigbó, A., Alcañiz, J.M., Charrière, B., Serve, L., 1990. Tracers and constituents indicating the nature of organic fluxes, their origin and the effect of environmental conditions. *Continental and Shelf Research*, 10 (9-11), 1039-1062.

Gooday, A.J., 1988. A response by benthic foraminifera to the deposition of phytodetritus in the deep sea. *Nature*, 332, 70-73.

Gooday, A.J., Hughes, J.A., 2002. Foraminifera associated with phytodetritus deposits at a bathyal site in the northern Rockall Trough (NE Atlantic): seasonal contrasts and a comparison of stained and dead assemblages. *Marine Micropaleontology*, 46, 83-110.

Gustafsson, M. and Nordberg, K., 2001. Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish west coast, with comparisons to Höglund's 1927 material. *Journal of Foraminiferal Research*, 31 1, 2-11

Hill, M.O. and Gauch, H.G., 1980. Detrended correspondence analysis, an improved ordination technique. *Vegetation*, 49, 47-58.

Jones, R.W., 1994. *The Challenger foraminifera*. Oxford University Press, 142 pp.

Jorissen, F.J., 1988. Benthic foraminifera from the Adriatic Sea; Principles of phenotypic variation. *Utrecht Micropaleontology Bulletin*, 37, 176 pp.

Jorissen, F.J., De Stigter, H.C., Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology*, 26, 3–15.

Jorissen, F. J. and Wittling, I., 1999. Ecological evidence from live–dead comparisons of benthic foraminiferal faunas off Cape Blanc (Northwest Africa). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 149, 151-170.

Lamshead, P.J.D., Gooday, A.J., 1990. The impact of seasonally deposited phytodetritus on epifaunal and shallow infaunal benthic foraminiferal populations in the bathyal northeast Atlantic: the assemblage response. *Deep-Sea Research*, 37, 1263-1283.

Langezaal, A.M., Jorissen, F.J., Braun, B., Chaillou, G., Fontanier, C., Anschutz, P., van der Zwaan, G.J., 2006. The influence of seasonal processes on geochemical profiles and foraminiferal assemblages on the outer shelf of the Bay of Biscay. *Continental Shelf Research*, 26, 1730-1755.

Levy, A., Mathieu, R., Poignant, A., Rosset-Moulinier, M., Ubaldo, M.L., Lebreiro, S., 1995. Foraminifères Actuels de la Marge Continentale Portugaise-inventaire et distribution. *Memórias do Instituto Geológico e Mineiro, Lisbon* 32, 116 pp.

Lévy, M., Mémery, L., Madec, G., 1999. The onset of the spring bloom in the MEDOC area: mesoscale spatial variability. *Deep Sea Research I*, 46, 1137-1160.

Loeblich, A.R., and Tappan, H., 1964. *Foraminiferal genera and their classification*. Van Nostrand Reinhold C°, New York, 2 vol. 970+847 pp.

Loubere, P., 1989. Bioturbation and sedimentation rate control of benthic microfossil taxon abundances in surface sediments: a theoretical approach to the analysis of species microhabitats. *Marine Micropaleontology*, 14: 317-325.

Loubere, P., Gary, A., Lagoe, M., 1993. Generation of the benthic foraminiferal assemblage: theory and preliminary data. *Marine Micropaleontology*, 20, 165-181.

Linke, P., Lutze, G.F., 1993. Microhabitat preferences of benthic foraminifera — a static concept or a dynamic adaptation to optimize food acquisition?. *Marine Micropaleontology*, 20, 215-234.

Mackensen, A., Schmiedl, G., Harloff, J. and Giese, M., 1995. Deep-sea foraminifera in the South Atlantic Ocean: ecology and assemblage generation. *Micropaleontology*, 41, 342-358.

Monaco, A., Biscaye, A., Soyer, J., Pocklington, R., Heussner, S., 1990. Particle fluxes and ecosystem response on a continental margin: the 1985–1988 Mediterranean ECOMARGE experiment. *Continental and Shelf Research*, 10 (9-11), 809-839.

Morel, A., André, J.M., 1991. Pigment distribution and primary production in the western Mediterranean as derived and modeled from Coastal Zone Scanner observations. *Journal of Geophysical Research*, 96, 12685-12698.

Murray, J.W., 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman Scientific & Technical, Harlow, 397 pp.

Murray, J.W., 2006. *Ecology and applications of benthic foraminifera*. Cambridge: Cambridge University Press, 426 pp.

Parker, F.L., 1964. Foraminifera from the experimental Mohole drilling near Guadalupe Island, Mexico: *Journal of Paleontology*, 38, 617-637.

Schiebel, R., 1992. *Rezente benthische Foraminiferen in Sedimenten des Schelfes und oberen Kontinentalhangs im Golf von Guinea (Westafrika)*. Berichte Geologisch-Paläontologisches Institut und Museum Christian-Albrechts-Universität Kiel, Deutschland, n° 51, 126 pp.

Rathburn, A.E. and Corliss, B.H., 1994. The Ecology of Living (Stained) Benthic Foraminifera from the Sulu Sea. *Paleoceanography*, 9, 87-150.

Comparison dead/living foraminifera in the Rhône prodelta

Appendix 4-1: Data (non-standardized) of dead benthic foraminifera in the > 150 µm fraction.

Stations		1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	18	19	20	22	23	24	
Sediment depth		3-4 cm	2-5 cm	3-4 cm	3-4 cm	2-5 cm	2-5 cm	3-4 cm	2-5 cm	3-4 cm	2-5 cm	2-5 cm	3-4 cm	3-4 cm	3-4 cm	2-5 cm	2-5 cm	3-4 cm	2-5 cm	3-4 cm	2-5 cm	2-5 cm	
Taxa																							
Perforates	<i>Ammodiscus</i> sp.					1	4																
	<i>Ammonia beccarii</i> f. <i>inflata</i>		5	8	15	5	28	1	9	2	384	224	2	52	48	1792	32	28	768	448	736	74	
	<i>Amphicoryna scalaris</i>					1	2		3		64	16	4	44	48	768	128	28	576	48	352	576	
	<i>Astacolus insolitus</i>											32		4									
	<i>Bolivina alata</i>															256	32	32	192	64	64	192	
	<i>Bolivina dilatata</i>								5						24								
	<i>Bolivina subaenariensis</i>													1	16	64	64	8	256	48	64	384	
	<i>Bulimina aculeata</i>		4	3	2	5	8		7			576	128	36	32	12	6144	224	544	2368	112	1888	3328
	<i>Bulimina costata</i>																						64
	<i>Bulimina marginata</i>		2	1	3		8	2	5		352	576	18	56	8	128	512	224	512	256	576	832	
	<i>Cassidulina carinata</i>		34	1	4	29	36	22	18	1	2432	1728	18	272	696	11264	1648	688	3584	176	336	4992	
	<i>Cassidulina oblonga</i>			1					1		96	96	4	8	8	768	8	144	192	112	288	64	
	<i>Chilostomella ovoidea</i>										32	32		8	8			16	64		64		
	<i>Cibicides lobatulus</i>					2											128						
	<i>Elphidium advenum</i>		54	8	4	7	32		7	1	32	16	1	8		128	32	16		64	64	64	
	<i>Elphidium macellum</i>		1	2					1			32								8	32		
	<i>Epistominella exigua</i>								3														
	<i>Fursenkoina complanata</i>								1					2									
	<i>Fursenkoina concava</i>								1				32					16					
	<i>Fursenkoina fusiformis</i>															8							
	<i>Gavelinopsis praegeri</i>		2			1	4					64					128						64
	<i>Globobulimina affinis</i>													8	8	128			64	32			
	<i>Gyroidinoides cf soldanii</i>								1		96	32	6	4		256	48	64	384	48	224	832	
	<i>Hyalinea balthica</i>					1			1		416	224	14	28	88	32	224	352	124	544	96	1344	
	<i>Lagena</i> sp.																	16					
	<i>Lenticulina atlantica</i>								1	1				2		16		32		64	16	32	
	<i>Melonis barleeanus</i>				1	1						32				8	896	16	96	192	16	128	384
	<i>Nonion scaphum</i>		92	4	6	4	132	6	2	8	576	8	48	72	72	384	256	256	74	352	256	192	
	<i>Nonionella turgida</i>		88	14	17	49	84	2	28		96	384	26	16	32	256	96	16	192	8	32	128	
	<i>Pseudoepionides falsobeccarii</i>									5	32	64	8	8	32	768	128	48	384	8	192	192	
	<i>Rectuvigerina phlegeri</i>		18				48	1	3		64	96	24	16	16	384	32	16	64	32			
	<i>Saidovina karreriana</i>		2			1	28				224	128	16	28	48	128	48		256	16		64	
	<i>Uvigerina mediterranea</i>																			48	64	384	
<i>Uvigerina peregrina</i>															128								
<i>Valvulinera bradyana</i>		78	1		5	24	11	41	4	864	156	118	192	152	3968	592	512	2432	464	992	16		
Miliolids	<i>Adelosina longirostra</i>		2	18	3	8	16	4	4		16	256	4	24		768		32	128	48	32	32	
	<i>Pyrgo subsphaerica</i>		2	1	1	2	4	11	2	2	32		4	4		384							
	<i>Quinqueloculina badenensis</i>													2			32						
	<i>Quinqueloculina grata</i>						4		4				2			384	32			8		128	
	<i>Quinqueloculina seminula</i> f. <i>longa</i>		2	14	14	3	9	24		15	2	16	224	2	8	24	248	48	32	124	48	512	124
	<i>Spiroloculina canaliculata</i>																128						
Agglutinates	<i>Adercotryma glomeratum</i>					4						32											
	<i>Bigenenerina nodosaria</i>															384		96	32		96		
	<i>Clavulina cylindrica</i>						16					16	4	4			16		64		32		
	<i>Cribrostomoides jeffreysii</i>		2		2	4	4		3														
	<i>Cribrostomoides subglobosus</i>																		128				
	<i>Eggerella advena</i>														16								
	<i>Eggerella scabra</i>		96	6	12	13	124	3	56	1	128	928	4	84	32	256	24		256	144	32	64	
	<i>Eratidus foliaceus</i>		2				16			1		64	2			256	16	16		16	32	256	
	<i>Lagenammina difflugiformis</i>		2				8					416	4	12	16	124	224	64	896	28	32	32	
	<i>Recurvoides trochamminiformis</i>		2			1	4							4		128					32	192	
	<i>Reophax scorpiurus</i>																		64	16	32		
<i>Reophax</i> sp.												32											
<i>Textularia agglutinans</i>		8			2	28	1	3	3	48	448	18	8	16	3456	176	28	1728	272	64	768		
Total		2	510	83	72	150	686	65	226	30	6576	6516	394	1004	1452	35412	4736	3372	16162	3500	7376	15766	

## Appendix 4-2. Recalculated percentages of living and dead foraminifera and L/L+D ratios.

Taxa	1			2			3			4			5			6			7			
	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	
<i>Ammodiscus</i> sp.													0.66	0.00		0.43	0.00					
<i>Ammonia beccarii</i> f. <i>inflata</i>	12.82		1.00	8.51	8.09	0.51	1.37	9.64	0.12	6.31	20.83	0.23	8.86	3.31	0.73	1.62	3.03	0.35	0.86	1.09	0.44	
<i>Amphicoryna scalaris</i>													0.66	0.00		2.16	0.00					
<i>Astacolus insolitus</i>																						
<i>Bolivina alata</i>										0.16		1.00	0.17		1.00							
<i>Bolivina dilatata</i>																						
<i>Bolivina seminuda</i>										0.16		1.00										
<i>Bolivina spathulata</i>																			0.11		1.00	
<i>Bolivina subaenariensis</i>													0.17		1.00	0.14		1.00	0.11		1.00	
<i>Bulimina aculeata</i>				0.20	0.65	0.23	2.00	3.61	0.36	3.79	2.78	0.58	6.35	3.31	0.66	0.63	0.87	0.42	0.11		1.00	
<i>Bulimina costata</i>																						
<i>Bulimina marginata</i>				0.10	0.32	0.23	0.25	1.20	0.17			4.17	0.00				0.87	0.00	0.75	2.17	0.26	
<i>Cassidulina carinata</i>				0.20	5.50	0.03	0.19	1.20	0.13	1.42	5.56	0.20	9.70	19.21	0.34	0.56	3.90	0.13	4.18	23.91	0.15	
<i>Cassidulina oblonga</i>								1.20	0.00													
<i>Chilostomella ovoidea</i>																						
<i>Cibicides lobatulus</i>														1.32	0.00							
<i>Dentalina bradyensis</i>																						
<i>Elphidium advenum</i>				1.86	8.74	0.18	0.37	9.64	0.04	0.47	5.56	0.08	0.17	4.64	0.03	0.49	3.46	0.12				
<i>Elphidium macellum</i>	7.69		1.00	2.15	1.62	0.57	0.25	2.41	0.09	0.32		1.00	0.33		1.00	0.85		1.00	0.54		1.00	
<i>Epistominella exigua</i>																						
<i>Fursenkoina complanata</i>							0.12		1.00				0.17		1.00							
<i>Fursenkoina concava</i>													0.33		1.00							
<i>Fursenkoina fusiformis</i>																						
<i>Gavelinopsis praegeri</i>				0.20	0.32	0.38				0.16		1.00		0.66	0.00		0.43	0.00				
<i>Globobulimina affinis</i>																0.07		1.00	0.11		1.00	
<i>Globobulimina pyrula</i> var. <i>pseudospinescens</i>																						
<i>Globulina rotundata</i>																						
<i>Gyroidinoidea cf soldanii</i>																						
<i>Hanzawaia boueana</i>																						
<i>Hyalinea balthica</i>														0.66	0.00				0.11		1.00	
<i>Lagena</i> sp.																						
<i>Lenticulina atlantica</i>														0.33		1.00			0.21	1.09	0.16	
<i>Lenticulina peregrina</i>																			0.11		1.00	
<i>Melonis barleaanus</i>				0.68		1.00	0.19	1.20	0.13					0.66	0.00				0.21		1.00	
<i>Nonion scaphum</i>	5.13		1.00	45.89	14.89	0.76	6.68	4.82	0.58	19.72	8.33	0.70	23.24	2.65	0.90	51.20	14.29	0.78	44.74	6.52	0.87	
<i>Nonionella iridea</i>																						
<i>Nonionella turgida</i>	25.64		1.00	13.41	14.24	0.48	6.18	16.87	0.27	32.97	23.61	0.58	15.38	32.45	0.32	10.86	9.09	0.54	6.22	2.17	0.74	
<i>Procerolagena gracillina</i>																						
<i>Pseudoepionides falsobeccarii</i>										0.16		1.00				0.21		1.00	0.11		1.00	
<i>Rectuvigerina phlegeri</i>				4.89	2.91	0.63				0.16		1.00	0.50		1.00	5.92	5.19	0.53	0.97	1.09	0.47	
<i>Saidovina karreriana</i>				0.10	0.32	0.23								0.66	0.00		3.03	0.00				
<i>Uvigerina mediterranea</i>	2.56		1.00																			
<i>Uvigerina peregrina</i>																						
<i>Valvulineria bradyana</i>	2.56		1.00	6.16	12.62	0.33		1.20	0.00	1.10		1.00	3.68	3.31	0.53	17.35	25.97	0.40	20.17	11.96	0.63	
<i>Adelostoma longirostra</i>				0.39	3.24	0.11		21.69	0.00			4.17	0.00	1.00	5.30	0.16	0.35	1.73	0.17	0.21	4.35	0.05
<i>Pyrgo subsphaerica</i>					3.24	0.00		1.20	0.00			1.39	0.00		1.32	0.00		0.43	0.00	0.32	11.96	0.03
<i>Quinqueloculina badenensis</i>							0.06		1.00											0.11	1.00	
<i>Quinqueloculina grata</i>																	0.43	0.00	0.11		1.00	
<i>Quinqueloculina seminula</i> f. <i>longa</i>	23.08	100.00	0.19	0.98	2.27	0.30	1.37	16.87	0.08	4.57	4.17	0.52	3.34	5.96	0.36	0.99	2.60	0.28	1.50		1.00	
<i>Quinqueloculina</i> sp.1																						
<i>Spiroloculina canaliculata</i>				0.20		1.00																
<i>Adelostoma glomatum</i>	Non fossilizable taxa																					
<i>Bigenerina nodosaria</i>	Non fossilizable taxa																					
<i>Ciavolita cylindrica</i>	Non fossilizable taxa																					
<i>Eribostomoides fulvegus</i>	Non fossilizable taxa																					
<i>Eribostomoides subglobosus</i>	Non fossilizable taxa																					
<i>Eggerella advena</i>	Non fossilizable taxa																					
<i>Eggerella scabra</i>	12.82		1.00	13.01	15.53	0.46	3.18	7.23	0.31	15.77	16.67	0.49	23.91	8.61	0.74	4.87	13.42	0.27	16.42	32.61	0.33	
<i>Evanilla foliatus</i>	Non fossilizable taxa																					
<i>Eggerella cylindrica</i>	Non fossilizable taxa																					
<i>Eribostomoides subglobosus</i>	Non fossilizable taxa																					
<i>Reophax insularis</i>	Non fossilizable taxa																					
<i>Reophax subplanus</i>	Non fossilizable taxa																					
<i>Reophax scabi</i>	Non fossilizable taxa																					
<i>Reophax</i> sp.	Non fossilizable taxa																					
<i>Textularia agglutinans</i>				0.49	1.29	0.27							0.17	1.32	0.11	1.69	3.03	0.36	0.11	1.09	0.09	
Total	92.3	100.0		99.4	95.8		22.2	100.0		87.2	97.2		97.8	96.7		97.8	94.4		98.4	100.0		

# Comparison dead/living foraminifera in the Rhône prodelta

## Appendix 4-2. Continued.

Taxa	8			9			10			12			13			14			15					
	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D			
<i>Ammodiscus</i> sp.																								
<i>Ammonia beccarii</i> f. <i>inflata</i>	1.48	2.65	0.36	1.44	6.67	0.18	1.40	5.26	0.21	4.21	2.59	0.62	1.34	3.18	0.30	2.54	5.18	0.33	4.87	3.08	0.61			
<i>Amphicoryna scalaris</i>	0.76	0.00					0.40	0.88	0.31	0.21	1.85	0.10	0.25	0.64	0.28	0.04	4.38	0.01	0.45	3.08	0.13			
<i>Astacolus insolitus</i>											0.37	0.00	0.17	1.00	0.08	0.40	0.17							
<i>Bolivina alata</i>				0.29	1.00	0.12		1.00	0.06		1.00	0.08		1.00	0.04		1.00		0.17		1.00			
<i>Bolivina dilatata</i>		1.52	0.00																	1.54	0.00			
<i>Bolivina seminuda</i>																								
<i>Bolivina spathulata</i>	0.21		1.00				0.12	1.00																
<i>Bolivina subaenariensis</i>							0.09	1.00	0.03		1.00	0.08	1.59	0.05	0.67		1.00	0.67	1.03		0.40			
<i>Bulimina aculeata</i>	0.74	1.89	0.28	2.31	1.00	4.35	7.89	0.36	3.58	1.48	0.71	3.60	5.73	0.39	7.86	3.19	0.71	9.12	7.69	0.54				
<i>Bulimina costata</i>				0.29	1.00										0.12		1.00	0.06		1.00				
<i>Bulimina marginata</i>	0.53	1.52	0.26	0.58	1.00	1.89	4.82	0.28	1.26	6.67	0.16	0.92	2.87	0.24	0.62	5.58	0.10	0.56	0.51	0.52				
<i>Cassidulina carinata</i>	6.76	30.68	0.18	14.41	3.33	0.81	16.53	33.33	0.33	2.46	20.00	0.11	2.01	28.66	0.07	13.39	27.09	0.33	21.42	44.62	0.32			
<i>Cassidulina oblonga</i>	0.38	0.00					1.32	0.00	0.06	1.11	0.05	0.17	0.64	0.21	0.08	0.80	0.09	0.22	0.51	0.30				
<i>Chilostomella ovoidea</i>							0.06	0.44	0.12	0.03	0.37	0.08			0.04	0.80	0.05	0.22	0.51	0.30				
<i>Cibicides lobatulus</i>																								
<i>Dentalina bradyensis</i>															0.04		1.00	0.06		1.00				
<i>Elphidium advenum</i>	0.32	1.89	0.14		3.33	0.00	0.06	0.44	0.12	0.27	1.85	0.13	0.25	1.59	0.14		0.80	0.00						
<i>Elphidium macellum</i>	0.95	0.38	0.72	0.29	1.00	0.09		1.00	1.29	0.37	0.78	0.25		1.00	0.46		1.00	0.06		1.00				
<i>Epistominella exigua</i>	0.76	0.00																						
<i>Fursenkoina complanata</i>	0.38	0.00	0.29		1.00				0.12		1.00		0.32	0.00	0.08		1.00							
<i>Fursenkoina concava</i>	0.38	0.00					0.03	1.00		0.37	0.00	0.17		1.00	0.08		1.00							
<i>Fursenkoina fusiformis</i>																				0.51	0.00			
<i>Gavelinopsis praegeri</i>							0.12	1.00	0.48	0.74	0.39													
<i>Globobulimina affinis</i>							0.15	1.00	0.12		1.00				0.46	0.80	0.36	0.45	0.51	0.47				
<i>Globobulimina pyrula</i> var. <i>pseudospinescens</i>				0.29	1.00	0.15		1.00	0.03		1.00													
<i>Globulina rotundata</i>																								
<i>Gyroidinoides cf soldanii</i>		0.38	0.00				0.06	1.32	0.04		0.37	0.00	0.17	0.96	0.15	0.25	0.40	0.39	0.22	1.00				
<i>Hanzawaia boueana</i>							0.09	1.00							0.08		1.00	0.06		1.00				
<i>Hyalinea balthica</i>	0.11	0.38	0.22	0.29	1.00	0.37	5.70	0.06	0.18	2.59	0.07	0.08	2.23	0.04	0.25	2.79	0.08	1.06	5.64	0.16				
<i>Lagena</i> sp.																								
<i>Lenticulina atlantica</i>		0.38	0.00				0.06	1.00	0.03		1.00			0.32	0.00	0.08	1.00	0.06	1.03	0.05				
<i>Lenticulina peregrina</i>																								
<i>Melonis barleuanus</i>									0.36	0.37	0.49			0.04		1.00	0.11	0.51	0.18					
<i>Nonion scaphum</i>	32.84	5.68	0.85	15.56	26.67	0.37	12.09	7.89	0.60	33.18	9.26	0.78	63.13	7.64	0.89	44.66	7.17	0.86	25.73	4.62	0.85			
<i>Nonionella iridea</i>																								
<i>Nonionella turgida</i>	9.61	7.95	0.55	6.63	1.00	2.16	1.32	0.62	7.48	4.44	0.63	9.62	4.14	0.70	4.49	1.59	0.74	2.57	2.05	0.56				
<i>Procerolagena gracillina</i>																								
<i>Pseudozonitoides falsobeccarii</i>				1.73	16.67	0.09	0.88	0.44	0.67	0.69	0.74	0.48	0.17	1.27	0.12	0.08	0.80	0.09	0.50	2.05	0.20			
<i>Rectuvigerina phlegeri</i>	0.63	0.76	0.46	2.59	1.00	2.80	0.88	0.76	5.35	1.11	0.83	7.86	3.82	0.67	7.40	1.59	0.82	4.03	1.03	0.80				
<i>Saidovina karrieriana</i>							3.07	0.00	1.48	0.00		2.55	0.00		2.79	0.00		3.08	0.00					
<i>Uvigerina mediterranea</i>	0.11		1.00				0.09	1.00	0.06		1.00				0.04		1.00	0.22		1.00				
<i>Uvigerina peregrina</i>																								
<i>Valvulineria bradyana</i>	19.43	11.74	0.62	8.36	13.33	0.39	5.24	11.84	0.31	14.13	12.22	0.54	4.10	18.79	0.18	7.32	19.12	0.28	11.69	9.74	0.55			
<i>Adelosina longirostra</i>	1.48	1.14	0.57	0.29	1.00	1.04	2.19	0.32	0.84	2.96	0.22	0.17	0.64	0.21	0.21	2.39	0.08	0.39		1.00				
<i>Pyrgo subsphaerica</i>		5.68	0.00	2.31	6.67	0.26	0.33	0.44	0.43	0.06		1.00		0.64	0.00	0.08	0.40	0.17						
<i>Quinqueloculina badenensis</i>									0.97		1.00			0.32	0.00									
<i>Quinqueloculina grata</i>		1.14	0.00				1.40	1.00						0.32	0.00									
<i>Quinqueloculina seminula</i> f. <i>longa</i>	2.53	4.17	0.38	2.59	6.67	0.28	5.94	2.19	0.73	1.26	2.59	0.33		0.32	0.00	0.62	0.80	0.44	0.45	1.54	0.23			
<i>Quinqueloculina</i> sp.1				0.58	1.00	1.52		1.00																
<i>Spiroloculina canaliculata</i>							0.03	1.00																
<i>Adelomyxa glomerosum</i>	Non fossilizable taxa																							
<i>Bigenerina nodosaria</i>							0.12	1.00											0.11	1.00				
<i>Candidula ciliatrica</i>	Non fossilizable taxa																							
<i>Cibicides stans jaffrenoi</i>	Non fossilizable taxa																							
<i>Chilostomoides subobtusus</i>	Non fossilizable taxa																							
<i>Eggerella salina</i>	Non fossilizable taxa																							
<i>Eggerella scabra</i>	21.33	15.91	0.57	29.97	3.33	0.90	9.84	1.75	0.85	8.84	10.74	0.45	3.26	6.37	0.34	4.12	8.37	0.33	5.98	2.05	0.74			
<i>Evandus jaffrenoi</i>	Non fossilizable taxa																							
<i>Laccionautina diffingensis</i>	Non fossilizable taxa																							
<i>Recurvirostra subquadrangulata</i>	Non fossilizable taxa																							
<i>Rhopax fusiformis</i>	Non fossilizable taxa																							
<i>Rhopax serripinus</i>	Non fossilizable taxa																							
<i>Rhopax sora</i>	Non fossilizable taxa																							
<i>Rhopax</i> sp.	Non fossilizable taxa																							
<i>Textularia agglutinans</i>	0.32	0.76	0.29	2.31	10.00	0.19	13.40	6.58	0.67	2.25	5.19	0.30	1.09	2.87	0.27	0.17	0.80	0.17	1.79	1.03	0.64			
<b>Total %</b>	<b>99.4</b>	<b>99.2</b>		<b>93.4</b>	<b>96.7</b>		<b>84.0</b>	<b>100.0</b>		<b>88.9</b>	<b>91.9</b>		<b>98.9</b>	<b>98.4</b>		<b>96.5</b>	<b>98.0</b>		<b>93.3</b>	<b>97.9</b>				



Appendix 4-2. Continued.

Taxa	16			18			19			20			22			23			24		
	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D	L	D	L/L+D
<i>Ammodiscus</i> sp.	0.14		1.00																		
<i>Ammonia beccarii</i> f. <i>inflata</i>	2.84	4.17	0.41	1.49	6.02	0.20	2.89	4.87	0.37	4.90	4.07	0.55	5.48	6.83	0.45	10.93	5.93	0.65	7.07	5.93	0.54
<i>Amphicoryna scalaris</i>	0.33	1.79	0.16	0.11	2.41	0.04	0.27	4.87	0.05	0.68	3.05	0.18	0.40	0.73	0.35	0.42	2.84	0.13	0.49	2.84	0.15
<i>Astacolus insolitus</i>							0.05		1.00										0.10		1.00
<i>Bolivina alata</i>	3.03	0.60	0.84	0.32	0.60	0.35	0.64	0.75	0.46	2.06	1.02	0.67	0.05	0.98	0.05	3.60	0.52	0.87	3.90	0.52	0.88
<i>Bolivina dilatata</i>																					
<i>Bolivina seminuda</i>																					
<i>Bolivina spathulata</i>									0.03			1.00									
<i>Bolivina subaenariensis</i>	1.73	1.49	0.54	0.19	1.20	0.13	0.75	1.87	0.29	0.91	1.36	0.40	0.25	0.73	0.25	1.07	0.52	0.68	2.00	0.52	0.80
<i>Bulimina aculeata</i>	10.87	14.29	0.43	6.34	4.22	0.60	13.95	12.73	0.52	9.98	12.54	0.44	5.04	17.07	0.23	8.36	15.21	0.35	17.31	15.21	0.53
<i>Bulimina costata</i>							0.32		1.00	0.47		1.00	0.05		1.00	1.40		1.00	0.44		1.00
<i>Bulimina marginata</i>	1.07	2.98	0.26	0.67	9.64	0.06	0.32	5.24	0.06	0.85	2.71	0.24	1.09	3.90	0.22	0.37	4.64	0.07		4.64	0.00
<i>Cassidulina carinata</i>	17.46	26.19	0.40	16.22	31.02	0.34	41.10	16.10	0.72	13.32	18.98	0.41	34.93	26.83	0.57	19.15	27.06	0.41	15.21	27.06	0.36
<i>Cassidulina oblonga</i>	0.57	1.79	0.24	0.11	1.51	0.07	0.27	3.37	0.07	0.30	1.02	0.23	0.15	1.71	0.08		2.32	0.00	0.34	2.32	0.13
<i>Chilostomella ovoidea</i>							2.51	0.37	0.87	0.85	0.34	0.71				0.89	0.52	0.63	1.66	0.52	0.76
<i>Cibicides lobatulus</i>		0.30	0.00																		
<i>Dentalina bradyensis</i>	0.07		1.00	0.08		1.00	0.11		1.00											0.05	1.00
<i>Elphidium advenum</i>	0.07	0.30	0.00		0.60	0.00	0.05	0.37	0.12				0.94	0.98	0.49		0.52	0.00			0.52
<i>Elphidium macellum</i>	0.07		1.00				0.16		1.00	0.03		1.00	1.93	1.22	0.61	0.56	0.26	0.69	0.34	0.26	0.57
<i>Epistominella exigua</i>																					
<i>Fursenkoina complanata</i>										0.07		1.00	0.05		1.00	0.09		1.00			
<i>Fursenkoina concava</i>				0.30		0.00															
<i>Fursenkoina fusiformis</i>																					
<i>Gavelinopsis praegeri</i>	0.09	0.30	0.24										0.10		1.00						
<i>Globobulimina affinis</i>	3.20	0.30	0.91	1.23		1.00	1.28		1.00	2.23	0.34	0.87	0.44	0.49	0.48	0.65		1.00	1.32		1.00
<i>Globobulimina pyrula</i> var. <i>pseudospinescens</i>	0.64		1.00	0.16		1.00	0.37		1.00				0.40		1.00	0.37		1.00	0.15		1.00
<i>Globulina rotundata</i>														0.05	1.00						
<i>Gyroidinoides cf soldanii</i>	0.19	0.60	0.24		0.90	0.00	0.11	1.50	0.07	0.10	2.03	0.05	0.05	0.73	0.06		1.80	0.00	0.10	1.80	0.05
<i>Hanzawaia boueana</i>	0.59		1.00				0.05		1.00	0.03		1.00	0.05		1.00					0.63	1.00
<i>Hyalinea balthica</i>	1.59	7.44	0.18	0.77	4.22	0.15	2.73	8.24	0.25	2.91	5.42	0.35	1.68	8.29	0.17	1.40	7.73	0.15	1.76	7.73	0.19
<i>Lagena</i> sp.							0.16	0.37	0.30					0.05	1.00	0.14		1.00	0.34		1.00
<i>Lenticulina atlantica</i>				0.11	0.60	0.15				0.17	0.34	0.33		0.24	0.00	0.05	0.26	0.15		0.26	0.00
<i>Lenticulina peregrina</i>	0.14		1.00							0.10		1.00	0.15		1.00	0.51		1.00	0.05		1.00
<i>Melonis barleaanus</i>	1.63	2.08	0.44	0.11	0.30	0.26	0.43	2.25	0.16	6.05	1.02	0.86	0.40	0.24	0.62	2.52	1.03	0.71	2.05	1.03	0.67
<i>Nonion scaphum</i>	6.92	0.89	0.89	38.77	4.82	0.89	1.12	5.99	0.16	2.57	3.73	0.41	15.46	5.37	0.74	6.68	2.06	0.76	6.19	2.06	0.75
<i>Nonionella iridea</i>																					
<i>Nonionella turgida</i>	2.91	0.60	0.83	3.70	1.81	0.67	1.18	0.37	0.76	0.61	1.02	0.37	15.37	1.22	0.93	1.40	0.26	0.84	1.61	0.26	0.86
<i>Procerolagena gracillina</i>														0.05							
<i>Pseudoeponides falsobeccarii</i>	1.37	1.79	0.43	0.72	2.41	0.23	0.48	1.12	0.30	1.76	2.03	0.46	2.08	1.22	0.63	3.50	1.55	0.69	0.24	1.55	0.14
<i>Rectuvigerina phlegeri</i>	2.34	0.89	0.72	4.21	0.60	0.87	0.21	0.37	0.36	0.85	0.34	0.71	0.40	0.49	0.45	0.79		1.00	0.63		1.00
<i>Saidovina karreriana</i>		0.30	0.00		0.90	0.00						1.36	0.00		0.24	0.00					
<i>Uvigerina mediterranea</i>	0.21		1.00	0.27		1.00	0.64		1.00	1.29		1.00	0.25	0.73	0.25	1.45	0.52	0.74	2.10	0.52	0.80
<i>Uvigerina peregrina</i>		0.30	0.00																		
<i>Valvulineria bradyana</i>	25.34	9.23	0.73	14.41	11.14	0.56	3.96	11.99	0.25	16.33	12.88	0.56	2.42	7.07	0.25	12.70	7.99	0.61	15.89	7.99	0.67
<i>Adelosina longirostra</i>	0.28	1.79	0.14	0.29		1.00	0.05	0.75	0.07	0.17	0.68	0.20		0.73	0.00		0.26	0.00		0.26	0.00
<i>Pyrgo subsphaerica</i>		0.89	0.00																		
<i>Quinqueloculina badenensis</i>	0.40		1.00	0.60		0.00				0.14		1.00									
<i>Quinqueloculina grata</i>		0.89	0.00	0.11	0.60	0.15								1.22	0.00						
<i>Quinqueloculina seminula</i> f. <i>longa</i>	7.11	4.76	0.60	1.38	0.90	0.61	2.99	7.49	0.29	1.22	5.42	0.18	0.69	0.73	0.49	1.49	4.12	0.27	2.15	4.12	0.34
<i>Quinqueloculina</i> sp.1																					
<i>Spiroloculina canaliculata</i>		0.30	0.00																		
<i>Adelomya glommarum</i>	Non fossilizable taxa																				
<i>Bigenerina nodosaria</i>	0.19	0.89	0.18				0.75	2.25	0.25	4.13	1.69	0.71	0.10		1.00	0.75	0.77	0.49	1.07		1.00
<i>Candidina calmarica</i>	Non fossilizable taxa																				
<i>Candidinoides infregan</i>	Non fossilizable taxa																				
<i>Chilostomoides subglobosus</i>	Non fossilizable taxa																				
<i>Eggerella adonis</i>	Non fossilizable taxa																				
<i>Eggerella scabra</i>	1.73	0.60	0.74	4.66	4.52	0.51	7.43		1.00	5.51	1.36	0.80	4.89	2.20	0.69	6.21	2.58	0.71	5.27	2.58	0.67
<i>Evandis jolacensis</i>	Non fossilizable taxa																				
<i>Laticostata diffugiens</i>	Non fossilizable taxa																				
<i>Recurvirostris trochammonitiformis</i>	Non fossilizable taxa																				
<i>Rhopus fusiformis</i>	Non fossilizable taxa																				
<i>Rhopus scarpatus</i>	Non fossilizable taxa																				
<i>Rhopus sord</i>	Non fossilizable taxa																				
<i>Rhopus</i> sp.	Non fossilizable taxa																				
<i>Textularia agglutinans</i>	0.47	8.04	0.06	0.61	3.31	0.16	6.31	4.87	0.56	9.13	9.15	0.50	0.64	4.15	0.13	2.24	5.15	0.30	1.80	5.15	0.26
<b>Total</b>	<b>95.6</b>	<b>96.7</b>		<b>97.0</b>	<b>95.2</b>		<b>93.6</b>	<b>98.1</b>		<b>89.8</b>	<b>93.9</b>		<b>96.0</b>	<b>96.3</b>		<b>89.7</b>	<b>96.4</b>		<b>92.2</b>	<b>95.6</b>	





**CHAPITRE 5. COMPARISON OF BENTHIC  
FORAMINIFERAL AND MACROFAUNAL RESPONSES TO  
ORGANIC POLLUTION IN THE FIRTH OF CLYDE  
(SCOTLAND)**

<b>RÉSUMÉ</b> .....	219
<b>5.1 ABSTRACT</b> .....	222
<b>5.2 INTRODUCTION</b> .....	222
<b>5.3 STUDY AREA</b> .....	224
<b>5.4 MATERIAL AND METHODS</b> .....	226
<b>5.5 RESULTS</b> .....	228
<b>5.5.1 Chemical properties of surficial sediments</b> .....	228
<b>5.5.2 Foraminiferal faunas</b> .....	232
<b>5.5.3 Macrofauna</b> .....	239
<b>5.6 DISCUSSION</b> .....	246
<b>5.7 CONCLUSIONS</b> .....	260
<b>5.8 REFERENCES</b> .....	261
<b>APPENDICES</b> .....	273
<b>PLATE</b> .....	282



## RÉSUMÉ

En comparant la réponse des foraminifères benthiques à celle de la macrofaune aux rejets des boues d'épuration dans le Firth of Clyde (Écosse), nous avons voulu étudié la possibilité d'employer les foraminifères comme bio-indicateurs de la dégradation d'un environnement marin. Les deux groupes présentent une succession faunistique assez semblable dans l'ensemble, avec des faunes pauvres à proximité du site de décharge, composées d'espèces tolérantes à l'hypoxie. Cette zone est entourée d'espèces opportunistes présentant de très fortes densités. Plus loin, les densités diminuent et les espèces stables remplacent progressivement les espèces opportunistes. Plus d'impact environnemental n'est perceptible au delà de 3 kilomètres. Néanmoins, quelques différences existent : les foraminifères semblent être affectés davantage par les rejets, probablement à cause du faible pH enregistré dans cette zone. Celui-ci pourrait constituer un facteur supplémentaire de stress pour des espèces munies d'un test calcaire. À 3 kilomètres à l'ouest de la décharge, la macrofaune est comparable à la station de référence, tandis que les foraminifères indiquent toujours une légère dégradation environnementale, suggérant leur plus forte sensibilité à ce type de pollution. Il s'avère donc que l'étude des foraminifères benthiques peut ajouter une information précieuse dans ce genre de suivi environnemental.

**Mots clés:** Foraminifères benthiques; macrofaune; eutrophisation; bio-indicateur; espèces opportunistes; Firth of Clyde.



**CHAPITRE 5. COMPARISON OF BENTHIC  
FORAMINIFERAL AND MACROFAUNAL RESPONSES TO  
ORGANIC POLLUTION IN THE FIRTH OF CLYDE  
(SCOTLAND)**

M. Mojtahid <sup>(1)</sup>, F. Jorissen <sup>(1)</sup> and T.H. Pearson <sup>(2)</sup>

<sup>(1)</sup> Laboratoire des Bio-Indicateurs Actuels et Fossiles (BIAF) UPRES EA 2644, Université d'Angers. 2, Boulevard Lavoisier, 49045 Angers Cedex, France, and Laboratoire d'Étude des Bio-Indicateurs Marins (LEBIM). Ker Chalon, 85350 Ile D'Yeu, France

<sup>(2)</sup> Akvplan-niva as, PolarEnvironment Centre, 9296 Tromsø Norway

Ce chapitre correspond à un article accepté dans la revue *Marine Pollution Bulletin*.

**Keywords:** Benthic foraminifera; macrofauna; eutrophication; bio-indicator; opportunistic taxa; Firth of Clyde.



## 5.1 ABSTRACT

By comparing benthic foraminiferal and macrofaunal responses to sewage sludge disposal in the Firth of Clyde (Scotland), we wanted to investigate the possibility of using foraminifera as bio-indicators of marine environmental degradation. Both groups present a similar distributional pattern, with poor faunas composed of species tolerant to strong oxygen depletion near to the disposal site, surrounded by high density of opportunistic species. Farther away, faunal density decreases and equilibrium taxa gradually replace opportunistic species. No more environmental impact is perceptible beyond 3 Km. Nevertheless, some differences exist: foraminifera appear to be more impacted at the disposal site, probably as a consequence of the low pH, a supplementary stress factor for organisms provided with a calcareous test. At 3 km west of the disposal site, macrofauna is comparable to the reference station, whereas foraminifera still indicate environmental degradation, suggesting their higher sensitivity to this type of pollution. It appears that benthic foraminifera may add valuable information to open marine environmental monitoring.

## 5.2 INTRODUCTION

Since 1974, up to  $1.5 \times 10^6$  tonnes of sewage sludge have been discharged annually in an area some 8 Km south of Garroch Head in the Arran/Ayrshire Basin (Firth of Clyde; Scotland; Fig. 5-1). This activity ceased in 1998 (*Webster and Campbell, 2002*). In June 1988, benthic macrofaunal and foraminiferal assemblages were sampled at 9 stations along two perpendicular sample transects centred around the disposal site. This study makes part of an environmental survey, based on macrofaunal analyses, carried out annually since 1979. This is the first time that the impact of sewage sludge on foraminiferal faunas has been studied at this site.

Essentially, disposal of sewage sludge at sea may create two types of environmental problems: a) localised organic enrichment causing higher sedimentary oxygen consumption, often leading to hypoxic and ultimately anoxic conditions at the sea floor (*Fenchel and Finlay, 1995*) and b) the potential toxicity or pathogenicity of the deposited material (*Pearson, 1986*). In hydrodynamically active open marine areas, organic enrichment is unlikely to cause more than temporary nuisance problems; nutrient and carbon inputs tend to be rapidly incorporated into the marine food web, which is well adapted to metabolize large

quantities of organic carbon (*DoE/WTD, 1984*). In enclosed, shallow, or hydrodynamically less active systems, on the contrary, severe but localised problems may be created (*Pearson, 1985*). The realisation of this dichotomy has led to the present opinion, that dumping at sea should preferably take place in dispersive (hydrodynamically active) areas. At present sewage disposal by dumping at sea is prohibited in the EU.

The impact of sewage disposals on benthic macrofauna is well-documented (*Mackay et al., 1972; MacIntyre, 1977; Pearson and Rosenberg, 1978; Pearson et al., 1983; Pearson, 1986; Pearson et al., 1986; Hellowell, 1986; Abel, 1989; Mason, 1991; Rosenberg and Resh, 1993 in Yong Cao et al, 1997*) and has been measured using a variety of indicators, including biomass, species richness, and species density and composition. Foraminifera are among the most abundant protists in marine benthic environments (*Murray, 1991*). Because of their short life cycles, high biodiversity and the specific ecological requirements of individual species, foraminifera react quickly to environmental disturbance, and can be successfully applied as bio-indicators of environmental changes, such as those brought about by anthropogenic pollution (as defined by *Kramer and Botterweg, 1991*). Foraminiferal assemblages are easy to collect; they are commonly abundant, and provide a highly reliable database for statistical analysis, even when only small sample volumes are available. Furthermore, many foraminiferal taxa secrete a carbonate shell, and leave an excellent fossil record, that may be used to characterise baseline conditions, or to reconstruct the state of the ecosystem prior to the impact of pollution (*Alve, 1995a*). Studies of the effects of pollution on benthic foraminiferal assemblages, and their possible use as pollution indicators were initiated in the early 1960's by *Resig (1960)* and *Watkins (1961)*. More recently, foraminifera have been increasingly used to monitor pollution in a wide range of marine environments, such as intertidal mudflats impacted by oil spillages (*Morvan et al., 2004, 2006*), tropical east Atlantic outer shelf environments impacted by drill cutting disposal (*Durrieu et al., 2006; Mojtahid et al., 2006*), harbours affected by heavy metal pollution (*Armynot Du Châtelet et al., 2004*), and eutrophicated continental shelves (*Sharifi et al., 1991; Yanko and Flexer, 1991; Platon et al., 2005*).

The aim of the present paper is to use an intensively studied sewage disposal site in order to assess the applicability of foraminifera as bio-indicators of this type of environmental impact and to compare the foraminiferal response with that of macrofauna. In order to do so, we will concentrate on three subjects:

- 1) changes of faunal density, composition and diversity along the sample transects;

- 2) the relationship between these distributional trends and varying degrees of environmental disturbance;
- 3) the quantification of foraminiferal and macrofaunal responses to sewage disposal and the development of a quantitative bio-indicator method based on foraminiferal distribution.

### 5.3 STUDY AREA

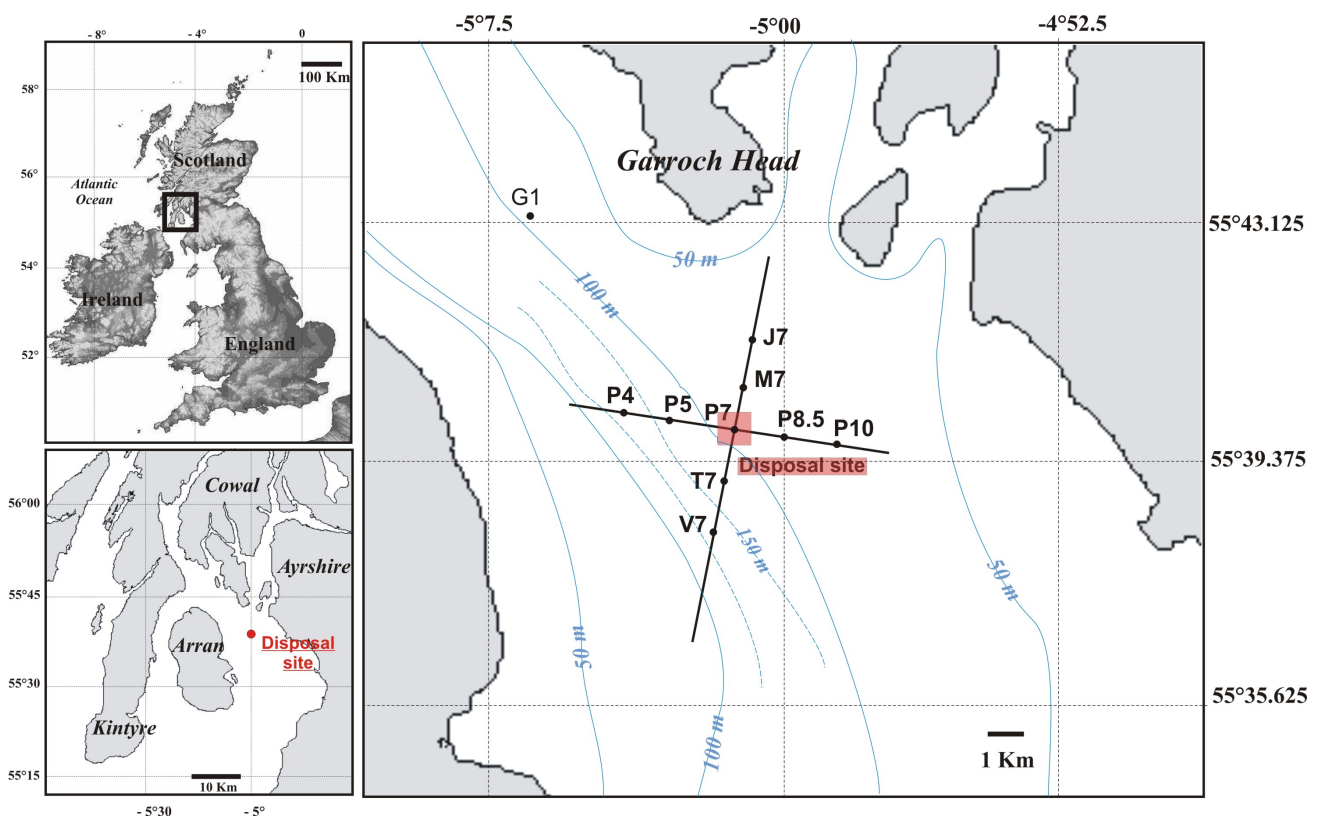


Figure 5-1. Study area and sampling location (50 m and 100 m bathymetric curves are represented according to Matthews *et al.*, 1999, whereas the 150 m bathymetric curve is tentatively indicated in function of our own depth measurements)

The study area is located in the western part of Scotland in the Firth of Clyde, at a water depth varying from 58 to 178 m (Fig. 5-1, Table 5-1). The disposal site itself is situated at a water depth of 79 m. Towards the north and the east, water depth remains rather stable, whereas towards the west and the south, the sea floor deepens considerably (with a maximum of 178 m at about 3 Km WSW of the disposal site).

Station	Water depth (m)	Distance from the disposal site (Km)	Latitude	Longitude
		8 Km North-		
G1	87	West	55°43.04'N	5°6.44'W
J7	79	2.8 Km North	55°41.29'N	5°1.00'W
M7	73	1.2 Km North	55°40.54'N	5°1.16'W
P4	154	2.9 Km West	55°40.27'N	5°4.05'W
P5	135	1.8 Km West	55°40.11'N	5°2.97'W
P7	79	0	55°39.81'N	5°1.36'W
P8.5	58	1.5 Km East	55°39.58'N	4°59.94'W
P10	75	3.2 Km East	55°39.34'N	4°58.45'W
T7	119	1.7 Km South	55°38.88'N	5°1.47'W
V7	178	2.6 Km South	55°38.41'N	5°1.58'W

Table 5-1. Geographical position of the sampling stations and their water depths

A general description of the surface sediments of the Firth of Clyde Sea was first provided by *Deegan et al. (1973)*, who show soft muddy sediments in the deeper areas grading into sandier sediments in areas shallower than 50 m, admixed with gravel in the even shallower fjordic areas. The precise succession of various sedimentary facies is of course considerably more complex than this very simplified picture. The sediments in our study area are predominantly silty clays (*Pearson, 1986*).

The Garroch Head site was described by *Pearson (1986)* as a non-dispersive area from a hydrodynamic point of view. Oceanographic conditions in the vicinity of the area have been described in some detail by *Dooley (1979)*. Residual currents over the disposal area, driven by tidal currents, are generally weak ( $< 10 \text{ cm s}^{-1}$ ). The low current velocities result in a rapid settlement of the sedimentary material present in the water column and consequently in the accumulation of important quantities of sediment enriched in organic carbon, metals and other components of anthropogenic origin. Wind driven currents, generally in a SE direction, with a current speed of 5 to 15 cm/s, cause relatively rapid renewal of the bottom water. However, both current speed and direction are variable over time. In non impacted areas the water immediately above the sediment surface is always fully oxygenated and organic matter degradation is maintained without creation of anoxia at the sea floor (*Pearson, 1986*).

## 5.4 MATERIAL AND METHODS

Ten stations were sampled between the 7<sup>th</sup> and the 10<sup>th</sup> of June 1988 with the R.V. Calanus (Table 5-1), along two perpendicular transects centred around the disposal site (Fig. 5-1). Five stations were sampled along the E/W transect and five along the N/S transect (the central station, P7, being common to both transects). In addition, a reference station was sampled some 8 Km NW of the disposal area. At each sampling station, a Craib core sample (Craib, 1965) and a 0.1 m<sup>2</sup> Van-Veen grab were obtained. The core samples provided material for physico-chemical analyses (Heavy metal, carbon and nitrogen, redox potential (Eh) and acidity (pH) measurements). The top centimetre of the grab samples was analysed for the presence of benthic foraminifera and macrofaunal organisms. It has been shown that the study of the first centimetre of grab samples gives a reliable picture of the macrofauna (Heip *et al.*, 1977). However, for small-sized organisms such as foraminifera and metazoan meiofauna, grab samples may not always be satisfactory. More specifically, part of the superficial sediment, together with the small-sized organisms inhabiting this niche, may be lost due to the bow wave generated by the impact of the sampling engine at the sea floor, or may be washed out during the recovery of the engine. In the case of foraminifera, especially epibenthic forms may be concerned (Murray, 2006). It is therefore important to realise that this potential sampling bias could be responsible for some of the differences between the foraminiferal and the macrofaunal records.

Eh and pH measurements were made in the Craib cores on board of the ship immediately after sampling. Measurements were made using a specially constructed electrode designed to give readings at different levels in the core in the course of stepwise penetration down to about 10 cm depth. The Eh electrodes had an internal reference electrode and a working length of 250 mm with a diameter of 10 to 12 mm. The electrode was designed with a ceramic bridge to an Ag/AgCl reference system using saturated KCl, and had a sensing element consisting of a small platinum plug approximately 3 mm long and 2 mm in diameter. This sensing element was small enough to measure differences in a few millimetres thick sediment layers. The electrodes were made by Russell pH Ltd., Auchtermuchty, Fife, Scotland (Type No. CMF 2/250/Model R/2). The Eh and pH electrodes were mounted side by side (10 mm apart) on a Palmer stand and were slowly wound down into the core. Readings were made on a digital mV/pH meter capable of reading down to 1 mV, and were corrected by +198 to the direct reading obtained on the mV meter (in order to correct for the Ag/AgCl

reference system). An initial reading was made in the overlying water 10 mm above the sediment surface and the electrode sensing elements was then lowered to just penetrate the sediment surface, where a further reading was taken after a period of 60 sec. Thereafter, readings were taken at fixed 5 mm intervals to 5 cm depth and at 2.5 cm intervals to 10 cm. Each reading was taken after period of 60 sec needed to arrive at an equilibrium state.

Total organic carbon (excluding carbonates) and total nitrogen were analysed with a Perkin-Elmer elemental analyser (Model 240). The samples were pretreated with diluted hydrochloric acid to remove carbonates.

For metal concentration measurements, freeze-dried sediments were gently ground to a fine powder with an agate mortar and pestle. The sample (1 g dry weight) was then digested with 5 ml concentrated nitric acid and 2 ml of 30 % hydrogen peroxide. The digest was allowed to stand at room temperature until frothing ceased and was gently heated to boiling on a hot plate and refluxed for a minimum of thirty minutes. If required, additional hydrogen peroxide was added to the cooled digest and digestion continued. After digestion, the solution was cooled, filtered, made up to known volume and the metal concentrations determined by Atomic Absorption Spectrophotometry.

Temperature measurements were performed on the water overlying the sediment in the cores immediately upon their return on board the ship. Salinity was measured in water sampled in the cores, 2 to 5 cm above the sediment surface. They were returned to the laboratory, where salinity was measured using a Guildline conductivity salinometer.

For the analysis of the macrofauna, the uppermost centimetre of the sediment was sampled with a stainless steel spoon, and was sieved on deck using a sieve-table with a 1 mm mesh. The sieve residue was stored in 4% formaldehyde solution buffered with borax. In the laboratory, this > 1 mm fraction was hand-sorted under a binocular microscope, and all organisms were identified and enumerated. Wet-weight biomass was determined for major taxonomic groups using an electronic balance.

For the study of the foraminiferal assemblages, the complete, untreated sediment of the topmost cm was preserved in a 4% formaldehyde solution buffered with Borax, with 1g/l Rose Bengal, in order to distinguish living specimens. In order to increase the comparability with other studies, the foraminiferal samples were sieved over sieves with 63  $\mu\text{m}$  and 150  $\mu\text{m}$  mesh sizes, and both size fractions (63-150  $\mu\text{m}$  and > 150  $\mu\text{m}$ ) were studied separately. Both sieve residues were hand-sorted under a binocular microscope, and all foraminifera were

identified, enumerated and determined, using commonly used taxonomic reference works (e.g. *Phleger, Parker and Pearson, 1953; Loeblich and Tappan, 1964; Jones, 1994, etc.*).

In order to better show spatial patterns of faunal variability, we applied a Principal Component Analysis (*StatSoft, Inc. (2004). STATISTICA (data analysis software system), version 7. www.statsoft.com*) both to the foraminiferal (63-150  $\mu\text{m}$  and  $> 150 \mu\text{m}$  fractions summed together) and macrofaunal percentage data. Only taxa occurring with more than 5% in at least one sample were retained in these PCA analyses. For each station, the Shannon Wiener index (H) (*Shannon, 1948; Hayek et Buzas, 1997*) was calculated according to

$$H = -\sum_{i=1}^s p_i \ln p_i$$

in which “s” is the number of species and “p” is the relative frequency of the “ith” species. Fisher alpha ( $\alpha$ ) indices were computed using

$$\alpha = n_1/x$$

where “x” is a constant having a value inferior to 1 and “n<sub>1</sub>” can be calculated from  $N(1-x)$ , N being the number of individuals (*Murray, 1991*).

## 5.5 RESULTS

### 5.5.1 Chemical properties of surficial sediments

Figure 5-2a presents the redox potential of the surficial sediments. Low redox values are indicative of highly reducing conditions in the sediment, brought about by the degradation of large amounts of organic matter. Since we do not dispose of oxygen measurements at the sea floor and/or within the sediment, we use redox values as a proxy for bottom-water oxygenation. At the dumping site (P7), reducing conditions (negative redox values) appear at the sediment-water interface. *Sutherland et al. (2007)* suggest that redox values higher than 50 characterise well oxygenated conditions, values from -50 to 50 indicate slightly oxic environments, whereas values between -50 and -150 are typical of hypoxic environments ( $< 2 \text{ mg/l}$ ; *Tyson and Pearson, 1991*). Redox values below -150 are only found in anoxic conditions. The value of -96, measured at station P7, therefore indicates strongly hypoxic conditions at the sediment-water interface. Relatively low (but positive) redox values (with respect to the base-line values found in station G1) are found until about 2 Km from the

disposal site. However, the positive redox values suggest that the sediment-water interface is well oxygenated ( $> 2 \text{ mg/l}$ ) at all sites except at station P7. At a distance of about 3 Km, redox potential values are comparable to those at the reference station (except for station J7 that shows a slightly lower value). In general, redox values in the most affected area were somewhat lower in June 1988 than in May 1987 (Pearson, 1988).

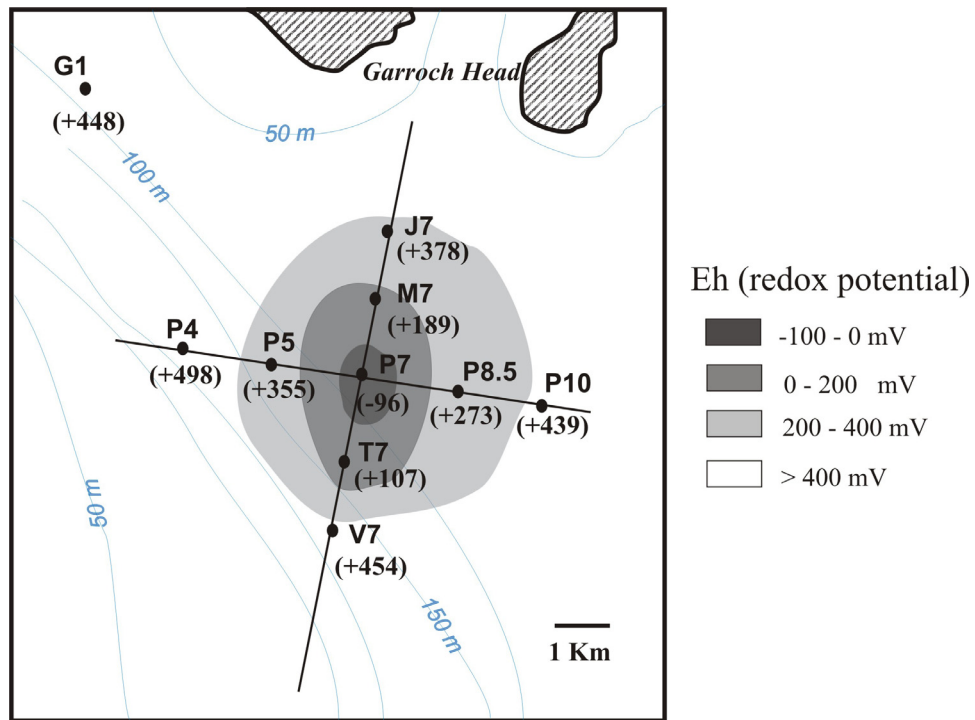


Figure 5-2a. Redox potential in the sediment surface

When we compare the redox potential profiles in the upper 10 cm of the sediment, the differences in redox potential between the stations become even clearer (Fig. 5-2b, Appendix 5-1). In fact, at the deepest stations P4 and V7 the redox potential stays above 300 down to 4 cm depth, suggesting well oxygenated conditions. Reference station G1, and stations P10 and J7, which are equally distant from the discharge point as P4 and V7, but in shallower water, appear to be well oxygenated in the upper 2 cm, and attain an Eh of about 100-170 mV deep in the sediment (below 5 cm depth). At all stations situated at about 2 Km from the dumpsite (M7, T7, P8.5 and P5) Eh values tend to fall below 100 mV in the top 2 cm of the sediment. Apparently, only the topmost sediment is well oxygenated at these sites. At the disposal site (P7), Eh values are already negative (-96 mV) at the surface and decrease to about -200 mV at 10 cm depth, denoting strongly hypoxic conditions at the sediment-water interface, with a very limited oxic penetration into the sediment.



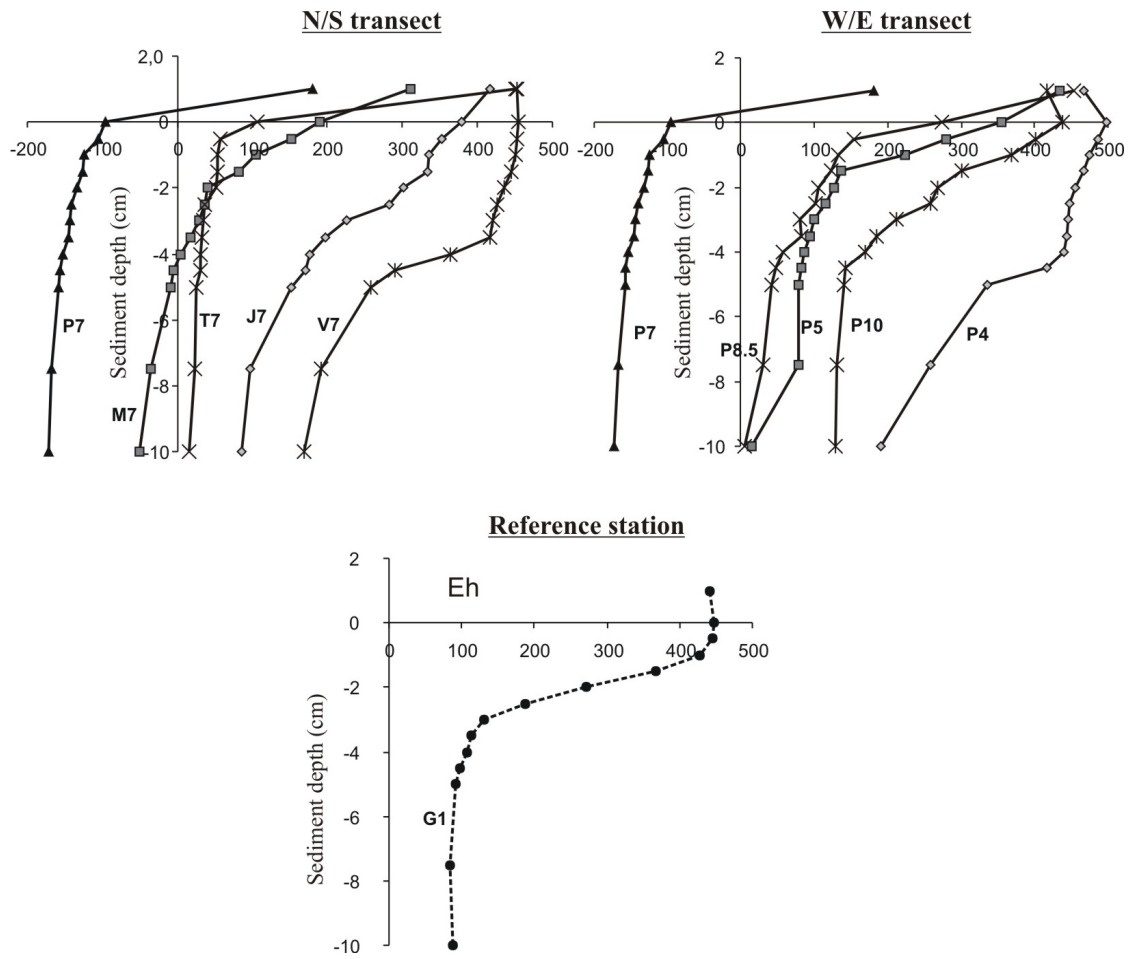


Figure 5-2b. Profiles of redox potential in the sediment until 10 cm depth

The pH at the sediment surface varies from 7.26 to 7.77, with a minimum value at the disposal site and a maximum at reference station G1 and at station V7 (Fig. 5-3; Appendix 5-1).

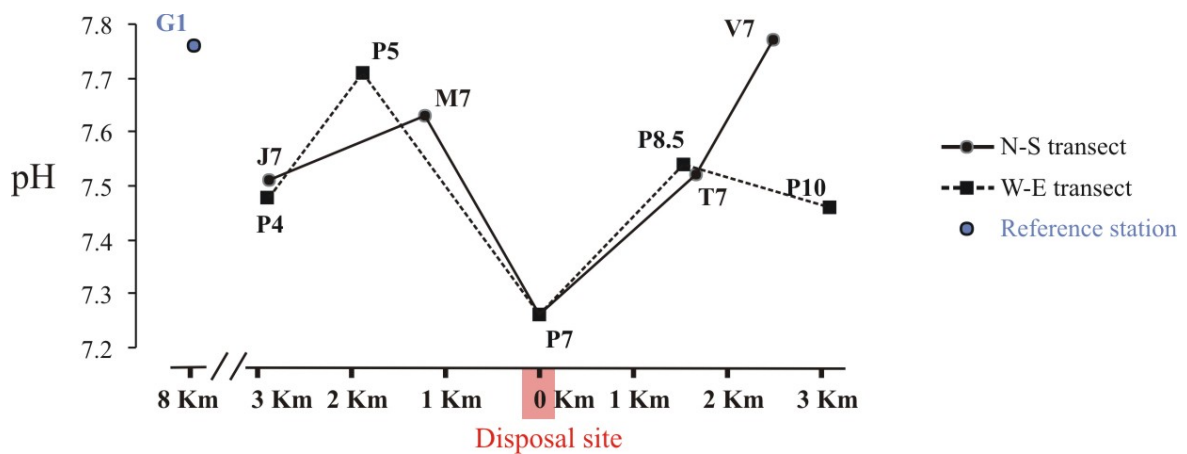


Figure 5-3. Acidity of the sediment surface along the transects

The results of organic carbon and nitrogen analyses are presented in figures 5-4 and 5-5. At the background station G1, the sediment contains 2.6 %  $C_{org}$  and 0.26 % total N. Maximal values, of 12.4 %  $C_{org}$  and 1.26 % total N, are found at the disposal site (P7). Until about 2 km from the disposal sites, high  $C_{org}$  (3-5.6 %) and total N values (0.3-0.6 %) are observed, especially to the east and south.

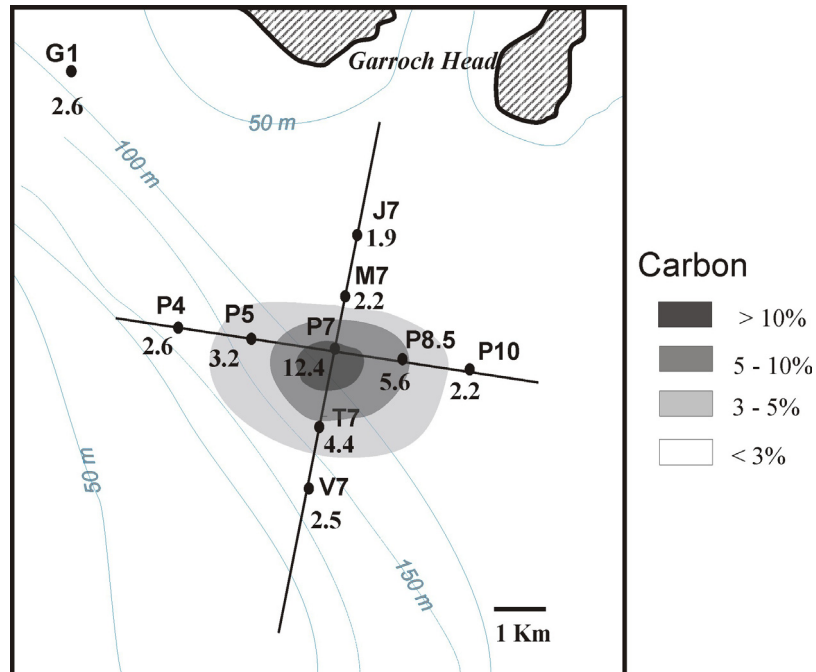


Figure 5-4. Distribution of organic carbon in the surficial sediment (% d.w.)

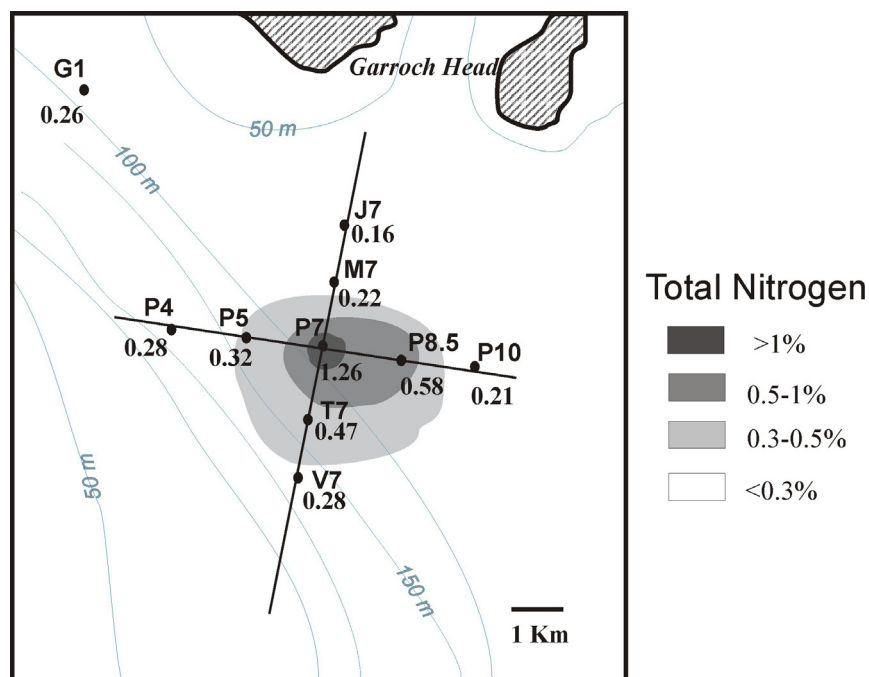


Figure 5-5. Distribution of total nitrogen in the surficial sediment (% d.w.)

The results of metal concentration measurements are presented in figure 5-6. This shows elevated concentrations for most metals at the disposal site P7. Zn, Cr, Cu and Pb are the most abundant heavy metals found in the impacted area. Concentrations of these elements (Appendix 5-3) are very high at the disposal site (a total of about 2500 mg/Kg dry weight) and decrease progressively to the stations farthest away from the dumpsite. At the reference station, heavy metal concentrations do not exceed 500 mg/Kg dry weight. *Pearson (1988)* described a general tendency towards increasing metal concentrations from 1979 to 1988.

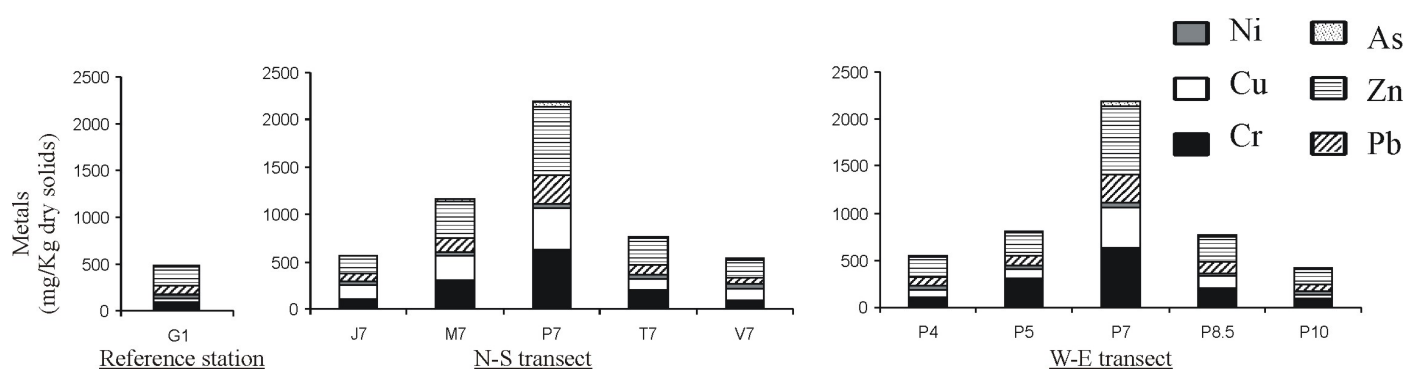


Figure 5-6. Distribution of heavy metals in the sediments along the transects

The temperature and salinity of the water immediately (1-2 cm) above the sediment surface were very uniform ( $T \sim 8^\circ\text{C}$  and  $S \sim 34\text{‰}$ ) in June 1988.

### 5.5.2 Foraminiferal faunas (Appendices 5-5 and 5-6)

Generally, the living (Rose Bengal stained) faunas in the larger size fraction ( $> 150\ \mu\text{m}$ ) of the superficial sediment (0–1 cm) are relatively poor. The total number of living individuals varies from 0 at station P7 (disposal site) to 101 per  $0.1\ \text{m}^2$  at station P10 (3 Km east of the disposal site). The species richness is also low, varying from a total absence at station P7 to 9 species at station P5 (2 Km west of the disposal site). In general, the fauna in the  $> 150\ \mu\text{m}$  fraction is dominated by the agglutinated species *Eggerella scabra*. In some of the stations, this taxon is accompanied by fair numbers of *Bulimina marginata*, *Reophax nodulosus* and *Stainforthia concava* (Fig. 5-7, Appendix 5-5).

## Comparison of foraminiferal and macrofaunal responses to organic pollution (Scotland)

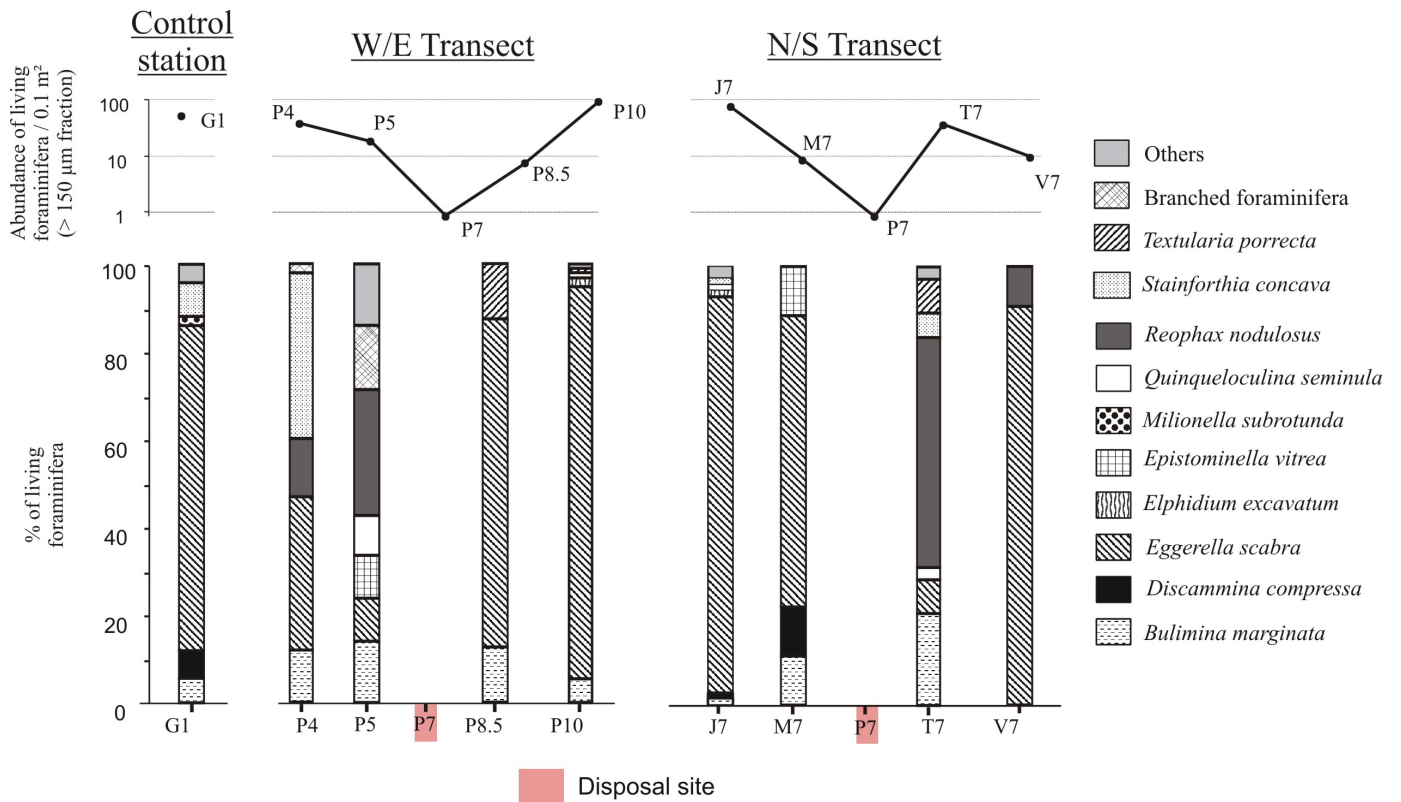


Figure 5-7. Density and composition of foraminiferal faunas (> 150 μm fraction) for 0.1 m<sup>2</sup> sediment surface.

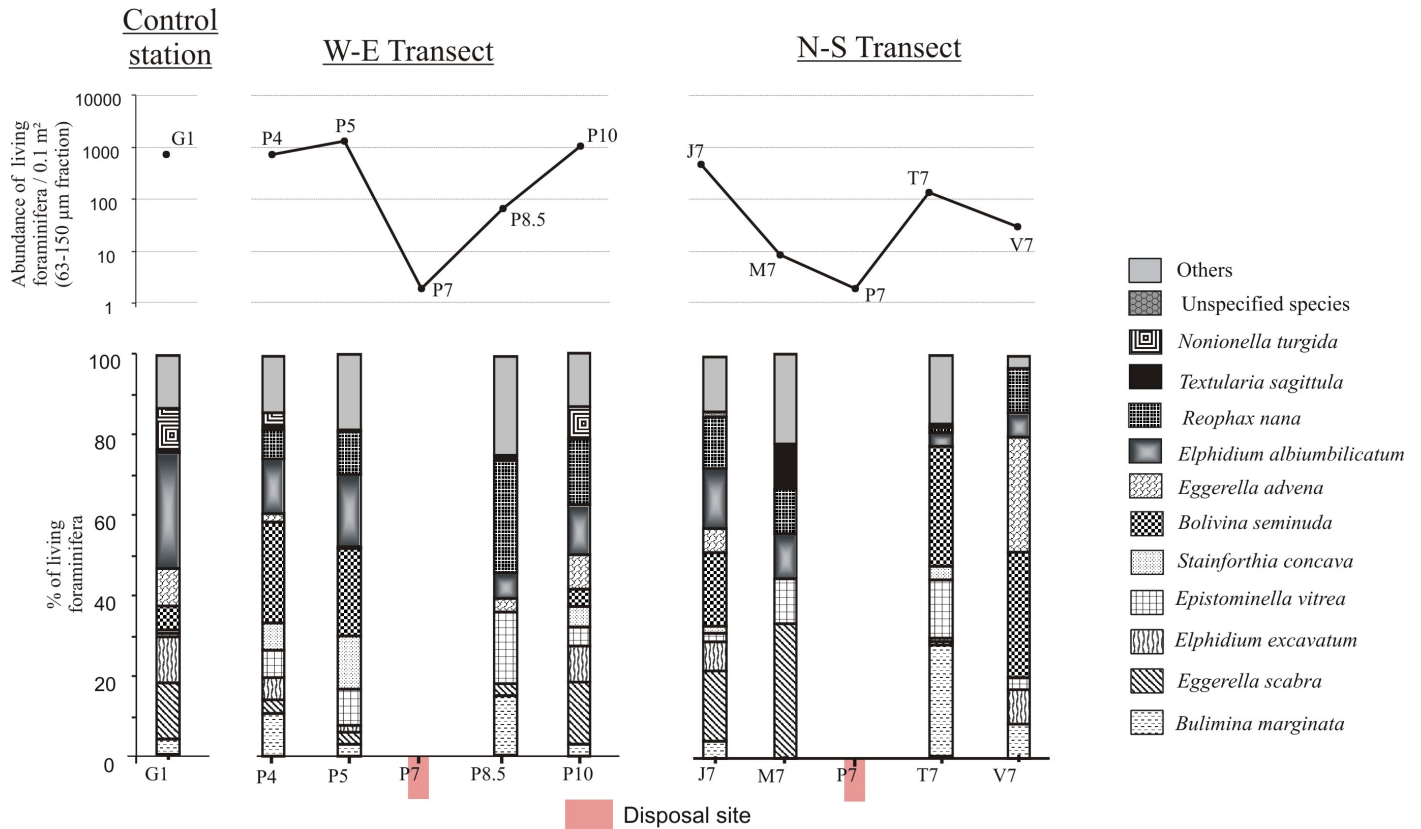


Figure 5-8. Density and composition of the foraminiferal faunas (63-150 μm fraction) for 0.1 m<sup>2</sup> sediment surface

The faunas in the 63-150  $\mu\text{m}$  size fraction are nearly always much richer. The total number of individuals found in the topmost cm varies from 2 at station P7 (disposal site) to 1093 individuals/0.1  $\text{m}^2$  at station P5 (2 Km west of the disposal site). The species richness is also higher than in the  $> 150 \mu\text{m}$  fraction and varies from 2 species at station P7 to 24 species at station P4 (3 Km west of the disposal site). In general, the fauna is dominated by *Bulimina marginata*, *Eggerella scabra*, *Bolivina seminuda*, *Elphidium albiumbilicatum* and *Reophax nana*. In some of the stations, these taxa are accompanied by *Elphidium excavatum*, *Epistominella vitrea*, *Stainforthia concava*, *Eggerella advena*, *Textularia sagittula* and *Nonionella turgida* (Fig. 5-8; Appendix 5-6).

Species	Stations		G1		P4		P5		P7		P8.5		P10		J7		M7		T7		V7		
	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	
<i>Bolivina seminuda</i>	43	5.6	200	23.7	241	21.6	1	50.0			0.0	44	4.0	87	15.8					39	23.4	11	23.9
<i>Bulimina marginata</i>	31	4.0	89	10.5	37	3.3					10	14.5	35	3.2	21	3.8	1	5.6	44	26.3	3	6.5	
<i>Eggerella advena</i>	68	8.8	20	2.4	5	0.4					2	2.9	84	7.6	27	4.9					10	21.7	
<i>Eggerella scabra</i>	138	17.9	43	5.1	32	2.9					8	11.6	244	22.1	156	28.3	9	50.0	4	2.4	10	21.7	
<i>Elphidium albiumbilicatum</i>	210	27.2	108	12.8	197	17.7					4	5.8	123	11.1	71	12.9	1	5.6	4	2.4	2	4.3	
<i>Elphidium excavatum</i>	85	11.0	44	5.2	20	1.8						0.0	96	8.7	35	6.4				1	0.6	3	6.5
<i>Epistominella vitrea</i>	4	0.5	56	6.6	100	9.0					11	15.9	43	3.9	11	2.0	2	11.1	19	11.4	1	2.2	
<i>Nonionella turgida</i>	75	9.7	28	3.3	5	0.4						0.0	79	7.1	6	1.1							
<i>Reophax nana</i>	4	0.5	60	7.1	113	10.1					17	24.6	167	15.1	59	10.7	1	5.6	2	1.2	4	8.7	
<i>Reophax nodulosus</i>	11	1.4	8	0.9	6	0.5						0.0	10	0.9	5	0.9				20	12.0	1	2.2
<i>Stainforthia concava</i>	11	1.4	72	8.5	143	12.8						0.0	54	4.9	9	1.6				6	3.6		
<i>Textularia porrecta</i>	11	1.4	20	2.4	84	7.5	1	50.0			13	18.8	65	5.9	21	3.8	1	5.6	5	3.0			
<i>Textularia sagittula</i>			4	0.5	1	0.1					1	1.4					1	5.6	1	0.6			
Others	80	10.4	93	11.0	130	11.7					3	4.3	62	5.6	43	7.8	2	11.1	22	13.2	1	2.2	
<b>Total</b>	<b>771</b>		<b>845</b>		<b>1114</b>		<b>2</b>				<b>69</b>		<b>1106</b>		<b>551</b>		<b>18</b>		<b>167</b>		<b>46</b>		
<b>Number of species</b>	<b>26</b>		<b>24</b>		<b>27</b>		<b>2</b>				<b>9</b>		<b>21</b>		<b>26</b>		<b>9</b>		<b>24</b>		<b>10</b>		
<b>Fisher alpha</b>	<b>5.19</b>		<b>4.59</b>		<b>4.98</b>		<b>0.00</b>				<b>2.76</b>		<b>3.67</b>		<b>5.66</b>		<b>7.16</b>		<b>7.68</b>		<b>3.93</b>		
<b>Shannon Wiener</b>	<b>2.35</b>		<b>2.57</b>		<b>2.44</b>		<b>0.69</b>				<b>1.95</b>		<b>2.45</b>		<b>2.34</b>		<b>1.71</b>		<b>2.29</b>		<b>1.96</b>		

Table 5-2. Most abundant foraminiferal taxa recorded for each station (density for 0.1  $\text{m}^2$  sediment surface and relative density), species richness and diversity indices (Fisher alpha and Shannon Wiener).

Figure 5-9 summarises the variation in species richness and abundance along the E/W and the N/S transects for the joint 63-150  $\mu\text{m}$  and  $> 150 \mu\text{m}$  fractions (Table 5-2). Both parameters show a conspicuous minimum at the disposal site, which is almost azoic (only 2 specimens in the 63-150  $\mu\text{m}$  fraction). For both parameters, there is an increasing tendency towards samples situated 2 to 3 Km away from the disposal site, where abundance and species richness attain values comparable to the background levels recorded at reference station G1.

Shannon Wiener and Fisher alpha diversity indices were computed on the basis of the abundance data at each station. Generally, both indices have elevated values at reference station G1, may show an increase to the stations between 1 and 2 Km from the disposal site (especially for the Fisher alpha index), and fall to almost zero at the discharge station P7 (Fig. 5-10).

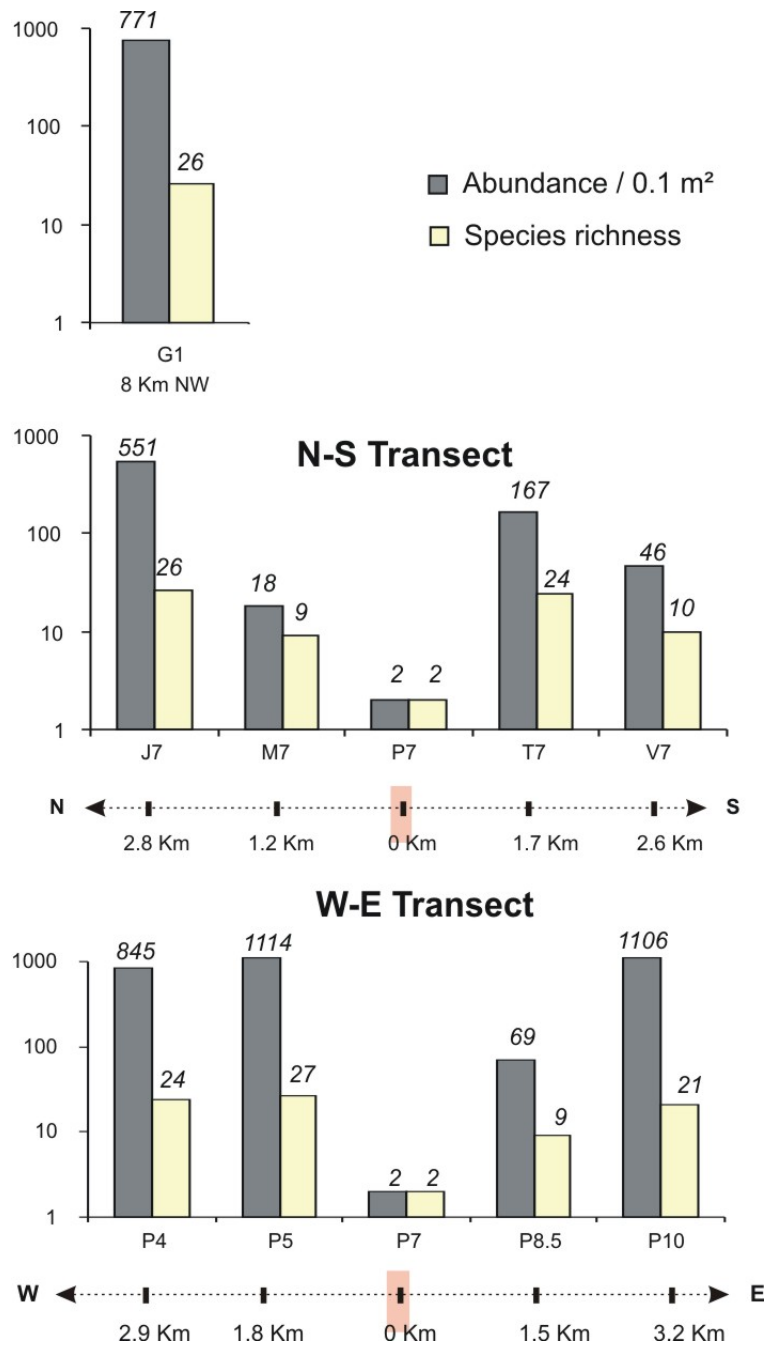


Figure 5-9. Abundance and species richness of the total foraminiferal fauna (> 150  $\mu$ m + 63-150  $\mu$ m)

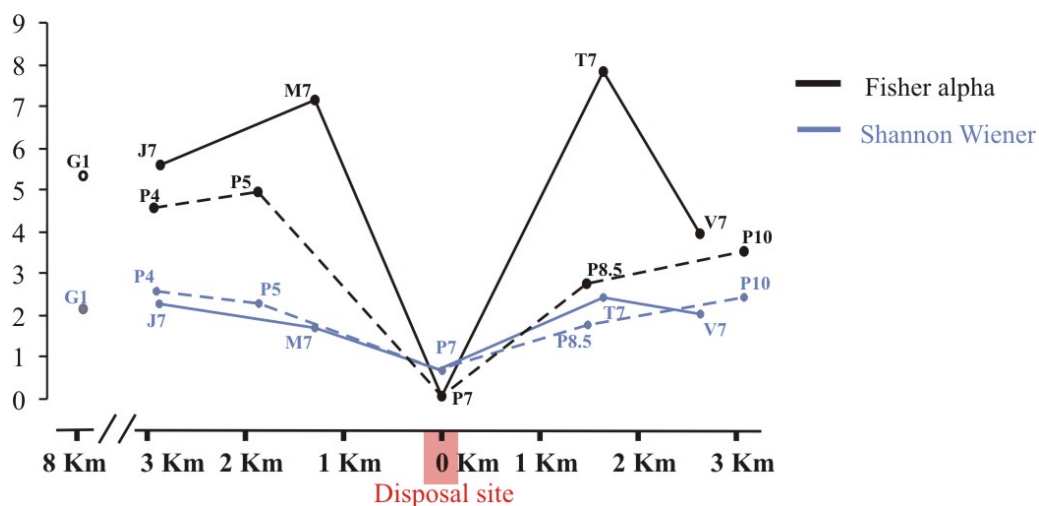


Figure 5-10. Fisher alpha index and Shannon Wiener index of benthic foraminifera along NS and WE transects

The PCA analysis is based on the percentage data (63-150  $\mu\text{m}$  and  $> 150 \mu\text{m}$  summarised) of all taxa occurring with more than 5 % in at least one sample. Station P7 was excluded from the database because it contains only 2 individuals. The results of this PCA analysis are presented in table 5-3 and in figure 5-11. The first two axes (Eigenvalues 308.3 and 152.6, respectively) account for 44.73 % and 22.13 % of the total variation in the dataset.

Value number	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	308.30	44.73	308.30	44.73
2	152.56	22.13	460.86	66.86
3	109.55	15.89	570.41	82.75
4	62.60	9.08	633.02	91.83
5	41.12	5.97	674.13	97.80
6	7.89	1.15	682.03	98.94
7	5.44	0.79	687.46	99.73
8	1.85	0.27	689.31	100.00

Table 5-3. Results of the foraminiferal PCA analysis

The cluster based on Ward's method (Fig. 5-11a; based on Euclidean distances) shows 2 groups of samples (T7, P5 and P4 versus V7, J7, P10 and G1), and two isolated stations with a much weaker correlation (M7 and P8.5).

Figure 5-11b shows that the first PCA axis is positively loaded by *Bolivina seminuda*, *Bulimina marginata*, *Stainforthia concava* and *Reophax nodulosus*, whereas *Eggerella scabra* has a strong negative contribution. The second PCA axis has positive loadings of *Elphidium albiumbilicatum*, *Bolivina seminuda*, *Eggerella advena*, *Elphidium excavatum* and *Nonionella*

*turgida*, whereas *Epistominella vitrea*, *Textularia porrecta*, *Reophax nana*, *Bulimina marginata* and *Textularia sagittula* have a negative contribution.

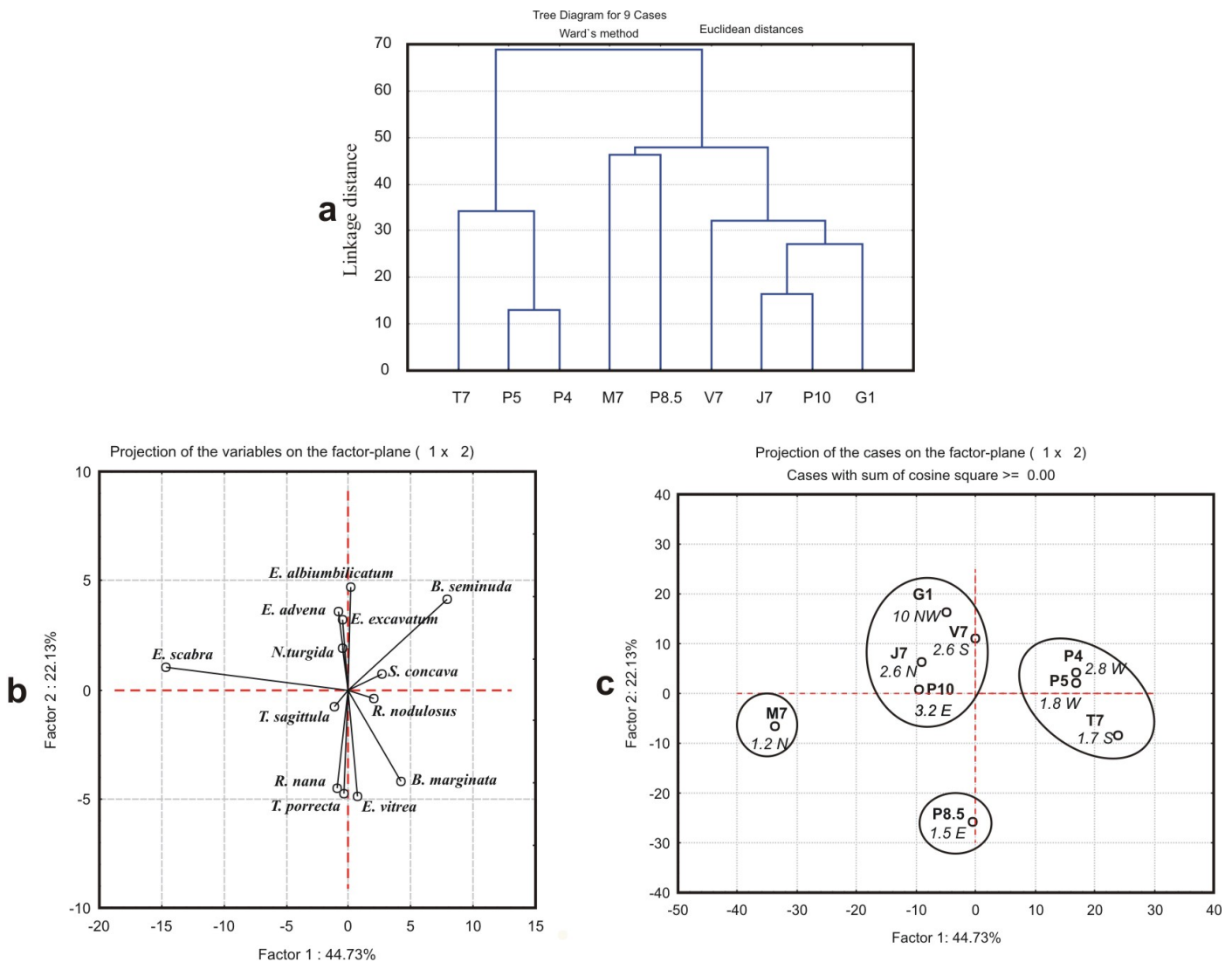


Figure 5-11. PCA analysis. a, Cluster according to euclidean distances; b, Projection of the variables (foraminifera) on the two main PCA axes; c, Plot of the 10 stations on the two main PCA axes, and four distinct assemblages (indicated by the dotted lines).

Figure 5-11c, which shows the position of the samples on the axial plot, distinguishes the two groups of samples and two isolated sites recognised by the cluster analysis (Fig. 5-11). As it can be seen in figure 5-12, the fauna of station M7, with a high negative loading on axis 1, is strongly dominated by *E. scabra*. On the other hand sample P8.5, with a high negative value on axis 2, has the highest values of *E. vitrea*, *T. porrecta*, *R. nana*, *B. marginata* and *T. sagittula*. Thus the group of samples with a positive score on axis 1 (P4, P5 and T7) are enriched in taxa with a positive score on this axis (*B. seminuda*, *B. marginata*, *S.*



*concava* and *R. nodulosus*, see Fig. 5-12). Finally, the group of samples with a positive score on axis 2 (G1, V7, J7 and P10) are rich in *E. albumbilicatum*, *E. advena*, *E. excavatum* and *N. turgida*, all of which grouped together in the central part of figure 5-11b, on the positive side of axis 2. These taxa are accompanied by *E. scabra* and *B. seminuda*, both also having a positive loading on axis 2 (Figs. 5-11b, 5-12).

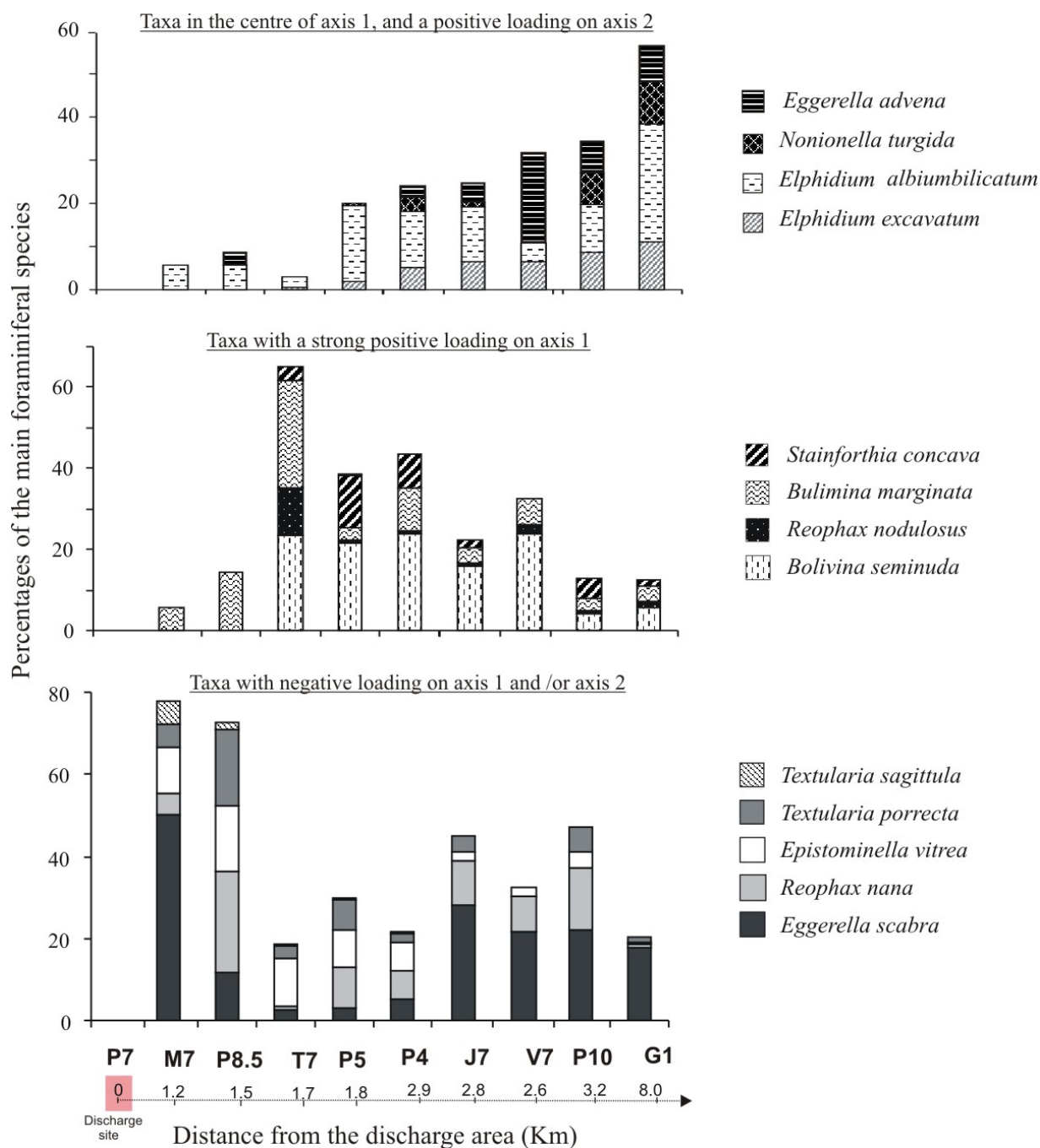


Figure 5-12. Change in dominant species of total benthic foraminifera (> 5%).

The four groups of samples recognised by the PCA analysis appear in a typical horse-shoe distribution (Fig. 5-11) on the factor plot (*Hill and Gauch, 1980; Digby and Kempton, 1987*). The control station G1 is plotted together with stations J7, V7 and P10, 2.6 to 3.2 km from the disposal site, that have rather similar faunas (Fig. 5-12). Samples T7, P5 and P4, respectively at 1.7, 1.8 and 2.8 km from the disposal site, are distinguished by their high positive score on axis 1. Sample P8.5, 1.5 km south of the disposal site plots negatively on axis 2, whereas sample M7, closest to the disposal site (1.2 km N) plots on the negative side of axis 1. It seems probable that this succession of samples reflects a gradient of an increasing foraminiferal response to environmental stress. In figure 5-12, where we present changes in faunal distribution, we have ordered the stations according to their position on this gradient. This ordination reflects the distance to the disposal site, with the exception of station P4 (2.8 km W of the disposal site), that is grouped together with P5 and T7, which are much closer to the disposal site (Fig. 5-12).

### 5.5.3 Macrofauna (Appendices 5-4)

The macrofaunal biomass found at the sampling stations gives an overall indication of the gross effects of sludge deposition on the fauna. Table 5-4 summaries densities and relative abundances of the most abundant macrofaunal species that occur with more than 5 % in at least one sample. Figure 5-13 compares the biomass recorded in each grab sample for the stations sampled in 1988 with the average of the same stations during the previous 9 years (*Pearson, 1988*). The biomass at station P7 (disposal site) was much lower in 1988 than this 9 year average. Also at station P8.5, 1.5 Km east of the disposal site, values lower than the 1979-87 average were found. However, the large standard errors, especially at sites P7 and M7, show a large interannual variability close to the disposal site. On the northern transect, values much higher than the 1979-87 average were found at both stations (J7 and M7). Also at station P5 (1.8 Km west) and P10 (3 Km east) the 1988 values were higher than the 9 year average. At the other stations, the 1988 values are quite similar to the 1979-87 average. The very low biomass ( $1.4 \text{ g /}0.1 \text{ m}^2$ ) found at the disposal site (P7) suggests an increased environmental stress in comparison to the average of the 1979-87 dataset. Very low biomass levels were also recorded at this site in 1983 ( $0.8 \text{ g /}0.1 \text{ m}^2$ ) and in 1986 ( $11.5 \text{ g /}0.1 \text{ m}^2$ ).

Species	P7		M7		P8.5		T7		P5		V7		J7		P4		P10		G1		
	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	
<i>Abra alba</i>																					
(mollusc bivalve)					26	2.7	4	0.2	4	0.5	4	1.8	65	15.0	15	12.7	28	17.5	1	1.7	
<i>Ameana</i> spp.																					
(annelid polychaete)					3	0.3	17	0.7	53	8.0	9	3.8	4	0.9	4	3.0			3	5.2	
<i>Amphiura filiformis</i>																					
(echinoderm)									3	0.5	12	5.3	2	0.3	3	2.1	5	3.2			
<i>Capitella capitata</i>																					
(annelid polychaete)	66	38.3	1724	7.5	7	0.8	81	3.6					7	1.6			1	0.3	1	0.9	
<i>Cirratulus cirratus</i>																					
(annelid polychaete)			24	0.1	173	18.5	214	9.5	53	8.0											
<i>Corbula gibba</i>																					
(mollusc bivalve)					1	0.1			10	1.4	11	4.9	3	0.7	8	6.8					
<i>Mediomastus fragilis</i>																					
(annelid polychaete)	1	0.6	248	1.1	346	37.1	1222	54.5	197	29.9	28	12.4	7	1.5	7	5.5	3	1.6	2	2.6	
<i>Melinna palmata</i>																					
(annelid polychaete)					3	0.3	117	5.2	3	0.5	1	0.2									
<i>Nematoda</i>	90	51.9	1044	4.6	85	9.1	121	5.4						4	0.9					1	0.9
<i>Nucula</i> spp.																					
(mollusc bivalve)			1	0.0	1	0.1	8	0.4	19	2.9	44	19.5	93	21.4	12	10.1	43	27.1	15	26.1	
<i>Ophiura albida</i>																					
(echinoderm)					2	0.2	13	0.6	14	2.1	18	8.0	3	0.7			2	1.3			
<i>Pectinaria koreni</i>																					
(annelid polychaete)									1	0.1		0.0	26	5.9			1	0.3	1	0.9	
<i>Polyphisia crassa</i>																					
(annelid polychaete)			11	0.0	5	0.5	205	9.1	70	10.5	3	1.1	5	1.0	13	10.5	10	6.4	1	0.9	
<i>Rhodine loveni</i>																					
(annelid polychaete)											3	1.1	4	0.8			9	5.7	4	6.1	
<i>Spiophanes kroyeri</i>																					
(annelid polychaete)							10	0.4	14	2.0	13	5.5	23	5.2	6	5.1	4	2.5	14	24.3	
<i>Terebellides stroemi</i>																					
(annelid polychaete)					1	0.1	1	0.0	10	1.5	2	0.7	2	0.5	9	7.2	5	2.9	1	1.7	
<i>Tubificoides benedeni</i>																					
(annelid polychaete)	12	6.7	19808	86.4	14	1.5	4	0.2			1	0.2	43	9.8							
Others	5	2.6	69	0.3	270	28.9	226	10.1	211	32.0	65	28.5	145	33.6	43	35.9	49	31.2	17	28.7	
<b>A : Abundance</b>																					
(Total per 0.1m <sup>2</sup> )	<b>173</b>		<b>22929</b>		<b>933</b>		<b>2241</b>		<b>660</b>		<b>226</b>		<b>432</b>		<b>119</b>		<b>157</b>		<b>58</b>		
Number of species	<b>10</b>		<b>15</b>		<b>60</b>		<b>53</b>		<b>72</b>		<b>51</b>		<b>64</b>		<b>37</b>		<b>38</b>		<b>30</b>		
Fisher alpha index	<b>2.31</b>		<b>1.56</b>		<b>14.31</b>		<b>9.73</b>		<b>20.58</b>		<b>20.51</b>		<b>20.76</b>		<b>18.46</b>		<b>15.93</b>		<b>25.3</b>		
Shannon Wiener index	<b>1.06</b>		<b>0.54</b>		<b>2.41</b>		<b>1.85</b>		<b>2.98</b>		<b>3.24</b>		<b>3.17</b>		<b>3.10</b>		<b>2.90</b>		<b>2.68</b>		

Table 5-4. Most abundant macrofaunal taxa recorded for each station (density for 0.1 m<sup>2</sup> sediment surface and relative density), species richness and diversity indices (Fisher alpha and Shannon Wiener).

Comparison of foraminiferal and macrofaunal responses to organic pollution (Scotland)

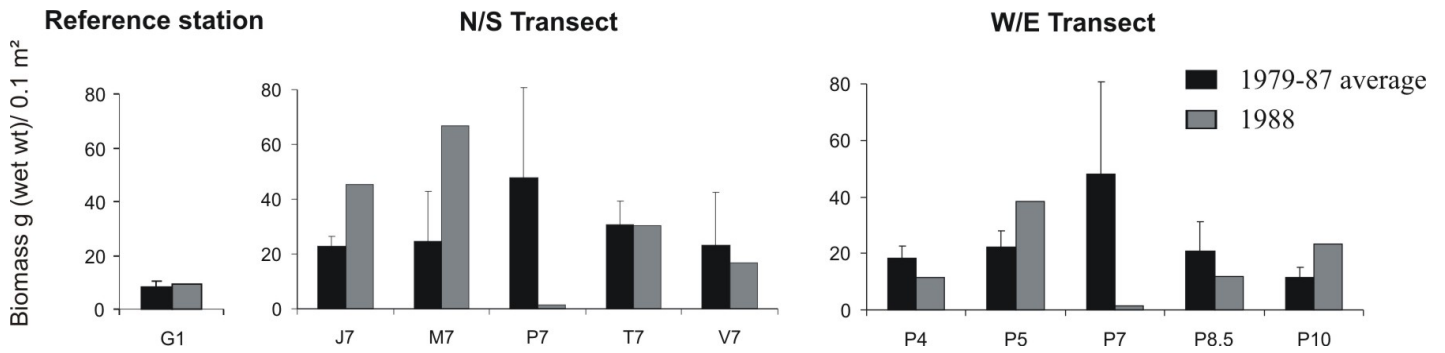


Figure 5-13. Comparison of macrofaunal biomass in 1988 with the average value of the 1979-1987 period.

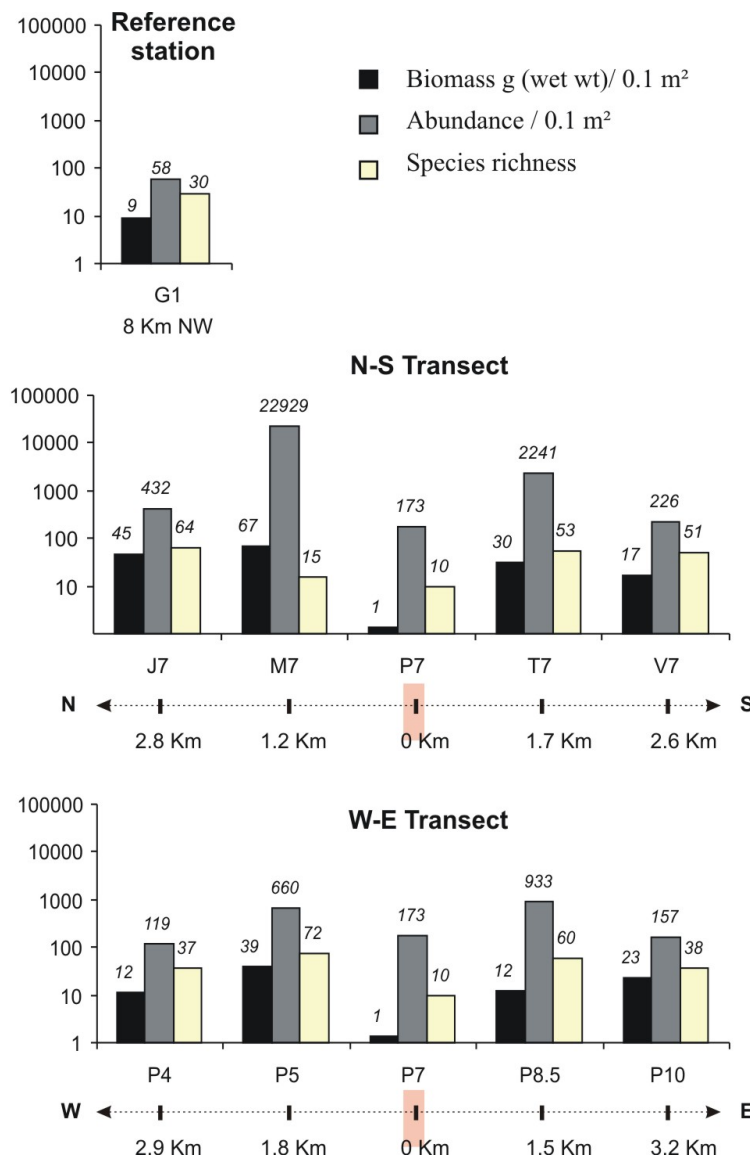


Figure 5-14. Spatial variability of the major macrofaunal parameters along the E/W and N/S transects and in the control station. S, total number of species per 0.1 m<sup>2</sup>; A, total abundance per 0.1 m<sup>2</sup> (number of individuals); B, total biomass per 0.1 m<sup>2</sup>.

A more detailed appreciation of the overall effect of sludge deposition on the benthic fauna of the area can be obtained by the comparison of the variation in species numbers, total abundances and biomass along the transects. Figure 5-14 shows the variation of these three parameters along the E/W and the N/S transects. All three parameters show low values in the centre of the disposal area. This area contains a limited number of individuals of nematode and annelid worms. Abundance, biomass and species richness values rise to maximum levels at the stations between 1 and 2 Km from the disposal site, dramatically so on the northern transect where over 20000 organisms per 0.1 m<sup>2</sup> were recorded at station M7. Farther than 2 Km away, these three parameters tend to decrease on both transects with the exception of station P10, where relatively high biomass levels can be observed 3 Km from the centre and station J7 where a high species richness is maintained 2.8 Km from the disposal site.

Figure 5-15 illustrates the variability of the Shannon Wiener and Fischer  $\alpha$  indices across the two transects. Generally, both diversity indices are relatively high at the reference station and decrease progressively as the disposal site was approached. The lowest value for both indices is recorded at station M7, 1.2 Km north of the disposal site. The highest values are found at J7, V7, P10, P4 and P5 between 2 and 3 Km to respectively the north, the south, the east and the west of the site. At the stations to the east, west and south of the centre (beyond 1.5 Km from the disposal site), the values of both indices are consistently higher than the levels recorded in 1987, indicating a general increase in diversity and a decrease in individual species dominance in these areas (Pearson, 1988).

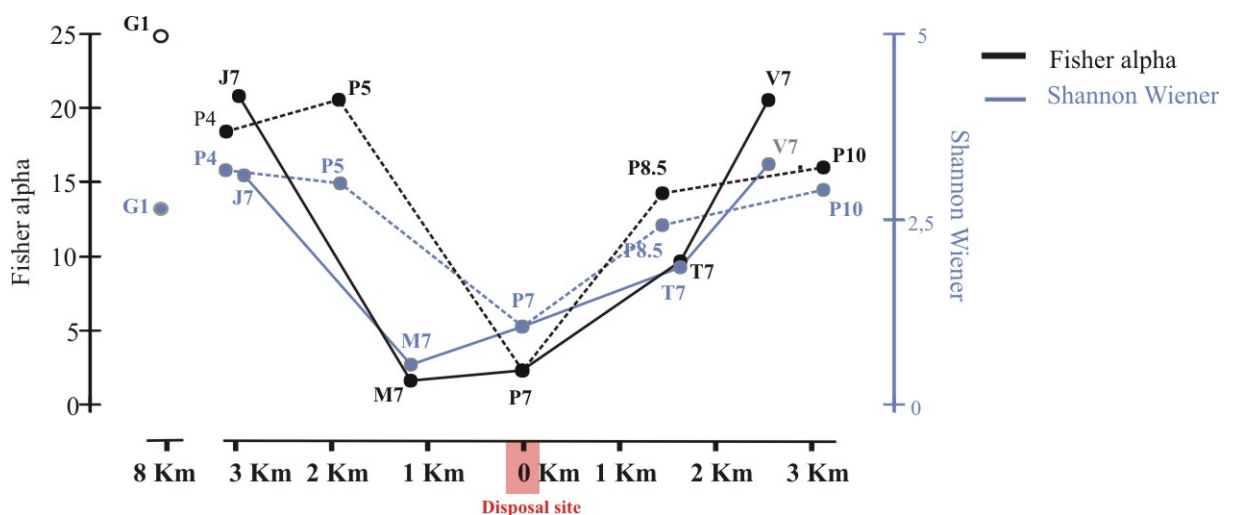


Figure 5-15. Fisher alpha index and Shannon Wiener index of macrofauna along NS and WE transects.

In order to objectively evaluate the differences between samples, a Principal Component Analysis was applied using the percentages of all taxa in the 10 stations with an occurrence of more than 5 % in at least one sample. The main results of these analyses are presented in figure 5-16 and table 5-5. Axis 1 (Eigenvalue = 808.6), axis 2 (Eigenvalue = 455.7) and axis 3 (Eigenvalue = 423.6) account respectively for 44.4 %, 25.0 % and 23.3 % of the total variation in the dataset (Table 5-5).

The cluster diagram based on Ward's method (Euclidean distances) shown in figure 16a, separates our 10 stations into 2 distinct groups and 2 separate samples. This separation is confirmed by the axial plots (Figs. 5-16d and 5-16e).

Axis 1 is positively loaded by the polychaetes *Tubificoides benedeni* and *Capitella capitata*, and by nematode worms, and is negatively loaded by the polychaetes *Mediomastus fragilis*, *Cirratulus cirratus* and the bivalves *Nucula* spp. and *Abra alba*. Samples M7 and P7, where the faunas are heavily dominated by taxa loading positively on the first axis (Fig. 5-16b) are therefore positioned on the positive side of axis 1, whereas all other samples, where these species have much lower percentages (Fig. 5-17), plot on the negative side of axis 1. The positive side of PCA axis 2 is dominated by the bivalves *Nucula* spp. and *A. alba*, and the polychaete *Spiophanes kroyeri* and a large group of subsidiary taxa. The polychaetes *M. fragilis*, *C. cirratus*, *C. capitata* and the nematodes have negative loadings on this axis. Figure 16b shows that this second axis separates samples G1, J7, P10, P4 and V7, with faunas similar to those found at control station G1 (Fig. 17), from samples P5, P8.5 and T7, that are strongly enriched in *M. fragilis*, *C. cirratus*, and *Melinna palmata* (Fig. 5-17). Axis 3, finally, that still accounts for 23.3 % of the total variability is positively loaded by nematodes and *C. capitata*, and negatively by *M. fragilis* and *T. benedeni*. It allows a better separation between stations P7 and M7.

Value number	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	808.65	44.43	808.65	44.43
2	455.67	25.03	1264.32	69.46
3	423.64	23.28	1687.96	92.74
4	58.32	3.20	1746.28	95.94
5	29.57	1.62	1775.84	97.57
6	18.67	1.03	1794.51	98.59
7	16.24	0.89	1810.75	99.49
8	5.07	0.28	1815.83	99.76
9	4.30	0.24	1820.13	100.00

Table 5-5. Results of the macrofaunal PCA analysis

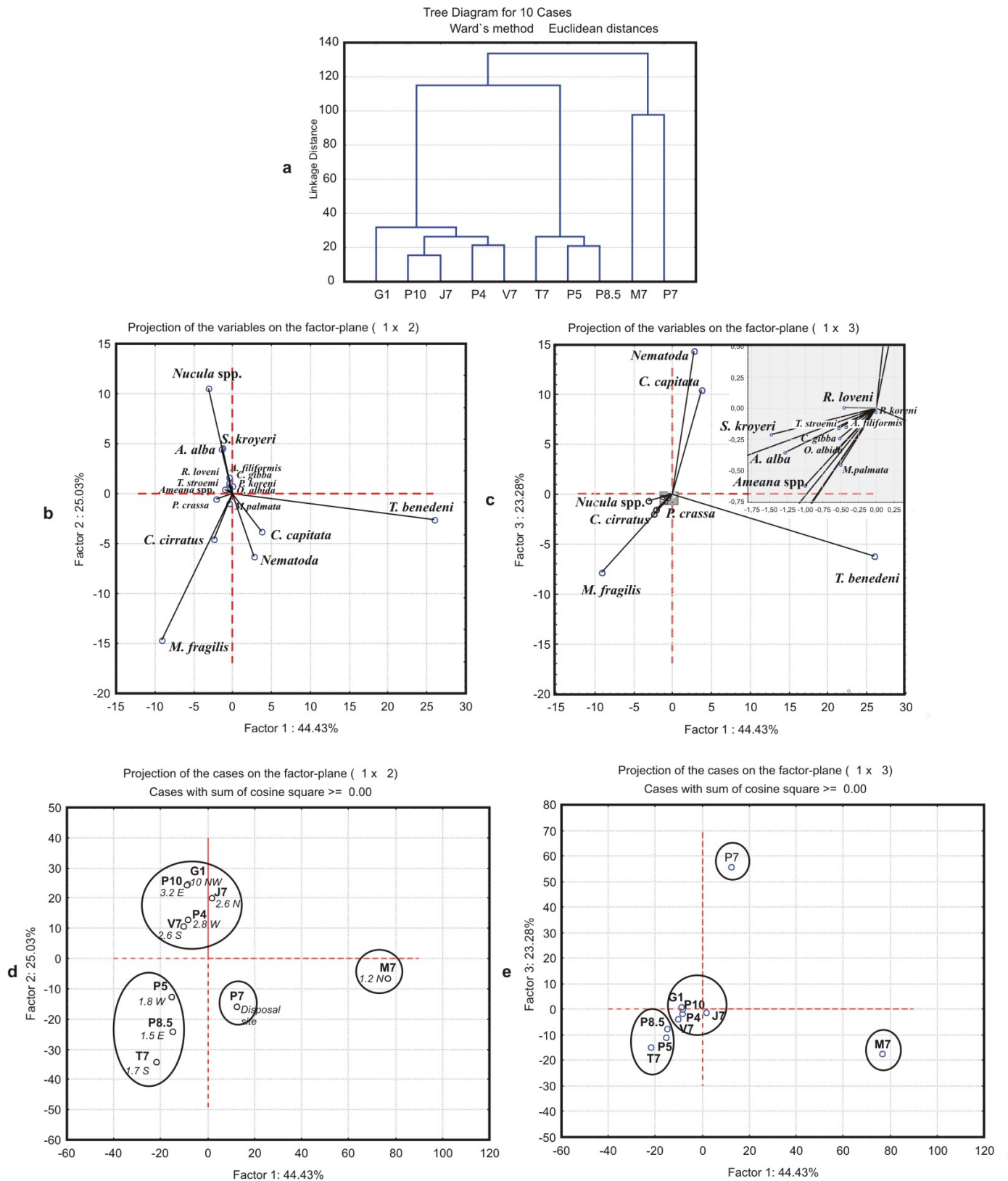


Figure 5-16. PCA analysis. a, Cluster according to Euclidean distances; b, Projection of the variables (macrofauna) on the first two PCA axes; c, Projection of the variables (macrofauna) on the factor-plane determined by PCA axes 1 and 3; d, Plot of the 10 stations on the first two PCA axes, and four distinct assemblages (indicated by the dotted lines); e, Plot of the 10 stations on the factor-plane determined by PCA axes 1 and 3.

Just as we observed for benthic foraminiferal faunas, the position of the samples on the factor plot reflects a gradient of increasing environmental impact, from the cluster with G1 (control station), P10, J7, P4 and V7, to the cluster of stations P5, P8.5 and T7, to sample M7, to end with sample P7, at the disposal site. In figure 5-17, which presents the faunal composition, the samples are presented in this order, that also represents the distance to the disposal site. The succession pictured in figure 5-17 shows the dominance of larger macrofaunal elements (bivalves, echinoderms) at the stations farthest away from the disposal site, gradually changing into a dominance of small-sized animals (annelids, nematodes) when the centre of the disposal site is approached.

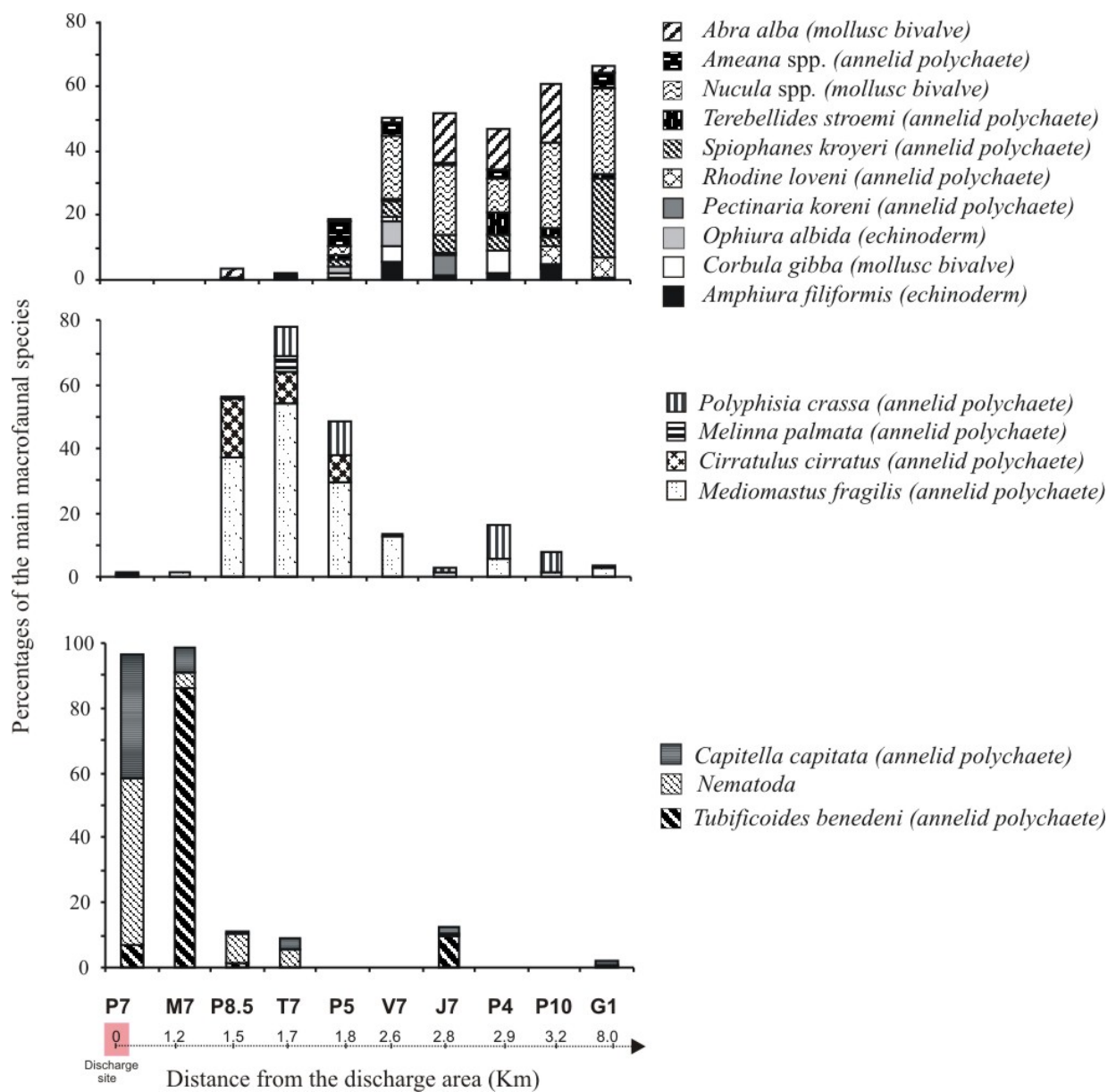


Figure 5-17. Change in dominant species of benthic macrofauna (> 5%) following the distance from the discharge point.



## 5.6 DISCUSSION

### Foraminiferal response to sewage sludge disposal

The sediments of the Garroch Head are predominantly fine silty clays with a natural organic carbon content of about 2 to 2.5 %. In the centre of the disposal area, this value increases to a maximum of 12 %. This high carbon content in the centre of the dumping area coincides with reduced conditions (negative redox potential), a high acidity and elevated nutrients and heavy metal concentrations.

The faunal distribution in the areas subjected to sewage sludge deposition allows us to draw some conclusions about the effects of sewage deposition. In addition, on the basis of these conclusions concerning the risk of sludge disposal in this type of marine environment, certain recommendations can be made. The anthropogenic detrital input at the disposal site is huge. Organic enrichment and oxygen depletion in the bottom water are likely to co-occur and to have an adverse effect on the benthic faunas. We expect increased growth of some opportunistic taxa in enriched environments and decreased growth and increased mortality in response to hypoxia. It is particularly important to quantify the interactions between these factors (organic enrichment and oxygen depletion) in order to understand their effect on benthic ecosystems.

Foraminiferal changes, caused by an increased supply of human-induced nutrients and seasonal bottom water hypoxia, have been noted in coastal seas around the world. The nutrient increase leads in some places to a strong dominance of the agglutinated faunal component (*Nagy and Alve, 1987; Alve, 1991a, 1995a*) or, more generally, to an increase in abundance of opportunistic species (*Nagy and Alve, 1987; Alve, 1991b*). Moreover, foraminiferal assemblages in the vicinity of sewage outfalls are characterized by a large number of specimens and low diversity (*Bandy et al., 1964; Bandy et al., 1965; Alve, 1995b; Thomas et al., 2000*). For example, after the development of sawmills (1550–1870), human-derived organic material caused oxygen depletion with occasional anoxia in fjordic areas of the Norwegian Skagerrak (*Alve, 2000*). *Barmawidjaja et al. (1995)* studied changes in foraminiferal assemblages influenced by the supply of human-derived nutrients to the northern Adriatic sea, and concluded that the increasing nutrient load and consequent stress led to the increase in abundance of a number of stress-tolerant taxa (e.g., *Nonionella turgida, Hopkinsina pacifica, Bolivina seminuda*). *Platon et al. (2005)* suggested that historical changes in the foraminiferal community in the Louisiana Bight were related to the increase in

nutrients and bottom water hypoxia over the last 100 years. In this area, the genus *Quinqueloculina* nearly became extinct due to hypoxia, whereas several hyaline taxa, such as *Nonionella basiloba*, *Buliminella morgani* and *Epistominella vitrea*, tolerated the increase of hypoxia in the Louisiana Bight over the last 100 years (Platon *et al.*, 2005). Few studies investigating the relationship between eutrophication and faunas have been conducted in inner bays, which have more stable natural environmental conditions than estuaries, and are characterised by high sedimentation rates that allow high-resolution studies (Tsujimoto *et al.*, 2006). In most benthic environments, the oxygen concentration is limiting benthic life; low oxygen values are responsible for low faunal densities within the sediment of some of the most organic-rich areas. In the Adriatic Sea, as soon as the oxygen concentration rises above a critical threshold value, food availability becomes the limiting factor, regulating abundance and species composition of the benthic faunas (Jorissen *et al.*, 1992). Areas with a high downward organic flux but still bearable oxygen levels are characterized by a number of highly opportunistic taxa, which can be epifaunal as well as potentially (mobile) infaunal (Jorissen *et al.*, 1992). These taxa are capable of profiting from the combination of high food availability and fair oxygen levels after the reoxygenation of the bottom environment in autumn. The areas with lower organic fluxes are characterized by a more stable fauna, consisting of less stress-tolerant epifaunal taxa in combination with less mobile infaunal species, which lack the possibility to track critical oxygen levels (Jorissen *et al.*, 1992). In our study, a very similar distribution is observed and the density and the composition of the living foraminiferal faunas allow us to subdivide the studied area into four distinct zones (Fig. 5-18).

Zone 1 groups stations J7, V7 and P10. Stations J7 and P10 contain high foraminiferal densities. The faunas at these stations, localised at about 3 Km from the dumpsite are dominated by species that are typical for the faunas at reference station G1 (*Elphidium excavatum/albumbilicatum*, *Nonionella turgida*, *Eggerella scabra/advena*). These taxa are accompanied in fair proportions by species considered in the literature as opportunistic (*Bolivina seminuda*, *Bulimina marginata*; e.g. Langezaal *et al.*, 2006; Lutze and Colbourn, 1984) and/or tolerant to oxygen depletion (*Reophax nana*, *Epistominella vitrea* and *Textularia* spp.).

*Elphidium excavatum* is a eutrophic species described in various coastal marine ecosystems by Murray (1991). It is also capable to successfully develop in polluted environments (Schafer, 1973; Buckley *et al.*, 1974; Schafer *et al.*, 1975; Bates and Spencer, 1979; in Alve, 1991a). *Elphidium albumbilicatum* has been recorded living in shallow and

deeper fjordic areas, with very variable conditions (e.g. *Alve, 1995*: depth 5–46 m, temperature 1.6–18.0 °C, salinity 0.1 to 31.5 ‰; *Gustafsson and Nordberg, 1999*: depth 28–43 m, temperature 3–5 °C, salinity 26 ‰; *Gustafsson and Nordberg, 2001*: depth 116 m, temperature 5–8 °C, salinity 34.4–34.8 ‰). *Alve and Murray (1999)* found this species in shallow (< 6 m) open waters around the Skagerrak and Kattegat and they considered these occurrences as the northern limit of distribution for this species. *Alve (1995)* found *E. albiumbilicatum* to be one of the most eurythermal and euryhaline species in the Drammensfjord and Oslofjord.

*Eggerella scabra* is a continental shelf species (e.g. *Murray, 1991*; *Barmawidjaja et al., 1992*) that lives in various microhabitats from the oxygenated sediment surface to the deepest anoxic layers (e.g. *Barmawidjaja et al., 1992*; *Jorissen et al., 1992*; *Ernst et al., 2002, 2005*; *Duijnste et al., 2003, 2004*). It appears therefore to be tolerant of strongly hypoxic conditions. For instance, *E. scabra* is common in the Adriatic Sea, in areas where large amounts of degraded organic matter cause oxygen depletion (*Donnici and Serandrei-Barbero, 2002*). *E. scabra* also occurs in estuarine areas (e.g. *Murray, 1991*), in association with *Elphidium excavatum*, where these species are also present in environments impacted by important anthropogenic discharges (e.g. *Debenay et al., 1996*). The related taxon *Eggerella advena* often co-occurs with *E. scabra* (e.g. *Murray, 1991*), but tends to occupy more superficial microhabitats (*Barmawidjaja et al., 1992*).

*Nonionella turgida* has been described as a continental shelf species that tolerates oxygen depletion fairly well (e.g. *Jorissen, 1987*; *Barmawidjaja et al., 1995*; *Platon et al., 2004*). In the northern Adriatic Sea, *Duijnste et al. (2004)* observed that high relative abundances coincide with low oxygen index values and low bottom-water temperatures. On the basis of a laboratory experiment, *Ernst et al. (2002)* showed that in case of disturbed sediment, this species rapidly migrates to its preferred microhabitat at the sediment–water interface. These findings were confirmed in a more recent experimental study (*Ernst et al., 2005*) that showed rapid migration to the sediment surface and strongly declining standing stock in response to bottom water anoxia. In our study, *N. turgida* is only present in the stations farthest away from the dumpsite and in the reference station where a good bottom oxygenation is maintained.

It appears that several of the taxa, that are typical for the reference station G1 and the stations farthest away from the sewage disposal site, have been described in other areas as typical of slightly eutrophicated conditions. The fact that the taxa dominating the background

studies are typical of enriched areas, suggests that the whole Garroch Head area is subject to the input of organic-rich sediments that create a naturally eutrophicated environment.

Zone 2 groups stations T7, P4 and P5, where high foraminiferal densities are recorded. The relative frequency of *Eggerella scabra* decreases significantly and it is replaced by large numbers of opportunistic species (*Bolivina seminuda*, *Bulimina marginata*, *Stainforthia concava*) found in relatively low proportions in zone 1. These species are accompanied by *Reophax nana*, *Reophax nodulosus*, *Epistominella vitrea* and *Textularia* spp., which will become much more important in zone 3.

*Bolivina seminuda* is a characteristic epifaunal or shallow infaunal taxon typical of eutrophic continental shelf environments (*Barmawidjaja, 1991; Barmawidjaja et al., 1992; Duijnste, 2001*). *Goody et al. (2000)* reported *B. seminuda* in the Arabian Sea oxygen minimum zone that is characterised by important (and highly seasonal) surface primary production, high organic carbon fluxes to the seafloor and high sediment TOC values and pigment concentrations. *B. seminuda* is a species that reacts to high nutrient availability with rapid reproduction (*Langezaal et al., 2006*). *Barmawidjaja et al. (1995)* studied the changes in foraminiferal assemblages influenced by the supply of human-induced nutrients to the northern Adriatic Sea, and concluded that the increasing nutrient load and consequent stress led to the increase in relative abundance of a limited number of stress-tolerant taxa (*B. seminuda*, *Hopkinsina pacifica* and *Stainforthia fusiformis*). Also in the low oxygen settings (0.02–0.5 ml/l) of Santa Barbara Basin, *B. seminuda* is a common taxon (*Bernhard et al., 1997*). A number of recent studies (*Alve and Bernhard, 1995; Barmawidjaja et al., 1995; Duijnste, 2001; Ernst, 2002*) have insisted on the opportunistic life strategy of this taxon. The opportunistic behaviour becomes evident after disturbances, such as high sedimentation event and or an important anthropogenic input of organic-rich material. *B. seminuda* is one of the most successful colonizers of such newly formed habitats (*Alve and Bernhard, 1995*).

*Bulimina marginata* is an infaunal continental shelf to slope taxon (e.g. *Jorissen et al., 1998*), that has often been considered as an indicator of high food availability (e.g. *Lutze and Colbourn, 1984; Debenay and Redois, 1997*). It has been reported in a wide range of highly productive areas (e.g. *Lutze and Colbourn, 1984; Jorissen et al., 1998; De Rijk et al., 2000; Fontanier et al., 2002*). For several continental shelf areas, it has been used as a marker of upwelling phenomena (*Phleger and Soutar, 1973; Bremner, 1983; Murray, 1995; Debenay and Redois, 1997; Li et al., 1999; Mendes et al., 2004; Szarek et al., 2006*). Because of its occurrence in low oxygen settings (e.g. *Lutze and Colbourn, 1984*), many scientists consider

it also as a good marker of low oxygen conditions. In a study of the impact of oil drill cutting discharges at the outer continental shelf off Congo, *Mojtahid et al. (2006)* showed that *B. marginata* tolerates the putative oxygen depletion at the discharge point, and shows an opportunistic response to anthropogenic enrichment. In a recent study in the Subantarctic area south-east of New Zealand that receives large amounts of phytodetritus from Subtropical, Subantarctic and Circumpolar surface water masses, *Hayward et al. (2006)* show that *B. marginata* dominates the benthic foraminiferal faunas, and shows a significant positive correlation with chlorophyll-a values and a negative correlation with bottom water oxygen concentrations.

In the northern Adriatic sea, *Stainforthia concava* belongs, together with *Hopkinsina pacifica*, *Bolivina dilatata*, *Bolivina seminuda*, *Bolivina spathulata*, *Nonionella turgida*, *Bulimina marginata* and *Epistominella vitrea* (determined as *E. exigua*), to the group of foraminiferal taxa that show a maximum density in the organic-rich clay-belt parallel to the Italian coast. *S. concava* apparently responds to the high food availability in this area by an opportunistic life strategy (*Jorissen et al., 1992*). The taxonomically close taxon *Stainforthia fusiformis* is also known as an opportunistic taxon and is typical of organically enriched inner continental shelf settings where it is sometimes extremely abundant (e.g. *Alve, 1994; Gooday, 2002*). In the Danish part of the Skagerrak, *Alve and Murray (1997)* found increased relative frequencies of *Stainforthia* spp. in response to high input of particulate organic matter. In the Drammensfjord, southern Norway, the genus *Stainforthia* is considered as the first and the most efficient colonizer of the reoxygenation of formerly anoxic areas (*Alve, 1991b; Alve, 1995a*).

Zone 3 groups stations P8.5 and M7, where we find low foraminiferal densities. The previously mentioned opportunistic species almost disappear and agglutinated taxa (*Eggerella scabra*, *Reophax nana*, *Textularia porrecta/sagittula*) dominate the assemblages. They are accompanied by the small calcareous species *Epistominella vitrea* and by some specimens of *B. marginata*. In Frierfjord, southern Norway, well oxygenated conditions were present throughout the water column in the pre-industrial period. With the onset of industrial pollution, dysoxic and anoxic conditions became established and the fauna changed to agglutinated species and in the anoxic areas, there was an absence of fauna (*Murray, 2006*).

*Eggerella scabra* is also a dominant faunal element in zone 1; its worldwide distribution has been described before. Its occurrence in the more stressed zone 3 can probably be explained by its high tolerance to low oxygen conditions.

The genus *Textularia* has been found to be tolerant of oxygen deficiency during summer stratification in the Adriatic Sea in front of the Po delta (*Van Der Zwaan and Jorissen, 1991*). In a study of the impact of drill cutting disposal off Congo (*Mojtahid et al., 2006*), *Textularia sagittula* was described in the vicinity of the disposal site where bottom water oxygenation is probably low due to the degradation of large amounts of organic matter.

*Epistominella vitrea* has been described on the outer shelf of the Bay of Biscay (*Langezaal et al., 2006; Duchemin et al., 2007*), where this shallow infaunal species responds with rapid reproduction to the deposit of spring phytodetritus bloom remains. In previous studies on the Louisiana inner continental shelf, in an area impacted by seasonal hypoxia due to Mississippi runoff, *Blackwelder et al. (1996)* and *Platon et al. (2005)*, observed that *E. vitrea* tolerates progressive oxygen depletion fairly well, and conclude that this species can be used in this area as a tracer of an elevated sedimentation rate and seasonal hypoxia. Also in other basins, *E. vitrea* has been observed under severely oxygen-depleted conditions (*see Bernhard and Sen Gupta, 1999, Table 12.2*). *Jorissen et al., (1992, as E. exigua)* and *Duijnsteet et al. (2004)* describe high densities of *E. vitrea* and *Eggerella* spp. in the eutrophicated northern Adriatic Sea, coinciding with low oxygen index values and low bottom-water temperatures. It should be realised, however, that *Epistominella vitrea* is not always associated with hypoxia. It may also occur in normal, oxic settings, e.g. in the McMurdo area in the Southern Ocean (*Ward et al., 1987*). Also *Epistominella exigua* (a deep-water relative of *E. vitrea*) has been described as an extremely opportunistic taxon, capable of rapidly colonising freshly deposited phytodetritus (*e.g. Gooday and Turley, 1990, Heinz et al., 2001, 2002; Fontanier et al., 2003; Ernst and Van der Zwaan, 2004*).

Zone 4 corresponds to the centre of the disposal site (station P7) that is characterised by the almost total absence of foraminifera. This may be due to various factors: the first one is the severe hypoxia occurring in this area as the result of a strong organic enrichment. Recent studies (*Alve and Bernhard, 1995, Moodley et al., 1997; Jannink et al., 1998*) show that anoxic conditions cause a direct effect on the majority of the foraminiferal species. The absence of some taxa in strict anoxia in bottom and interstitial waters is probably the result of reproductive inhibition in such environments. However, numerous taxa are capable of surviving prolonged periods of anoxia (*Moodley et al., 1997; Ernst et al., 2005*), and it has

recently been shown (*Risgaard-Petersen et al., 2006*) that some foraminiferal taxa are, under such conditions, capable to shift to anaerobic metabolism, by reducing nitrates.

The second factor that may be responsible for the almost total absence of foraminifera at the dumping site is the low pH value recorded at the sediment/water interface. This low pH may cause the dissolution of calcareous tests, and possibly inhibit calcification in these environments. We think that the near-total disappearance of foraminifera in zone 4, and perhaps also the strong increase in the relative abundance of agglutinated taxa in zone 3, may be a response to the progressive decrease in pH at the sediment-water interface towards the disposal site. The pH of normal seawater ranges between 7.8 and 8.3. In estuarine environments subject to the input of acid freshwater, or to the accumulation of organic matter, either anthropogenic or natural, the pH is generally lower (*Boltovskoy, 1965; Boltovskoy and Wright, 1976; Nagy and Johansen, 1991*). For instance, *Shafer (1970)* recorded a pH value of 7.2 near an industrialized outfall. *Alve and Nagy (1986)* reported values below 7.0 on a mudflat close to a paper mill outlet. Both studies report a reduction of the relative frequency of calcareous foraminifera over time, with the recent faunas only containing arenaceous species. *Boltovskoy and Wright (1976)* indicated that calcareous foraminifera start to dissolve at pH values of less than 7.8. However, these authors do not indicate whether living or dead specimens have been considered. It is probable that living specimens are less easily attacked due to the presence of a “protective” cytoplasm. *Le Cadre et al. (2003)* observed, in a laboratory study of the effects of pH on the calcification of the hyaline species *Ammonia beccarii*, that the decalcification of the tests of living specimens started when the pH fell below 7.5.

A last factor that may contribute to the strongly adverse conditions at the disposal site is the eventual presence of sulphidic substances close to the sediment-water interface. In environments impacted by important organic matter input, the destruction of organic matter by microbial activity may cause anoxic and sulphidic conditions, due to the formation of ferrous sulphide minerals, close to the sediment water interface. When these ferrous sulphides are oxidized, a decrease of the pH is the result, which may cause carbonate dissolution (*Reaves, 1986*). In a classical foraminiferal study, *Bandy (1964)* reported a 'dead zone' around a Californian outfall area, where the sediment was black due to the presence of sulphides. However it is not evident that the absence of foraminifera at this site is exclusively caused by the presence of sulphides.

Summarizing, the foraminiferal distribution presents a typical picture, with 1) azoic conditions at the disposal site and 2) strongly impoverished faunas composed exclusively of species tolerant to important oxygen depletion closest to the disposal site. This strongly impacted area is surrounded by an aureole of high density faunas with large numbers of opportunistic species, gradually changing into a dominance of a small number of more stable taxa at the outer ends of the transects (Fig. 5-18). At about 3 Km of the disposal site, faunas are more or less comparable to those found at reference station G1.

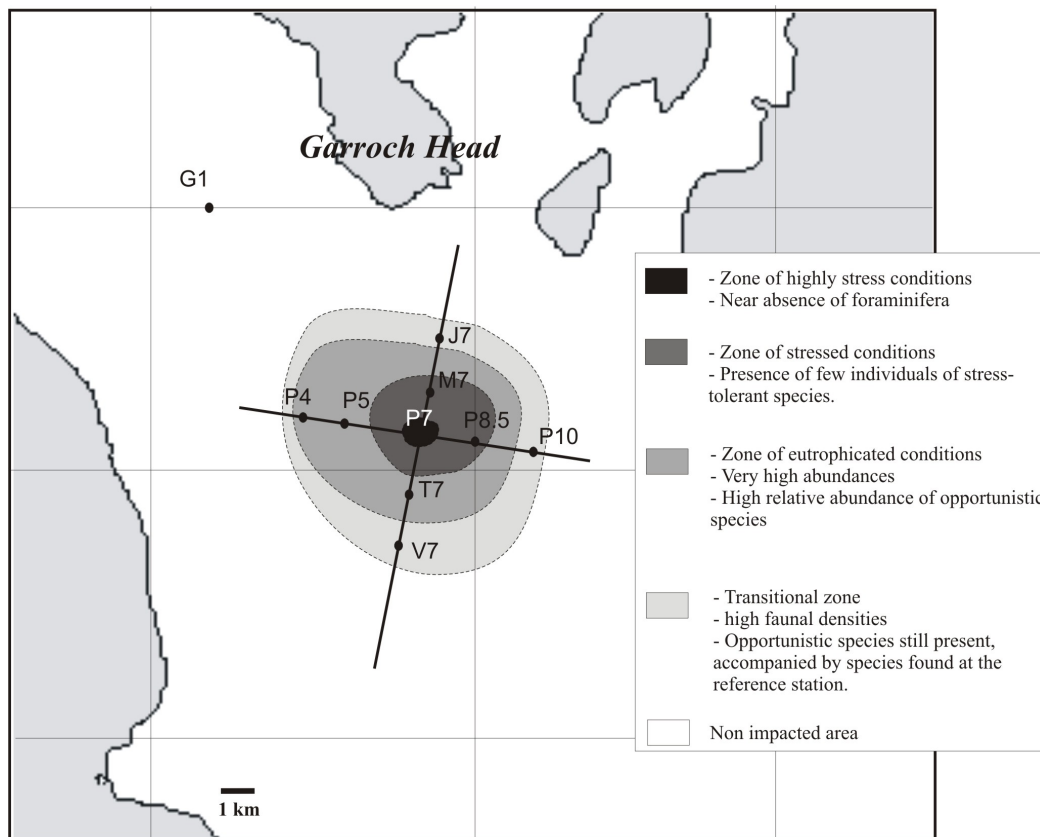


Figure 5-18. Overview map, indicating the succession of foraminiferal zones with decreasing environmental impact at increasing distance from the sewage sludge disposal site.

#### Macrofaunal response to sewage sludge disposal

The successional changes in faunal composition along the increasing gradient of organic enrichment towards the centre of the disposal site closely follow the ideal pattern of such successions (Pearson and Rosenberg, 1978). Chandler (1970), Washington (1984) and Hellowell (1986) suggest that sensitive species progressively decrease in numbers when the water quality deteriorates and are replaced by more tolerant taxa, which are rare or absent at unimpacted sites. In our study, we clearly observe such a succession, both along our N/S and



W/E transects. The faunal distribution varies in response to an organic enrichment gradient, as described by *Pearson and Rosenberg (1978)*. The density and composition of the faunas allow us to subdivide the studied area into three distinct zones. Although the foraminiferal and macrofaunal zonations are very similar, they are not comparable. In case of foraminifera, four assemblages and biofacial zones were recognized whereas in the case of macrofauna, only 3 assemblages can be distinguished:

Zone 1 contains stations located between 2 and 3 km from the disposal site (V7, J7, P4 and P10). These four stations are characterized by intermediate biomass (from 12 to 46 g wet weight/0.1 m<sup>2</sup>) abundance (between 120 and 430 individuals/ 0.1 m<sup>2</sup>) and species richness (between 37 and 64 species). The faunas of this zone are characterised by important proportions of *Amphiura filiformis*, *Corbula gibba*, *Ophiura albida*, *Pectinaria koreni*, *Rhodine loveni*, *Spiophanes kroyeri*, *Terebellides stroemi*, *Nucula spp.*, *Ameana spp.* and *Abra alba*. The majority of these taxa are also typical for the macrobenthic community in the supposedly unimpacted control area, 8 Km NW of the disposal site. These species are in general large animals with a slow turnover rate (K-strategy) that live in stable, well-oxygenated environments. They are accompanied by low numbers of species with a more opportunistic life style (*A. alba* and *C. gibba*), that occur in much higher percentage in zone 2.

A study of *Nilsson (1999)* on the effects of hypoxia and organic enrichment demonstrated that the burrowing brittle star *Amphiura filiformis* is very sensitive to hypoxia. Experimental studies have shown reduced growth rates of *A. filiformis* in oxygen concentrations below 2.7 mg O<sub>2</sub>/l. At 1.2 mg O<sub>2</sub>/l, the species initiates an escape response from its burrow in the sediment. Below oxygen concentrations of 0.5 mg O<sub>2</sub>/l, its mortality increases (*Rosenberg et al., 1991; Nilsson and Rosenberg, 1994; Nilsson and Sköld, 1996; Vistisen and Vismann, 1997*). A high abundance and biomass of *A. filiformis* and *Amphiura chiajei* has been observed at well ventilated sites in the Skagerrak (*Josefson, 1990*). In the same areas, severe hypoxic events (< 0.7 mg O<sub>2</sub>/l) led to a mass mortality of *A. filiformis* (*Rosenberg and Loo, 1988*).

The spionid polychaete *Spiophanes kroyeri* and its congener *Spiophanes missionensis* decline toward sewage outfall areas (*Aschan and Skullerud, 1990; Maurer et al., 1998, respectively*). Also *Spiophanes bombyx* has a low tolerance to seasonal oxygen depletion (*Niermann et al., 1990*). *Conlan et al. (2004)* studied the benthic changes during 10 years of organic enrichment due to sewage and hydrocarbon disposal off Antarctica. They observed

high abundances of *Spiophanes tcherniae* at supposedly unimpacted reference stations. Apparently, this species does not tolerate high organic enrichment levels (Lenihan *et al.*, 2003).

*Nucula turgida* is a small bivalve that is common in shallow water assemblages along the French Cotentin coast in areas with well-oxygenated waters and fine-grained sediments (Dauvin, 2004).

In addition to these taxa, that are generally considered to have a low tolerance to organic pollution, we find also in this area some species (*Abra alba* and *Corbula gibba*) that are near absent at the reference station (G1) and are in the literature considered as more opportunistic (Dauvin, 1984; 2000; Simonini *et al.*, 2004):

The *Abra alba* community forms a well-established faunal unit in coastal areas of the North Sea (Dewarumez *et al.*, 1986; Van Hoey *et al.*, 2005), where it is mostly found in bays, estuaries and in a narrow zone along the coast. It appears to be positively affected by the input of terrestrial organic matter input (Sanvicente-Anorve *et al.*, 2002). *Abra alba* is considered as an opportunistic species, comparable to *Melinna palmata* and *Pectinaria koreni* that also show rapid growth in the presence of important food inputs (Dauvin, 1984; 2000).

The bivalve *Corbula gibba* is often considered as an indicator of sediment instability (Pérès and Picard, 1964) and organic enrichment (Diaz and Rosenberg, 1995). This species dominates the macrofaunal community in the muddy C<sub>org</sub>-enriched sediments of the Obidos Lagoon (Portugal) (Carvalho *et al.*, 2005). Also coastal stations in the northern Adriatic Sea with muddy sediments are characterized by a high abundance of the opportunistic bivalve *C. gibba*, that appears to be typical of unstable areas with a high sedimentation rate (Simonini *et al.*, 2004). It is also widely distributed in estuaries in northern Europe and in the Mediterranean Sea and is one of the most resistant species with respect to severe hypoxia. It is therefore often abundant in eutrophicated areas (Christensen, 1970; Pearson and Rosenberg, 1978; Diaz and Rosenberg, 1995).

Zone 2 contains stations located 1.5 to 2 km from the disposal site (P8.5, T7 and P5). The faunas of these three stations are characterized by high biomasses (varying from 12 to 40 g wet weight/0.1 m<sup>2</sup>, high abundances (between 660 and 2240 individuals/ 0.1 m<sup>2</sup>) and a high species richness (between 53 and 72 species). In zone 2, the taxa typical of zone 1 progressively disappear and are replaced by the more opportunistic species *Mediomastus fragilis* and *Cirratulus cirratus*, that are accompanied by *Melinna palmata* and *Polyphisia crassa*.

In a study of the impact of the Amoco Cadiz oil spill on benthic organisms in the Bay of Morlaix (Dauvin, 1984; 2000), only two small opportunistic subsurface deposit feeding polychaetes (*Mediomastus fragilis* and *Tharyx marioni*) increased their abundance just after the oil spill, probably as a response to an increase in organic matter. Levin et al. (2006) studied the influence of sulphide on the benthic faunal recruitment and survival and observed that the polychaete *Mediomastus* sp. belongs to a community that exhibits significantly higher densities in sulfidic sediments. In the Rhône delta, *Mediomastus* sp. exhibits a high growth rate and an ability to adapt its reproductive behaviour in order to rapidly exploit inputs of organic matter after flood events (Salen-Picard et al., 2003). This polychaete had also been described in large numbers in polluted environments or following phytoplankton bloom events (Pearson and Rosenberg, 1978; Blake, 1993; Bachelet and Laubier, 1994).

*Cirratulus cirratus* is a predominantly intertidal polychaete. It can appear in large numbers in areas with high concentrations of organic waste. It usually lives buried in mud or sand or under rocks. It is common along the entire Norwegian coast (Neal et al., 2006). This species has been described as an opportunistic deposit feeder characteristic of areas of organic enrichment (Penry and Jumars, 1990).

*Melinna palmata* is not considered as an opportunistic taxon in the literature. It belongs to a community that is common in rias and estuaries of Brittany where hydrodynamic energy is low, allowing the sedimentation of large amounts of fine-grained sediments rich in organic matter (Dauvin, 1984; 2000).

Zone 3 groups stations P7 and M7. At these stations, the species typical of zone 2 entirely disappear and only populations of annelids (*Capitella capitata*, *Tubificoides benedeni*) and nematode worms are present. Station M7, 1.2 km north of the disposal site, is characterised by a faunal density one to two orders of magnitude higher than at all other sites, and a very strong dominance of *T. benedeni*. The fauna at station P7, on the contrary, has a relatively low density, and is dominated by *C. capitata* and by nematodes.

The cosmopolitan polychaete *Capitella capitata* is a non-selective subsurface deposit feeder (Fauchald and Jumars, 1979) that is often associated with polluted environments, and has been widely used as a bio-indicator of organic pollution (Warren, 1976; Tsutsumi, 1990; Méndez, 1997). Field studies on the population dynamics of *C. capitata* have found early colonization of azoic areas, followed by rapid population increase, and finally, by a

subsequent rapid decline (*Grassle and Grassle, 1974; Rosenberg, 1976; McCall, 1977; Pearson and Rosenberg, 1978; Kikuchi, 1979; Gray, 1981; Tsutsumi and Kikuchi, 1984*).

The oligochaete *Tubificoides benedeni* is known in the literature to live in stressed habitats characterized by high levels of hydrogen sulphide, such as eutrophic tidal flats and polluted coastal sites. It has a high capacity to tolerate anoxic (and sulfidic) conditions. Earlier physiological studies (*Giere et al., 1988; Dubilier et al., 1994; 1995; 1997*) suggest the presence of adaptive strategies (a highly specialized physiology combined with supplementary behavioural and structural adaptations) that make *T. benedeni* one of the most successful inhabitants of ecologically stressed, sulfidic benthic environments. *Giere et al. (1999)*, who measured respiration rates of *T. benedeni* at various oxygen concentrations, show that aerobic respiration is maintained even at very low oxygen concentrations. This ability to continue aerobic respiration is combined with a high regulatory capacity of oxygen uptake. This study is corroborated by the comparison with other typical 'sulphide annelids' such as the polychaetes *C. capitata*, that use very similar ecological strategies to survive in these hostile environments.

In many studies, nematodes occur in areas enriched in heavy metals and organic pollutants (*Fenske and Günther, 2001; Szymelfenig et al., 2006*). *Neira et al. (2001)* observe high nematode abundances at oxygen concentrations below 0.02 ml/l. The high densities are probably an indirect effect of low oxygen causing a strong reduction of predators and competitors and the preservation of organic matter leading to an abundance of high quality food. Free-living nematodes are an important component of marine suboxic, anoxic and sulfidic benthic habitats (*Moodley et al., 1997 and Modig and Ólafsson, 1998*). Sulfidic habitats occur whenever an excess of organic material leads to exhaustion of the available electron acceptors O<sub>2</sub>, nitrate, iron oxides and manganese oxides by bacterial respiration. In these environments, not only oxygen is lacking, but the resident higher organisms have to avoid the toxic effects of hydrogen sulphide. Physiological adaptations allowing the organism to do so are: 1) switching to an anaerobic metabolism, 2) excluding sulphide from sensitive tissues, and 3) oxidizing sulphide to more benign forms (*Somero et al., 1989; Steyaert et al., 2007*).

Summarizing, also our macrofaunal data present a typical picture, with strongly impoverished faunas composed exclusively of species tolerant to important oxygen depletion closest to the disposal site. This area is surrounded by an aureole of high density faunas with important opportunistic mainly small-sized species gradually changing into a dominance of a small number of larger sized equilibrium species at the outer ends of the transects (Fig.5-19).

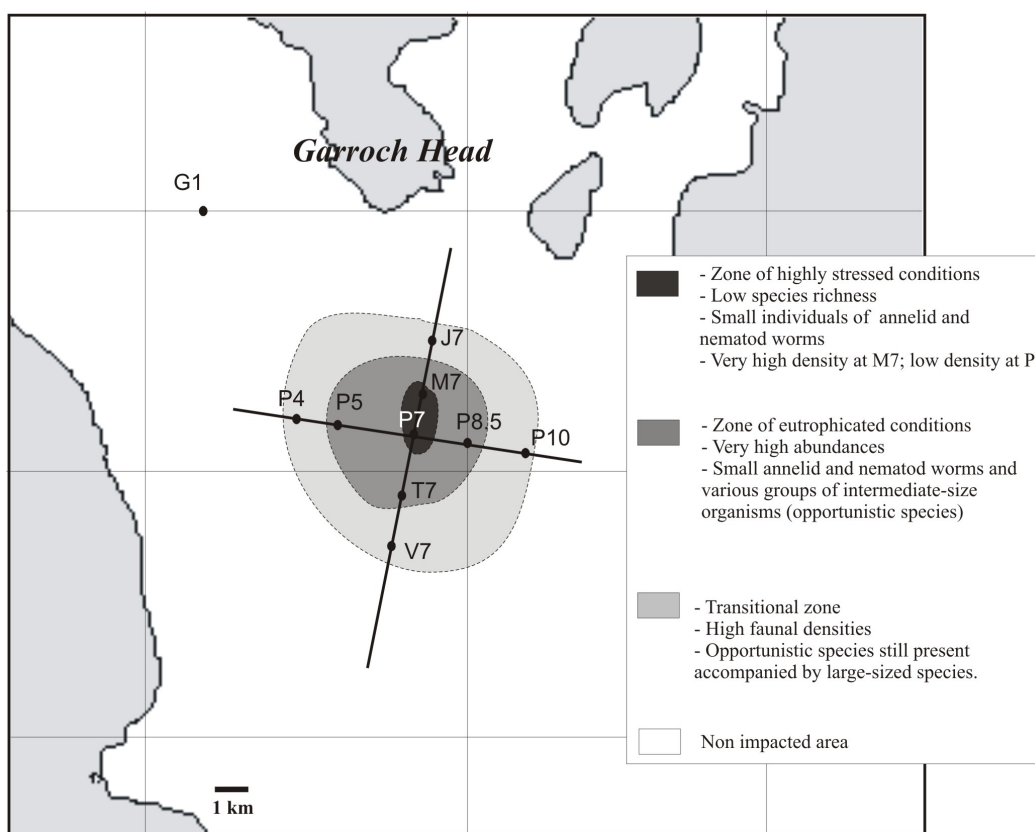


Figure 5-19. Overview map, indicating the succession of macrofaunal zones with decreasing environmental impact at increasing distance from the sewage sludge disposal site.

### Comparison of foraminiferal and macrofaunal bio-indicators of ecosystem eutrophication

In order to better represent the faunal differences between the impacted stations, we developed an index based on the cumulative percentages of species indicative of stress and of anthropogenic eutrophication, related to the sewage sludge disposal. Because of their distributional patterns in the study area, we selected the foraminiferal taxa *Textularia porrecta*, *Textularia sagittula*, *Reophax nana*, *Eggerella scabra*, *Bolivina seminuda*, *Reophax nodulosus*, *Bulimina marginata*, *Stainforthia concava* and *Epistominella vitrea* as bio-indicators of organic enrichment. The macrofaunal bio-indicators we selected are *Tubificoides benedeni*, *Nematoda*, *Capitella capitata*, *Mediomastus fragilis*, *Cirratulus cirratus*, *Melinna palmata*, *Polyphisia crassa*, *Abra alba*, *Corbula gibba* and *Rhodine loveni*.

In figure 5-20, for both groups, foraminifera and macrofauna, the cumulative percentage of these index taxa is plotted as a function of the distance to the disposal site. It can be seen that foraminifera and macrofauna show a very similar response to sewage

disposal, with stress-tolerant species dominating in the area close to the disposal site, and less tolerant taxa become progressively more important at a greater distance from the disposal site.

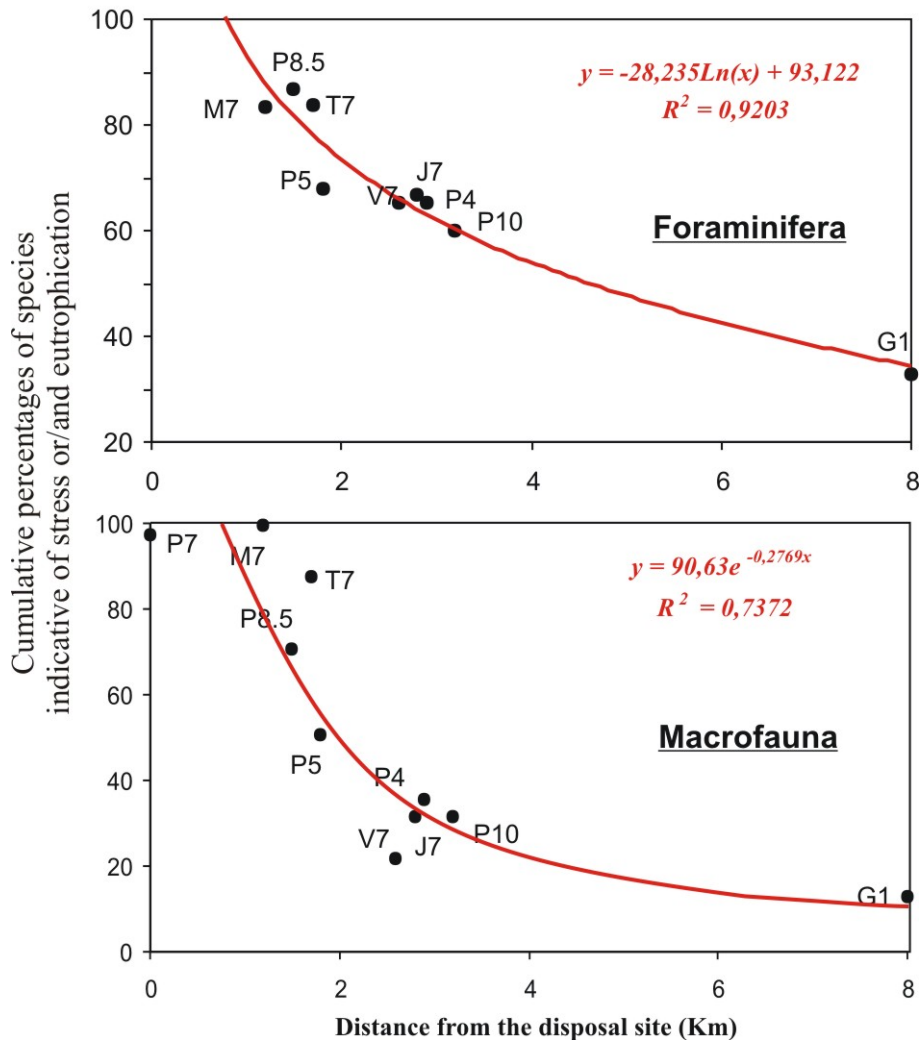


Figure 5-20. Cumulative percentages of all taxa indicative of natural and/or anthropogenic eutrophication and ecosystem stress, in function of distance to the drill cutting disposal.

When comparing the foraminiferal and macrofaunal patterns in more detail, some important differences can nevertheless be observed:

- 1) At the disposal site (station P7), foraminifera are totally absent whereas some nematode and annelid worms are present. This difference may be due to the low pH recorded in this area that could inhibit the calcification of the tests of calcareous taxa, which are more resistant to stressed conditions than agglutinated taxa.

2) At station M7, the extremely rich macrofauna, dominated by the polychaete *Tubificoides benedeni* contrasts with the very poor foraminiferal fauna, consisting mainly of agglutinated taxa. Again, this difference may be due to the sensitivity of the calcareous taxa to a low pH.

3) The foraminiferal composition at stations P7 and M7 suggests strongly stressed conditions in this area, whereas the composition and high density of the macrofauna indicate strongly eutrophicated conditions, without physical stress for the dominant taxa. Furthermore, the foraminiferal faunas at station P4 are indicative of eutrophicated conditions, whereas the macrofaunal community structure, that is similar to that observed at the reference station, is indicative of a transitional ecosystem. We conclude that foraminifera are more sensitive to this particular type of environmental stress than macrofauna and suffer a more important impact by sewage sludge. Since foraminifera are particularly tolerant to organic enrichment and oxygen depletion in many other areas, we assume that their lower tolerance in the Garroch Head area is caused by the low pH of the sewage effluents.

## 5.7 CONCLUSIONS

- We used an ecological approach using benthic foraminifera and macrofauna to investigate the impact of sewage sludge discharge in the Firth of Clyde. The comparison of both faunal groups, complemented by physico-chemical analyses of sediment and bottom-waters, allows an adequate description of the health of the surrounding marine environment.

- Sedimentary organic carbon and nitrogen contents are very high in the vicinity of the disposal site and decrease progressively further away. Low redox values in the vicinity of the disposal site, at the sediment surface as well as within the topmost sediment, are indicative of highly reducing conditions brought about by the degradation of large amounts of organic material. Also metals concentration show maximum values close to the discharge point.

- The faunal analysis shows for both analysed bio-marker groups (macrofauna and foraminifera) a comparable ecological succession that is typical for strongly eutrophicated areas:

1) a zone of severely stressed conditions in the immediate vicinity of the disposal grounds where abundances and biodiversity are very low and where the faunas contain only a few species that are tolerant to strong oxygen depletion,

2) a second zone contains a fauna typical of enriched conditions, characterised by a high faunal density and a strong dominance of a limited number of opportunistic species,

3) a third zone appears to present a transitional situation, where the environmental impact is minimal, but still perceptible. Faunal densities are still elevated and the faunal composition shows a slightly elevated percentage of opportunistic taxa in comparison to the unpolluted reference station. These opportunistic taxa are accompanied by equilibrium taxa typical of unimpacted environments.

- When the two groups of bio-indicators, foraminifera and macrofauna are compared in more detail, some important differences show up, which suggest that foraminifera are more sensitive to this specific type of environmental disturbance than macrofauna. Environmental impact is still perceptible in the foraminiferal faunas at relatively low levels, where macrofauna apparently is no longer affected. This makes foraminifera particularly useful for this type of environmental survey. We think that the higher sensitivity of foraminifera is caused by the consistently low pH values in the upper sediment layers, that especially appear to affect species provided with calcareous tests, that in other areas are most resistant to dysoxic conditions. These calcareous taxa may have serious problems to calcify in the acidic sedimentary environments around the disposal site.

## 5.8 REFERENCES

- Abel, P.D., 1989. *Water Pollution Biology*. John Wiley and Sons, Chichester, 231 pp.
- Alve, E., 1991a. Benthic foraminifera in sediment cores reflecting heavy metal pollution in Sørfjord, western Norway. *Journal of Foraminiferal Research*, 21, 1-19.
- Alve, E., 1991b. Foraminifera, climatic change, and pollution, a study of late Holocene sediments in Drammensfjord, southeast Norway. *The Holocene*, 1, 243-261.
- Alve, E., 1995. Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Drammensfjord, southern Norway. *Marine Micropaleontology*, 25, 169-186.



Alve, E., 1995a. Benthic foraminiferal responses to estuarine pollution, a review. *Journal of Foraminiferal Research*, 25, 190-203.

Alve, E., 1995b. Benthic foraminiferal distribution and recolonisation of formerly anoxic environments in Drammensfjord, southern Norway. *Marine Micropaleontology*, 25, 169-186.

Alve, E., 2000. A case study reconstructing bottom water oxygen conditions in Frierfjord, Norway, over the past five centuries. In, Martin, R.E. (Ed.), *Environmental Micropaleontology, The Application of Microfossils to Environmental Geology*. Kluwer Academic/Plenum Publishers, New York, pp. 323-350.

Alve, E. and Nagy, J., 1986. Estuarine foraminiferal distribution in Sandebukta, a branch of the Oslo fjord: *Journal of Foraminiferal Research*, 16, 261-284.

Alve, E., Bernhard, J.M., 1995. Vertical migratory response of benthic foraminifera to controlled oxygen concentrations in an experimental mesocosm. *Marine Ecology Progress Series*, 116, 137-151.

Alve, E. and Murray, J.W., 1997. High benthic fertility and taphonomy of foraminifera, a case study of the Skagerrak, North Sea. *Marine Micropaleontology*, 31, 157-175.

Alve, E., Murray, J.W., 1999. Marginal marine environments of the Skagerrak and Kattegat, a baseline study of living (stained) benthic foraminiferal ecology. *Palaeogeography, Palaeoclimatology, Palaeoceanography*, 146, 171-193.

Alves Martins, V., Patinha, C., Ferreira da Silva, E., Jouanneau, J.-M., Weber, O., Rocha, F., 2006. Holocene record of productivity in the NW Iberian continental shelf. *Journal of Geochemical Exploration*, 88, 408-411.

Armynot du Châtelet, E., Debenay, J.P. and Soulard, R., 2004. Foraminiferal proxies for pollution monitoring in moderately polluted harbors. *Environmental Pollution*, 127, 27-40.

Aschan, M.M. and Skullerud, A.M., 1990. Effects of changes in sewage pollution on soft-bottom macrofauna communities in the inner Oslofjord, Norway. *Sarsia*, 75, 169-190.

Bachelet, G. and Laubier, L., 1994. Morphology, ecology and juvenile development of *Cossura pygodactylata* Jones (Polychaeta, Cossuridae) in Arcachon Bay, SW France, with a reassessment of the geographical distribution of *C. pygodactylata* and *C. soyeri* Laubier. *Mémoires du Muséum national d'histoire naturelle (Zool.)*, 162, 355-369.

Bandy, O. L., Ingle, J.C., and Resig, J.M., 1964. Foraminiferal Trends, Laguna Beach Outfall Area, California. *Limnology and Oceanography*, 9, 112-123.

Bandy, O. L., Ingle, J.C., and Resig, J.M., 1965. Foraminiferal Trends, Hyperion Outfall Area, California. *Limnology and Oceanography*, 10, 314-332.

Barker, R.W., 1960. Taxonomic notes of the species figured by H.B. Brady in this report on the foraminifera dredged by H.M.S Challenger during the years 1873-1876. *Society of Economic Paleontologists and Special Publication n° 9*. Tulsa, Oklahoma, USA.

Barmawidjaja, D.M., 1991. Studies in living and fossil foraminifers from seasonally productive regions. *Geologica Ultraiectina* 82, 221 pp.

Barmawidjaja, D.M., Jorissen, F.J., Puskaric, S., Van der Zwaan, G.J., 1992. Microhabitat selection by benthic foraminifera in the northern Adriatic Sea. *Journal of Foraminiferal Research*, 22, 297-317.

Barmawidjaja, D.M., Van Der Zwaan, G.J., Jorissen, F.J., Puskaric, S., 1995. 150 years of eutrophication in the northern Adriatic Sea, evidence from a benthic foraminiferal record. *Marine Geology*, 122, 367-384.

Bates, J.M. and Spencer, R.S., 1979. Modification of foraminiferal trends by the Chesapeake-Elisabeth sewage outfall, Virginia Beach, Virginia. *Journal of Foraminiferal Research* 9(2), 125-140.

Bernhard, J.M. and Sen Gupta, B.K., 1999. Foraminifera of oxygen depleted environments. In, Sen Gupta, B.K. (Ed.), *Modern Foraminifera*. Kluwer, Dordrecht, pp. 201-216.

Bernhard, J.M., Sen Gupta, B.K. and Borne, P.F., 1997. Benthic foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations, Santa Barbara basin, U.S. Pacific continental margin. *Journal of Foraminiferal Research*, 27, 301-310.

Bizon, G. and Bizon, J.J., 1985. Méthode d'études et mode de prélèvement des sédiments d'ECOMED. In, J.J. Bizon and P.F. Burolet (Editors), *Ecologie des Microorganismes en Méditerranée occidentale 'ECOMED'*. Association Française des Techniciens du Pétrole, Paris, pp. 81-83.

Blackwelder, P., Hood, T., Alvarez-Zarikian, C., Nelsen T.A. and McKee, B., 1996. Benthic foraminifera from the NECOP study area impacted by the Mississippi River plume and seasonal hypoxia. *Quaternary International*, 31, 19-36.

Blake, J. A., 1993. Life history analysis of five dominant infaunal polychaete species from the continental slope off North Carolina. *Journal of the Marine Biology Association of the United Kingdom*, 73, 123-141.

Boltowskoy, E., 1965. Los foraminiferos Recientes. Editorial Universitaria de Buenos Aires, Argentina, 510 pp.

Boltowskoy, E. and Wright, R., 1976. *Recent foraminifera*: Dr. W. Junk b.v., The Hague, 515 pp.

Bremner, J.M., 1983. Biogenic sediments on the southwest African (Namibian) continental margin. In, Thiede, J., Suess, E. (Eds.), *Costal Upwelling. Its Sediment Record, Part B*. NATO Conference Series, New York, 4, 423-430.

Buckley, D.E. et al., 1974. Canso strait and Chedaucto bay, a multidisciplinary study of the impact of man on the marine environment. *Geological Survey of Canada*, 1, 74-30.

Cao, Y., Bark, W.A. and Williams, W.P., 1997. Analysing benthic macroinvertebrate community changes along a pollution gradient, A framework for the development of biotic indices. *Water Research*, 31, 884-89.

Carvalho, S., Moura, A., Gaspar, M.B., Pereira, P., Cancela da Fonseca, L., Falcão, M., Drago, T., Leitão, F. and Regala, J., 2005. Spatial and inter-annual variability of the macrobenthic communities within a coastal lagoon (Óbidos lagoon) and its relationship with environmental parameters. *Acta Oecologica*, 27, 143-159

Chandler, J. R., 1970. A biological approach to water quality management. *Water Pollution Control*. London, 69, 415-422.

Christensen, A. G., 1970. Feeding biology of the sea-star *Astropecten irregularis* Pennant. *Ophelia*, 8, 1e134. Comparisons to Hoglund's 1927 material. *Journal of Foraminiferal Research*, 31, 2-11.

Conlan, K.E., Kim, S. L., Lenihan, H. S., Oliver, J. S. 2004. Benthic changes during 10 years of organic enrichment by McMurdo Station, Antarctica. *Marine Pollution Bulletin*, 49, 43-60.

Craib, J. S., 1965. A sampler for taking short undisturbed cores. *Journal du Conseil International de l'Exploration de la Mer*, 30, 34-39.

Dauvin, J. C., 1984. Dynamique des écosystèmes macrobenthiques des fonds sédimentaires de la baie de Morlaix et leur perturbation par les hydrocarbures de l'Amoco Cadiz. Thèse de doctorat Etat, ès sciences, Université de Paris VI, 456 pp + annexes, 192 pp.

Dauvin, J.C., Laubier, L. and Reish, D. J., 1994. Actes de la 4ème Conférence Laubier internationale des Polychètes. *Mémoires du Museum National d'Histoire Naturelle*, 162, 355-369.

Dauvin, J.C., 2000. The Muddy Fine Sand *Abra alba* ± *Melinna palmata* Community of the Bay of Morlaix Twenty Years After the Amoco Cadiz Oil Spill. *Marine Pollution Bulletin*, 40, 528-536.

Dauvin, J.C., Thiébaud, E., Gesteira, J.L.G., Ghertsos, K., Gentil, F., Ropert, M., Sylvand, B., 2004. Spatial structure of a subtidal macrobenthic community in the Bay of Veys (western Bay of Seine, English Channel). *Journal of Experimental Marine Biology and Ecology*, 307, 217-235.

Davis, J.C., 1986. *Statistics and Data Analysis in Geology*, 2nd Edition. Wiley, New York, 656 pp.

De Rijk, S., Jorissen, F.J., Rohling, E., Troelstra, S.R., 2000. Organic flux control on bathymetric zonation of Mediterranean benthic foraminifera. *Marine Micropaleontology*, 40, 151-166.

Debenay, J.P. Beck-Eichler, B., Fernandez-Gonzalez, M., Mathieu, R., Bonetti, C., Duleba, W., 1996. Les foraminifères paraïques des côtes d'Afrique et d'Amérique du Sud, de part et d'autre de l'Atlantique, comparaison et discussion. In, S. Jardiné, I. Klazis and J.-P. Debenay (Editors), *Géologie de l'Afrique et de l'Atlantique sud. Compte rendu des colloques de géologie d'Angers*. Elf-Aquitaine Edition, Pau, Angers, pp. 463-471.

Debenay, J.P., Redois, F., 1997. Distribution of the twenty seven dominant species of shelf benthic foraminifera on the continental shelf, north of Dakar (Senegal). *Marine Micropaleontology*, 29, 237-255.

Deegan, C.E., Kirby, R., Rae, I. and Floyd, R., 1973. The superficial deposits of the Firth of Clyde and its sea lochs. Report of the Institute of Geological sciences N° 73/9. *Deep-Sea Research*, 50, 457-494.

Dewarumez, J.M., Quisthoudt, C. and Richard, A., 1986. Suivi pluriannuel du peuplement à *Abra alba* dans la partie méridionale de la Mer du Nord (région de Dunkerque-France). *Hydrobiologia*, 142, 187-197.

Diaz, R.J. and Rosenberg, R., 1995. Marine benthic hypoxia, a review of its ecological effects and the behavioural responses of benthic macrofauna. *Oceanography and Marine Biology: Annual Review*, 33, 245-303.

Digby, P.G.N. and Kempton, R.A., 1987. *Multivariate analysis of ecological communities*. Chapman and Hall, London, 206 pp.

DoE/WTD, 1984. Sewage sludge disposal in Liverpool bay. Research into effects 1975 to 1977. Part 2- appendices. Water Technical division. Department of the environment, London, 194 pp.

Donnici, S. and Serandrei-Barbero, R., 2002. The benthic foraminiferal communities of the North Adriatic continental shelf. *Marine Micropaleontology*, 44, 93-123.

Dooley, H.D., 1979. Factors influencing water movements in the Firth of Clyde. *Estuarine and Coastal Marine science*, 9, 631-641.

Dubilier, N., Giere, O. and Grieshaber, M. K., 1994. Concomitant effects of sulfide and hypoxia on the aerobic metabolism of the marine oligochaete *Tubificoides benedii*. *Journal of Experimental Zoology*, 269, 287-297.

Dubilier, N., Giere, O. and Grieshaber, M. K., 1995. Morphological and ecophysiological adaptations of the marine oligochaete *Tubificoides benedii* to sulfidic environments. *American Zoology*, 35, 163-173.

Dubilier, N., Windoffer, R., Grieshaber, M. K. and Giere, O., 1997. Ultrastructure and anaerobic metabolism of mitochondria in the marine oligochaete *Tubificoides benedii*, effects of hypoxia and sulfide. *Marine Biology*, 127, 637-645.

Duijnste, I., 2001. Experimental ecology of foraminifera, towards better quantitative paleoecological reconstructions, Ph.D. thesis, Utrecht University, Utrecht, Nijmegen University.

Duijnste, I., Ernst, S.R., Van Der Zwaan, G.J., 2003. Effect of anoxia on the vertical migration of benthic foraminifera. *Marine Ecology Progress Series*, 246, 85-94.

Duijnste, I., De Lugt, I., Vonk Noordegraaf, H. and Van Der Zwaan B., 2004. Temporal variability of foraminiferal densities in the northern Adriatic Sea. *Marine Micropaleontology*, 50, 125-148.

Durrieu, J., Mojtahid, M., Cazes, L., Galgani, F., Jorissen, F. and Camps, R., 2006. Aged Drilled Cuttings Offshore Gabon , New methodology for assesing their impact. Vol. 98414. Society of Petroleum Engineers Inc. SPE, Abu Dhabi. 8 pp.

Eberwein, A. and Mackensen, A., 2006. Regional primary productivity differences off Morocco (NW-Africa) recorded by modern benthic foraminifera and their stable carbon isotopic composition. *Marine Micropaleontology*, 61, 58-75.

Ernst, S., Duijnste, I. and Van Der Zwaan, B., 2002. The dynamics of the benthic foraminiferal microhabitat, recovery after experimental disturbance. *Marine Micropaleontology*, 46, 343-361.

Ernst, S. and Van Der Zwaan, B., 2004. Effects of experimentally induced raised levels of organic flux and oxygen depletion on a continental slope benthic foraminiferal community. *Deep Sea Research*, 51, 1709-1739.

Ernst, S., Bours R., Duijnste I., and Van Der Zwaan, B., 2005. Experimental effects of an organic matter pulse and oxygen depletion on a benthic foraminiferal shelf community. *Journal of Foraminiferal Research*, 35, 177-197.

Fauchald, K. and Jumars, P.A., 1979. The diet of worms, a study of Polychaete feeding guilds. *Oceanography and Marine Biology Annual Review*, 17, 193-284.

Fenchel, T. and Finlay, B.J., 1995. Ecology and Evolution in Anoxic Worlds. Oxford university press. Oxford.

Fenske, C. and Günther, B., 2001. Electro-fishing in the lab, A new method to detect acute effects of heavy metals and organic pollutants in invertebrate indicator organisms. International Journal of Hygiene and Environmental Health, 204, 157-163.

Fontanier, C., Jorissen, F.J., Chaillou, G., Anschutz, P. and Lafon, V., 2003. Seasonal and interannual variability of benthic foraminiferal faunas at 550m depth in the Bay of Biscay. Deep Sea Research I, 50, 457-494.

Fontanier, C., Jorissen, F.J., Licari, L., Alexandre, A., Anschutz, P., Carbonel, P., 2002. Live benthic foraminiferal faunas from the Bay of Biscay, faunal density, composition and microhabitats. Deep Sea Research I, 49, 751-785.

Giere, O., Rhode, B. and Dubilier, N., 1988. Structural peculiarities of the body wall of *Tubificoides benedii* (Oligochaeta) and possible relations to its life in sulphidic sediments. Zoomorphology, 108, 29-39.

Giere, O., Preusse, J.H. and Dubilier, N., 1999. *Tubificoides benedii* (Tubificidae, Oligochaeta)—a pioneer in hypoxic and sulfidic environments. An overview of adaptive pathways. Hydrobiologia, 406, 235-241.

Gooday, A.J. and Turley, C.M., 1990. Responses by benthic organisms to inputs of organic material to the ocean floor, a review. Philosophical Transactions of the Royal Society of London A. 331, 119-138.

Gooday, A.J., Bernhard, J.M., Levin, L.A. and Suhr, S.B., 2000. Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings, taxonomic composition, diversity, and relation to metazoan faunas. Deep Sea Research II, 47, 25-54.

Grassle, J.F. and Grassle, J.P., 1974. Opportunistic life histories and genetic systems in marine polychaetes. Journal of Marine Research, 32 (2), 253-284.

Gray, J.S., 1981. The Ecology of Marine Sediments. An Introduction to the Structure and Function of Benthic Communities. Cambridge University Press, Cambridge, 185 pp.

Gustafsson, M. and Nordberg, K., 1999. Benthic foraminifera and their response to hydrography, periodic hypoxic conditions and primary production in the Koljö Fjord on the Swedish west coast. Journal of Sea Research, 41, 163-178.

Gustafsson, M. and Nordberg, K., 2001. Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish West Coast, with comparisons to Höglud's 1927 material. Journal of Sea Research, 31, 2-11.

Hayek, L.A.C. and Buzas, M.A., 1997. Surveying Natural Populations. New York: Columbia.

Hayward, W.B., Grenfella, H.R., Sabaa, A.T., Cartera, R., Cochran, U., Lipps, J.H., Shaned, P.R., Morleya, M.S., 2006. Micropaleontological evidence of large earthquakes in the past 7200 years in southern Hawke's Bay, New Zealand. Quaternary Science Review, 25, 1186-1207.

Heinz, P., Hemleben, C., Kitazato, J., 2002. Time-response of cultured deep-sea benthic foraminifera to different algal diets. *Deep Sea Research I*, 49, 517-537.

Heinz, P., Schmiedl, G., Kitazato, H., Hemleben, C., 2001. Response of deep-sea benthic foraminifera from the Mediterranean Sea to simulated phytoplankton pulses under laboratory conditions. *Journal of Foraminiferal Research*, 31 (3), 210-227.

Heip, C., Willems, K. A. and Goossens, A., 1977. Vertical distribution of meiofauna and the efficiency of the Van Veen grab on sandy bottoms in lake Grevelingen (the Netherlands). *Aquatic ecology*, 11, 35-45.

Hellawell J. M., 1978. *Biological Surveillance of Rivers, A Biological Monitoring Handbook*. Water Research Centre, Medmenham and Stevenage.

Hellawell J. M. 1986. *Biological Indicators of Freshwater Pollution and Environmental Management*. Applied Science Publishers, London.

Hill, M.O. and Gauch, H.G., 1980. Detrended correspondence analysis, an improved ordination technique. *Vegetation*, 49, 47-58.

Jones, R.W., 1994. *The Challenger foraminifera*. Oxford University Press, 142 pp.

Jorissen, F.J., Barmawidjaja, D.M., Puskaric, S. and van der Zwaan, G.J., 1992. Vertical distribution of benthic foraminifera in the northern Adriatic Sea, The relation with the organic flux. *Marine Micropaleontology*, 19, 131-146.

Jorissen, F.J., Wittling, I., Peypouquet, J.P., Rabouille, C. and Relexans, J.C. 1998. Live benthic foraminiferal faunas off Cape Blanc, NW Africa; community structure and microhabitats. *Deep-Sea Research I*, 45, 2157-2188.

Jorissen, F.J., Wittling, I., 1999. Ecological evidence from livedead comparisons of benthic foraminiferal faunas off Cape Blanc (Northwest Africa). *Palaeogeography, Paleoclimatology, Paleoecology*, 149, 151-170.

Josefson, A.B., 1990. Increase of benthic biomass in the Skagerrak–Kattegat during the 1970s and 1980s – effects of organic enrichment. *Marine Ecology Progress Series*, 66, 117-130.

Kikuchi, T., 1979. Some aspects of ecology, life cycle and taxonomy of the polychaete *Capitella capitata*, so called pollution indicator. *A Review of Benthos Research*, 17/ 18, 33-51.

Kramer and Botterweg, 1991. Aquatic biological early warning systems, an overview. In, Jeffrey, D.W., Madden B. (eds) *Bioindicators and environmental management*. Academic press, London, 95-126.

Langezaal, A.M., Jorissen, F.J., Brauna, B., Chailloud, G., Fontanier, C., Anschutz, P., van der Zwaan, G.J., 2006. The influence of seasonal processes on geochemical profiles and foraminiferal assemblages on the outer shelf of the Bay of Biscay. *Continental Shelf Research*, 26, 1730-1755.

Lenihan, H.S., Peterson, C.H., Kim, S.L., Conlan, K.E., Fairey, R., McDonald, C., Grabowski, J.H., Oliver, J.S., 2003. Variation in marine benthic community composition allows discrimination of multiple stressors. *Marine Ecology Progress Series*, 261, 63-73.

Levin L.A., Ziebis W., Mendoza G.F., Growney-Cannon V. and Walther S., 2006. Recruitment response of methane-seep macrofauna to sulfide-rich sediments, An in situ experiment. *Journal of Experimental Marine Biology and Ecology*, 330, 132-150.

Li, Q., James, N.P., Bone, Y., McGowran, B., 1999. Palaeoceanographic significance of recent foraminiferal biofacies on the southern shelf of Western Australia, a preliminary study. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 147, 101-120.

Loeblich, A.R., and Tappan, H., 1964. Foraminiferal genera and their classification. Van Nostrand Reinhold C°, New York, 2 vol. 970+847 pp.

Lutze, G.F. and Colbourn, W.T., 1984. Recent benthic foraminifera from the continental margin of Northwest Africa, community structure and distribution. *Marine Micropaleontology*, 8, 361-401.

Mackay, D.W., Halcrow, W. and Thornton, I., 1972. Sludge dumping in the Firth of Clyde. *Marine pollution Bulletin*, 3, 7-11.

Mason C. F., 1991. *Biology of Freshwater Pollution*. 2<sup>nd</sup> edition. Longman Scientific and Technical, Essex, 351 pp.

Maurer, D., Gerlinger, T., Nguyen, H., 1998. The response of two spionid polychaetes to natural processes and anthropogenic activities on the San Pedro Shelf, California. *Ophelia*, 48, 185-206.

Matthews, J.B.L., Buchholz, F., Saborowski, R., Tarling, G.A., Dallot, S., and Labat, J.P., 1999. On the physical oceanography of the Kattegat and Clyde Sea area, 1996–98, as background to ecophysiological studies on the planktonic crustacean, *Meganyctiphanes norvegica* (Euphausiacea). *Helgoland Marine Research*, 53, 70-84.

McCall, P.L., 1977. Community patterns and adaptative strategies of the infaunal benthos of Long Island Sound. *Journal of Marine Research*, 35, 221-265.

McIntyre, A.D. 1977. Effects of pollution on inshore benthos. In *ecology of marine benthos*, ed. Coull, B.C. Columbia, University of South Carolina press, pp. 301-318.

Mendes, I., Gonzalez, R., Dias, J.M.A., Lobo, F., Martins, V., 2004. Factors influencing recent benthic foraminifera distribution on the Guadiana shelf (Southwestern Iberia). *Marine Micropaleontology*, 51, 171-192.

Mendez, N., Romero, J. and Flos, J., 1997. Population dynamics and production of the polychaetes *Capitella capitata* in the littoral zone of Barcelona (Spain, NW Mediterranean). *Journal of Experimental Marine Biology and Ecology*, 218(2), 263-284.

Modig, H. and Ólafsson, E., 1998. Responses of Baltic benthic invertebrates to hypoxic events. *Journal of Experimental Marine Biology and Ecology*, 229, 133-148.

Moodley, L., Van Der Zwaan, G.J., Herman, P.M.J., Kempers, L., Van Breugel, P., 1997. Differential response of benthic meiofauna to anoxia with special reference to Foraminifera (Protista, Sarcodina). *Marine Ecology Progress Series*, 158, 151-163.

Mojtahid, M., Jorissen, F., Durrieu, J., Galgani, F., Howa, H., Redois, F., Camps, R. 2006. Benthic foraminifera as bio-indicators of drill cutting disposal in tropical east Atlantic outer shelf environments. *Marine Micropaleontology*, 61, 58-75.

Morvan, J., Le Cadre, V., Jorissen, F. and Debenay, J.P., 2004. Foraminifera as potential bio-indicators of the « Erika » oil spill in the Bay of Bourneuf, Field and experimental studies. *Aquatic Living Research*, 17, 317-322.

Morvan, J., Debenay, J.P., Jorissen, F., Redois, F., Bénéteau, E., Delplancke, M. and Ama, A-S., 2006. Patchiness and life cycle of intertidal foraminifera, Implication for environmental and paleoenvironmental interpretation. *Marine Micropaleontology*, 61, 131-154.

Murray, J.W., 1991. *Ecology and Palaeoecology of Benthic Foraminifera*. Longman Scientific & Technical, Harlow, 397 pp.

Murray, J.W., 1995. Microfossil indicators of ocean water masses, circulation and climate. In, Bosence, D.W.J., Allison, P.A. (Eds.), *Marine Palaeoenvironmental Analysis from Fossils*. Geological Society Special Publication, 83, 245-264.

Murray, J.W., 2006. *Ecology and applications of benthic foraminifera*. Cambridge: Cambridge University Press, 426 pp.

Nagy, J. and Alve, E., 1987. Temporal changes in foraminiferal faunas and impact of pollution in Sandebukta, Oslo fjord. *Marine Micropaleontology*, 12, 109-128.

Nagy, J. and Johansen, H.O., 1991. Delta-influenced foraminiferal assemblages from the Jurassic (Toarcian-Bajocian) of the northern North Sea. *Micropaleontology*, 37, 1-40.

Neal, K.J. and Ballerstedt, S., 2006. *Cirratulus cirratus*. A bristleworm. Marine Life Information Network, Biology and Sensitivity Key Information Sub-programme [on-line]. Plymouth, Marine Biological Association of the United Kingdom. Available from, "<http://www.marlin.ac.uk/species/Cirratuluscirratus.htm>".

Niermann, U., Bauerfeind, E., Hickel, W., Westernhagen, H.V., 1990. The recovery of benthos following the impact of low oxygen content in the German Bight. *Netherlands Jour.of Sea Res.* 25, 215-226. Nijmegen, The Netherlands, 149 pp.

Nilsson, H. C., 1999. Effects of hypoxia and organic enrichment on growth of the brittle stars *Amphiura filiformis* (O.F. Müller) and *Amphiura chiajei* Forbes. *Journal of Experimental Marine Biology and Ecology*, 237, 11-30

Nilsson, H.C., Rosenberg, R., 1994. Hypoxic response of two marine benthic communities. *Marine Ecology Progress Series*, 115, 209-217.

Nilsson, H.C., Sköld, M., 1996. Arm regeneration and spawning in the brittle star *Amphiura filiformis* (O.F. Müller) during hypoxia. *Journal of Experimental Marine Biology and Ecology*, 199, 193-206.

Pearson, T.H., M. Takahashi and B. Hargrave. 1977. *Biological Oceanographic Processes*, 2nd edition. Pergamon Press, Oxford, 332 pp.



Pearson, T. H. and Rosenberg, R. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology Annual Review*, 16, 229-311.

Pearson, T.H., 1982. The Loch Eil Project, assessment and synthesis with a discussion of certain biological questions arising from the study of the organic pollution of sediments. *Journal of Experimental Marine Biology and Ecology* 57, 93-124.

Pearson, T.H., Gray, J. and Johannessen, P.J. 1983. Objective selection of sensitive species indicative of pollution-induced change in benthic communities. 2. Data analyses. *Marine Ecology Progress Series* 12, 237-255.

Pearson, T.H. 1985. The benthic ecology of an accumulating sludge disposal ground. *Proceedings of the Fourth International Ocean Disposal Symposium*, Plymouth, England, April, 1983.

Pearson, T.H., 1986. Disposal of sewage in dispersive and non-dispersive areas, contrasting case histories in British coastal waters. G. Kullenberg (ed.), *the role of the oceans as a waste disposal option*, 577-595.

Pearson, T.H., Duncan, G. and Nuttal, J., 1986. Long term changes in benthic communities of Loch Linnhe and Loch Eil (Scotland). *Hydrobiologia* 142, 113-119.

Pearson, T.H., 1988. Survey report. Garroch Head sludge disposal ground survey 1988.

Penry, D. L., and P. A. Jumars., 1990. Gut architecture, digestive constraints and feeding ecology of deposit-feeding and carnivorous polychaetes. *Oecologia* 82, 1-11.

Perés, J.M., and Picard. J., 1964. Nouveau manuel de bionomie benthique de la Méditerranée. *Bulletin Travaux Station Marine d'Endoume* 31, 5- 137.

Phleger, F.B., Parker, F.L. and Peirson, J.F. 1953. "North Atlantic Foraminifera". *Reports of the Swedish Deep-Sea Expedition* 7(1), 1-122.

Phleger, F.B., Soutar, A., 1973. Production of benthic foraminifera in the tree east Pacific minima. *Micropaleontology* 19, 110-115.

Platon, E., Sen Gupta, B.K., Rabalais, N.N., Turner, R.E., 2005. Effect of seasonal hypoxia on the benthic foraminiferal community of the Louisiana inner continental shelf, The 20th century record. *Marine Micropaleontology* 54, 263-283.

Poag, C.W., 1981. *Ecological Atlas of Benthic Foraminifera in the Gulf of Mexico*, Hutchinson Ross Publishing Co., Stroudsburg, PA, 174 pp.

Reaves, C.M., 1986. Organic matter metabolizability and calcium carbonate dissolution in nearshore marine muds. *Journal of Sedimentary Petrology* 56, 486-494.

Resig, J.M., 1960. Foraminiferal ecology around ocean outfalls off southern California. In, E. Person (Editor), *Disposal in the marine environment*. Pergamon Press, London, pp. 104-121.

Risgaard-Petersen N., Langezaal, A.M., Ingvarsdén, S., Schmid, M.C., Jetten, M.S.M., Op den Camp, H.J. M., Derksen, J.W.M., Piña-Ochoa, E., Eriksson, S.P., Nielsen, L.P., Peter Revsbech, N., Cedhagen, T. and van der Zwaan, G. J., 2006. Evidence for complete denitrification in a benthic foraminifer. *Nature* 443, 93-96.

Rosenberg, R., 1976. Benthic faunal dynamics during succession following pollution abatement in a Swedish estuary. *Oikos* 27, 414-427.

Rosenberg, R. and Loo, L.O., 1988. Marine eutrophication induced oxygen deficiency, effects on soft bottom fauna, western Sweden. *Ophelia*, 29, 213-225.

Rosenberg, R., Hellman, B., Johansson, B., 1991. Hypoxic tolerance of marine benthic fauna. *Marine Ecology Progress Series* 79, 127-131.

Rosenberg D. M. and Resh V. H., 1993. *Freshwater Biomonitoring and Benthic Macro-invertebrates*. Chapman and Hall, London.

Salen-Picard, C., Arlhac, D. and Alliot, E., 2003. Responses of a Mediterranean soft bottom community to short-term (1993–1996) hydrological changes in the Rhone River. *Marine Environmental Research* 55, 409-427.

Sanvicente-Anorve, L., Leprêtre, A., Davout, D., 2002. Diversity of benthic macrofauna in the eastern English Channel, comparison among and within communities. *Biodiversity and Conservation* 11, 265-282.

Shafer, C.T., 1970. Studies of benthonic foraminifera in the Restigouche estuary: Faunal distributional patterns near pollution sources. *Maritime sediments* 6, 121-134.

Schafer, C.T., 1973. Distribution of foraminifera near pollution sources in Chaleur Bay. *Water, Air, and Soil pollution* 2, 219-233.

Schafer, C.T., Wagner, F.J.E. and Ferguson, C., 1975. Occurrence of foraminifera, molluscs and ostracods adjacent to the industrialized shoreline of Canso Strait, Nova Scotia. *Water, Air and Soil Pollution* 5, 79-96.

Seki, H. 1982. *Organic Materials in Aquatic Ecosystems*. CRC press, Boca Raton, Florida, 201 pp.

Shannon, C.E., 1948. A mathematical theory of communication. *Bell system technical journal* 27, 379-423; 623-656.

Sharifi, A.R., Croudace, I.W. Austin, R.L., 1991. Benthic foraminiferids as pollution indicators in Southampton Water, southern England, UK. *Journal of micropaleontology* 10 (1), 109-113.

Simonini, R., Ansaloni, I., Bonvicini Pagliai, A.M. and Prevedelli, D. 2004. Organic enrichment and structure of the macrozoobenthic community in the northern Adriatic Sea in an area facing Adige and Po mouths. *ICES Journal of Marine Science* 61, 871-881.

Somero, G.N., Childress, J.J., Anderson, A.E., 1989. Transport, metabolism, and detoxification of hydrogen sulfide in animals from sulfide-rich marine environments. *Review of Aquatic Science* 1, 591-614.

Steyaert, M., Moodley, L., Nadong, T., Moens, T., Soetaert, K. and Vincx, M., 2007. Responses of intertidal nematodes to short-term anoxic events. *Journal of Experimental Marine Biology and Ecology*, 345, 175-184.

Sutherland, T.F., Levings, C.D., Petersen, S.A., Poon, P., Piercey, B., 2007. The use of meiofauna as an indicator of benthic organic enrichment associated with salmonid aquaculture. *Marine Pollution Bulletin*, 54, 1249-1261.

Szarek, R., Kuhnt, W., Kawamura, H., Kitazato, H., 2006. Distribution of recent benthic foraminifera on the Sunda Shelf (South China Sea). *Marine Micropaleontology*, 61, 171-195.

Szymelfenig, M., Kotwicki, L., and Graca, B., 2006. Benthic re-colonization in post-dredging pits in the Puck Bay (Southern Baltic Sea). *Estuarine Coastal and Shelf Science*, 68, 489-498.

Thomas, E., Gapotchenko, T., Varekamp, J.C., Mecray, E.L., Buchholz ten Brink, M.R., 2000. Benthic foraminifera and environmental changes in Long Island Sound. *Journal of Coastal Research*, 16, 641-655.

Tsujimoto, A., Nomura, R., Yasuhara, M., Yamazaki, H., Yoshikawa, S., 2006. Impact of eutrophication on shallow marine benthic foraminifers over the last 150 years in Osaka Bay, Japan. *Marine Micropaleontology*, 60, 258-268.

Tsutsumi, H., Kikuchi, T., 1984. Study of the life history of *Capitella capitata* (Polychaeta, Capitellidae) in Amakusa, South Japan including a comparison with other geographical regions. *Marine Biology*, 80, 315-321.

Tsutsumi, H., 1990. Population persistence of *Capitella* sp. (Polychaeta; Capitellidae) on a mud flat subject to environmental disturbance by organic enrichment. *Marine Ecology Progress Series*, 63, 147-156.

Tyson, R.V. and Pearson, T.H., 1991. *Modern and Ancient Continental Shelf Anoxia*. Geological Society of London Special Publication, 474 pp.

Van Der Zwaan, G.J., 2000. Variation in natural vs. anthropogenic eutrophication of shelf areas in front of major rivers. *Environmental micropaleontology*, Vol 15 of *Topics in Geobiology*, edited by Ronald E. Martin. Kluwer Academic/Plenum Publishers, New York, 2000.

Van Hoey G., Vincx M. and Degraer S., 2005. Small- to large-scale geographical patterns within the macrobenthic *Abra alba* community. *Estuarine, Coastal and Shelf Science*, 64, 751-763.

Vistisen, B., Vismann, B., 1997. Tolerance to low oxygen and sulfide in *Amphiura filiformis* and *Ophiura albida* (Echinodermata, Ophiuroidea). *Marine Biology* 128, 241-246.

Ward, B.L., Barrett, P.J. and Vella, P. 1987. Distribution and ecology of benthic foraminifera in McMurdo Sound, Antarctica. *Paleogeography, Palaeoclimatology, Paleoecology*, 58, 139-153.

Warren, L.M., 1976. A population study of the polychaete *Capitella capitata* in Plymouth. *Marine Biology*, 38, 209-216.

Washington, H. G., 1984. Diversity, biotic and similarity indices, a review with special relevance to aquatic ecosystems. *Water Research*, 18, 653-694.

Watkins, J.G., 1961. Foraminiferal ecology around the Orange County, California, ocean sewer outfall. *Micropaleontology*, 7(2), 199-206.

Webster, L. and Campbell, L. A., 2002. Chlorobiphenyl contaminants at Pladda and Garroch Head in the Firth of Clyde following the cessation of sewage sludge dumping. *Journal of Environmental Monitoring*, 4, 284-290

Yanko, V. and Flexer, A., 1991. Foraminiferal benthonic assemblages as indicators of pollution (an example of north- western shelf of the Black Sea). *Third Annual Symp. on the Mediterranean Margin of Israel*. Haifa-Israel, 5pp.

Comparison of foraminiferal and macrofaunal responses to organic pollution (Scotland)

**Appendix 5-1.** Results of acidity and redox potential measurements in the sediment.

Station	G1		J7		M7		P7		T7		V7		P4		P5		P8.5		P10	
Depth (m)	87		79		73		79		119		178		154		135		58		75	
Level (cm)	PH	Eh	PH	Eh	PH	Eh	PH	Eh	PH	Eh	PH	Eh	PH	Eh	PH	Eh	PH	Eh	PH	Eh
1.0	8.02	442	7.99	417	7.98	311	7.9	180	7.92	451	7.89	452	7.87	468	8.06	435	7.95	454	7.94	417
0.0	7.76	448	7.51	378	7.63	189	7.26	-96	7.52	107	7.77	454	7.48	498	7.71	355	7.54	273	7.46	439
-0.5	7.74	446	7.49	352	7.57	152	7.22	-105	7.32	57	7.63	453	7.54	486	7.59	280	7.45	154	7.41	402
-1.0	7.69	428	7.48	335	7.54	104	7.2	-124	7.36	53	7.56	451	7.62	475	7.56	223	7.46	133	7.4	369
-1.5	7.65	367	7.48	334	7.52	82	7.2	-127	7.33	53	7.62	446	7.76	468	7.57	136	7.47	123	7.41	301
-2.0	7.66	271	7.48	301	7.49	40	7.22	-133	7.31	51	7.72	435	7.84	456	7.6	127	7.49	105	7.42	268
-2.5	7.64	188	7.47	282	4.47	36	7.23	-141	7.32	36	7.77	426	7.91	448	7.64	115	7.51	101	7.44	258
-3.0	7.61	131	7.46	226	7.44	28	7.24	-143	7.34	34	7.81	421	7.99	445	7.72	99	7.54	81	7.47	212
-3.5	7.67	114	7.46	197	7.4	18	7.23	-145	7.35	33	7.83	416	8.03	443	7.77	93	7.58	82	7.54	184
-4.0	7.71	108	7.46	176	7.35	5	7.23	-153	7.36	30	7.84	364	8.04	440	7.8	87	7.6	58	7.61	169
-4.5	7.73	98	7.47	170	7.31	-6	7.22	-157	7.37	30	6.86	290	8.05	416	7.81	83	7.6	48	7.65	142
-5.0	7.73	91	7.49	152	7.3	-9	7.21	-158	7.38	26	6.86	257	8.05	336	7.79	79	7.58	41	7.64	141
-7.5	7.73	84	7.57	97	7.19	-35	7.22	-167	7.4	24	7.76	191	7.6	258	7.75	78	7.47	30	7.56	131
-10.0	7.74	87	7.52	85		-50	7.26	-172	7.44	16	7.63	168	7.43	191	7.65	14	7.55	5	7.57	129

**Appendix 5-2.** Results of organic carbon and nitrogen measurements.

Station	G1	J7	M7	P7	T7	V7	P4	P5	P8.5	P10
Water depth (m)	87	79	73	79	119	178	154	135	58	75
Distance from the disposal site (Km)	8 Km NW	2.8 Km N	1.2 Km N	0 Km	1.7 Km S	2.6 Km S	2.9 Km W	1.8 Km W	1.5 Km E	3.2 Km E
C (% d.w)	2.6	1.9	2.2	12.4	4.4	2.5	2.6	3.2	5.6	2.2
N (% d.w)	0.26	0.16	0.22	1.26	0.49	0.28	0.28	0.32	0.58	0.21
C/N	10.0	11.9	10.0	9.8	9.0	8.9	9.3	10.0	9.7	10.5

**Appendix 5-3.** Results of metal concentrations in the surficial sediment.

Sample	Sample size (g)	Wt. Of sed. (g)	Metals (mg/Kg dry solids)										
			Cd	Cr	Cu	Hg	Ni	Pb	Zn	As	Co	Fe	Mn
<b>G1</b>	14	1	<0.5	94	40	0.4	45	96	202	14	16	0.0369	1770
<b>J7</b>	25.9	1	0.5	105	150	0.5	41	84	175	11	12	0.0242	380
<b>M7</b>	21.5	1	2.5	308	258	0.9	42	146	379	24	12	0.0258	283
<b>P7</b>	8.3	1	7.0	634	433	1.5	43	302	723	52	10	0.0228	212
<b>T7</b>	18.3	1	1.0	195	125	0.5	44	110	270	15	14	0.033	385
<b>V7</b>	14.1	1	<0.5	92	125	0.3	44	76	190	13	16	0.036	1550
<b>P4</b>	13.2	1	<0.5	99	86	0.3	43	88	215	11	17	0.0365	2400
<b>P5</b>	16.0	1	0.5	134	94	0.3	46	104	238	14	16	0.0366	723
<b>P8.5</b>	29.0	1	2.0	195	140	0.6	31	120	260	19	9	0.022	220
<b>P10</b>	30.0	1	<0.5	86	44	0.3	42	70	152	10	14	0.0308	419

**Appendix 5-4.** Census data and percentages of macrofauna in the topmost centimetre of a 0.1 m<sup>2</sup> samples.

Distance (km)	8		2.8		1.2		0		1.7		2.6		2.9		1.8		1.5		3.2	
Species	G1	%	J7	%	M7	%	P 7	%	T7	%	V7	%	P4	%	P5	%	P8.5	%	P10	%
<i>Abra alba</i> (mollusca)	1	1.7	65	15					4	0.2	4	1.8	15	12.7	4	0.5	26	2.7	28	17.5
<i>Abra nitida</i> (mollusca)			2	0.3											1	0.1				
<i>Abra</i> sp.indet. (mollusca)															15	2.3				
<i>Ameana trilobata</i> (polychaeta)	3	5.2	4	0.9							3	1.3	4	3						
<i>Ameana/Polycirrus</i> (polychaeta)									17	0.7	6	2.4			53	8	3	0.3		
<i>Ampharete baltica</i> (polychaeta)																	21	2.3		
<i>Ampharete finnarchia</i> (polychaeta)									21	0.9			1	0.4	10	1.4	4	0.4	1	0.6
<i>Ampharete</i> sp.indet. (polychaeta)			6	1.4					3	0.1			1	0.4	1	0.1	4	0.4		
<i>Amphicteis gracilis</i> (polychaeta)															2	0.2	1	0.1	3	1.6
<i>Amphicteis gunneri</i> (polychaeta)																				
<i>Amphipoda</i> sp.indet. (Crsutacea, Amphipoda)	1	0.9	2	0.5	2	0					1	0.2			3	0.4	7	0.7		
<i>Amphitrite cirrata</i> (polychaeta)															1	0.2				
<i>Amphiura chiajei</i> (Echinodermata)	2	2.6									1	0.4	3	2.1					4	2.5
<i>Amphiura filiformis</i> (Echinodermata)			2	0.3							12	5.3	3	2.1	3	0.5			5	3.2
<i>Anaitides groenlandica</i> (polychaeta)													1	0.4						
<i>Ancistrosyllis groenlandica</i> (polychaeta)															1	0.1				
<i>Anobothrus gracilis</i> (polychaeta)			3	0.6							9	3.8			2	0.2				
<i>Aphrodita aculeata</i> (polychaeta)											1	0.2			2	0.3				
<i>Aporrhais pes-pelecani</i> (mollusca)															1	0.2				
<i>Arabellidae</i> sp.indet. (polychaeta)	3	4.3																		
<i>Arctica islandica</i> (mollusca)																	1	0.1		
<i>Brissopsis lyrifera</i> (Echinodermata)																				
<i>Calocaris macandaeae</i> (decapoda, macrofauna)			1	0.1											1	0.1				
<i>Capitella capitata</i> (polychaeta)	1	0.9	7	1.6	1724	7.5	66	38.3	81	3.6							7	0.8	1	0.3
<i>Caprellidae</i> sp.indet. (Crsutacea, Amphipoda)									1	0							2	0.2		
<i>Chaetoderma nitidulum</i> (mollusca)											3	1.3			1	0.1			1	0.3
<i>Chaetognathidae</i>																	1	0.1		
<i>Chaetozone/Tharyx</i> (polychaeta)			9	2.1					4	0.2			1	0.8	12	1.8	5	0.5	2	1.3
<i>Chaetozone setosa</i> (polychaeta)	1	0.9					1	0.3					6	5.1			3	0.3	4	2.2
<i>Cerianthus lloydi</i> (Cnidaria)					1	0	1	0.6												
<i>Cirratulidea</i> sp.A (polychaeta)			2	0.5																

Comparison of foraminiferal and macrofaunal responses to organic pollution (Scotland)

Appendix 5-4. Continued.

Species	Distance (km) 8		2.8		1.2		0		1.7		2.6		2.9		1.8		1.5		3.2	
	G		J7		M7		P		T7		V7		P4		P5		P8.5		P10	
	1	%		%		%	7	%		%		%		%		%		%		%
<i>Cirratulidea</i> sp.B ( <i>polychaeta</i> )																				
<i>Cirratulus cirratus</i> ( <i>polychaeta</i> )					24	0.1			214	9.5					53	8	173	19		
<i>Cirratulus filiformis</i> ( <i>polychaeta</i> )	1	0.9									6	2.7			2	0.2	1	0.1	1	0.6
<i>Cirriformia tentacula</i> ( <i>polychaeta</i> )					37	0.2					2	0.7								
<i>Cirrophorus lyra</i> ( <i>polychaeta</i> )															1	0.1				
<i>Copepoda</i> sp.indet. ( <i>copepoda</i> )															1	0.2	1	0.1		
<i>Corbula gibba</i> ( <i>mollusca</i> )			3	0.7							11	4.9	8	6.8	10	1.4	1	0.1		
<i>Cultellus pellucidus</i> ( <i>mollusca</i> )																			1	0.6
<i>Cumacea</i> sp.indet. ( <i>Crsutacea</i> )	1	0.9			1	0			1	0	1	0.4	1	0.4	2	0.3	1	0.1		
<i>Dasybranchus caducus</i> ( <i>polychaeta</i> )			1	0.2					9	0.4	3	1.3	2	1.3	14	2	5	0.5	1	0.3
<i>Dyastilis rathkei</i> ( <i>Crsutacea</i> )			1	0.1																
<i>Diplocirrus glaucus</i> ( <i>polychaeta</i> )	1	0.9	17	3.8					5	0.2	2	0.9	3	2.1	6	0.8	2	0.2	3	1.9
<i>Erinacea</i> sp.indet															3	0.5				
<i>Eteone longa</i> ( <i>polychaeta</i> )			2	0.3	5	0			45	2	1	0.2			3	0.4	46	4.9		
<i>Eteone</i> sp. ( <i>polychaeta</i> )											1	0.2								
<i>Eulalia viridis</i> ( <i>polychaeta</i> )			1	0.2											3	0.4				
<i>Eulalia</i> sp.indet ( <i>polychaeta</i> )			1	0.2			1	0.3												
<i>Eumida punctifera</i> ( <i>polychaeta</i> )	1	0.9							2	0.1							1	0.1		
<i>Gastropoda</i> sp.indet. ( <i>mollusca</i> )									1	0					2	0.2				
<i>Gattyana cirrosa</i> ( <i>polychaeta</i> )									3	0.1			1	0.8			3	0.3		
<i>Glycera alba</i> ( <i>polychaeta</i> )			12	2.7					17	0.7	2	0.9	2	1.7	10	1.4	1	0.1		
<i>Glycera rouxii</i> ( <i>polychaeta</i> )	1	1.7											2	1.3	4	0.5	31	3.3	1	0.6
<i>Goniada maculata</i> ( <i>polychaeta</i> )									1	0										
<i>Harmathoe impar</i> ( <i>polychaeta</i> )																			1	0.3
<i>Harmathoe</i> sp.indet ( <i>polychaeta</i> )			1	0.2									1	0.4	1	0.1				
<i>Hemicordata</i> ( <i>macrofauna</i> )																			1	0.3
<i>Heterocirrus</i> sp.indet. ( <i>polychaeta</i> )															3	0.4				
<i>Hydroidea</i> ( <i>macrofauna</i> )											1	0.2					1	0.1		
<i>Isopoda</i> sp.indet. ( <i>macrofauna</i> )									1	0										
<i>Kefersteina cirrata</i> ( <i>polychaeta</i> )			1	0.1																
<i>Lagisca extenuata</i> ( <i>polychaeta</i> )															1	0.1				



## Appendix 5-4. Continued.

Species	Distance (km)		8		2.8		1.2		0		1.7		2.6		2.9		1.8		1.5		3.2	
	G		1	%	J7	%	M7	%	7	%	T7	%	V7	%	P4	%	P5	%	P8.5	%	P10	%
<i>Leptosynapta inhaerens</i> (Echinodermata)					1	0.1																
<i>Litocorsa stremma</i> (Echinodermata)																	1	0.2				
<i>Lucinoma borealis</i> (mollusca)					1	0.1																
<i>Lumbrinereis fragilis</i> (polychaeta)										1	0											
<i>Lumbrinereis latrielli</i> (polychaeta)										9	0.4								1	0.1		
<i>Lumbrinereis tetraura</i> (polychaeta)	2	2.6	6	1.4										1	0.8	4	0.5	29	3.1	6	3.5	
<i>Lumbrinereis sp.indet.</i> (polychaeta)												3	1.3									
<i>Malacoceros fuliginosa</i> (polychaeta)							20	0.1														
<i>Maldanidea sp.</i> Indet																						
<i>Mediomastus fragilis</i> (polychaeta)	2	2.6	7	1.5	248	1.1	1	0.6	1222	54.5	28	12.4	7	5.5	197	29.9	346	37.1	3	1.6		
<i>Melinna palmata</i> (polychaeta)									117	5.2	1	0.2			3	0.5	3	0.3				
<i>Mollusca sp.</i> Indet (macrofauna)												1	0.2									
<i>Montacuta ferruginosa</i> (mollusca)									4	0.2											1	0.6
<i>Myriochele heeri</i> (polychaeta)			5	1					1	0	6	2.4										
<i>Mysella bidentata</i> (mollusca)			1	0.1												4	0.6					
<i>Mystides</i>																1	0.2					
<i>Natica sp.</i> (mollusca)									1	0												
<i>Nematoda</i> (meiofauna)	1	0.9	4	0.9	1044	4.6	90	51.9	121	5.4								85	9.1			
<i>Nemertea T1</i> (macrofauna)	1	0.9	11	2.4			1	0.3	9	0.4	2	0.7	1	0.4	16	2.4	7	0.8				
<i>Nemertea T2</i> (macrofauna)	1	1.7	1	0.2					9	0.4					1	0.2	14	1.4	2	1		
<i>Nemertea T3</i> (macrofauna)			1	0.1					1	0	2	0.9			1	0.1	8	0.9	1	0.3		
<i>Nemertea T4</i> (macrofauna)			1	0.1					1	0							1	0.1				
<i>Nephtys hombergii</i> (polychaeta)																		2	0.2			
<i>Nephtys hystrixis</i> (polychaeta)	2	3.5	8	1.7							1	0.4	4	3	1	0.2	2	0.2	8	5.1		
<i>Nereis punctata</i> (polychaeta)																1	0.1					
<i>Nereis sp.indet</i> (polychaeta)									1	0								1	0.1			
<i>Notomastus latericeus</i> (polychaeta)									9	0.4	1	0.2						2	0.2			
<i>Nucula minuta</i> (mollusca)									2	0.1	16	7.1										
<i>Nucula tenuis</i> (mollusca)	3	21.7	59	13.5	1	0			4	0.2	20	8.6	12	10.1	13	2	1	0.1	29	18.5		
<i>Nucula turgida</i> (mollusca)	3	4.3	34	7.9					3	0.1	9	3.8			6	0.9	1	0.1	14	8.6		
<i>Nucula sulcata</i> (mollusca)											1	0.2	4	3.4								

Comparison of foraminiferal and macrofaunal responses to organic pollution (Scotland)

Appendix 5-4. Continued.

Species	Distance (km) 8		2.8		1.2		0		1.7		2.6		2.9		1.8		1.5		3.2	
	G1	%	J7	%	M7	%	P7	%	T7	%	V7	%	P4	%	P5	%	P8.5	%	P10	%
<i>Ophiodromus flexuosus</i> ( <i>polychaeta</i> )			6	1.4					3	0.1	1	0.4	1	0.4	9	1.4	1	0.1	1	0.6
<i>Ophiotrocha</i> sp.indet. ( <i>polychaeta</i> )			1	0.2													8	0.8		
<i>Ophiura albida</i> ( <i>Echinodermata</i> )			3	0.7					13	0.6	18	8			14	2.1	2	0.2	2	1.3
<i>Ophiura</i> sp.indet. ( <i>Echinodermata</i> )					1	0							3	2.1	6	0.8				
<i>Ophiura texturata</i> ( <i>Echinodermata</i> )										1	0.2			1	0.1					
<i>Owenia fusiformis</i> ( <i>polychaeta</i> )			2	0.3																
<i>Parvicardium ovale</i> ( <i>mollusca</i> )			7	1.6							3	1.1	1	0.4	9	1.3			1	0.6
<i>Parvicardium scabrum</i> ( <i>mollusca</i> )																	1	0.1	1	0.6
<i>Pectinaria koreni</i> ( <i>polychaeta</i> )	1	0.9	26	5.9										1	0.1				1	0.3
<i>Pectinaria auricoma</i> ( <i>polychaeta</i> )											1	0.4								
<i>Pista cristata</i> ( <i>polychaeta</i> )			1	0.1																
<i>Philine</i> sp.indet.														3	0.4	4	0.4			
<i>Pholoe minuta</i> ( <i>polychaeta</i> )			3	0.6					7	0.3			1	0.4	4	0.5	6	0.6		
<i>Phoronis</i> sp.indet. ( <i>macrofauna</i> )			1	0.1																
<i>Phyllodoce</i> sp.indet. ( <i>polychaeta</i> )	1	0.9																		
<i>Platyhelminthes</i> ( <i>macrofauna</i> )			1	0.1																
<i>Policirrus</i> sp.indet. ( <i>polychaeta</i> )			1	0.1										1	0.1				1	0.6
<i>Polyphisia crassa</i> ( <i>polychaeta</i> )	1	0.9	5	1	11	0			205	9.1	3	1.1	13	10.5	70	10.5	5	0.5	10	6.4
<i>Polydora</i> sp. Indet. ( <i>polychaeta</i> )			2	0.5																
<i>Polynoidae</i> sp.indet. ( <i>polychaeta</i> )											1	0.2								
<i>Praxillella affinis</i> ( <i>polychaeta</i> )			11	2.5										1	0.2					
<i>Priapulid</i> sp. ( <i>polychaeta</i> )									2	0.1	1	0.2							1	0.6
<i>Prionospio cirrifera</i> ( <i>polychaeta</i> )			2	0.3							1	0.2			1	0.2				
<i>Prionospio malmgreni</i> ( <i>polychaeta</i> )	1	0.9	1	0.1					1	0				2	0.2	2	0.2			
<i>Prionospio</i> sp.indet. ( <i>polychaeta</i> )													1	0.4						
<i>Pseudopolydora antennata</i> ( <i>polychaeta</i> )									4	0.2										
<i>Raricirrus</i> sp. ( <i>polychaeta</i> )			1	0.1			1	0.6	3	0.1				3	0.5	12	1.2			
<i>Rhodine loveni</i> ( <i>polychaeta</i> )	4	6.1	4	0.8							3	1.1							9	5.7
<i>Sabellidae</i> sp.indet. ( <i>polychaeta</i> )			1	0.1					2	0.1							2	0.2		
<i>Scalibregma inflatum</i> ( <i>polychaeta</i> )			2	0.3					1	0	9	4	3	2.1	3	0.5	15	1.6	3	1.6
<i>Scaphandidae</i> sp.indet. ( <i>mollusca</i> )									1	0										
<i>Scutopus ventralienatus</i> ( <i>mollusca</i> )											1	0.4	2	1.3						
<i>Sphaerodurum gracilis</i> ( <i>polychaeta</i> )			1	0.1			1	0.6					1	0.8						
<i>Spionidea</i> ( <i>macrofauna</i> )			1	0.1																
<i>Spiophanes kroyeri</i> ( <i>polychaeta</i> )	14	24.3	23	5.2					10	0.4	13	5.5	6	5.1	14	2			4	2.5
<i>Tanaidacea</i> sp.indet. ( <i>Isopoda</i> )																	1	0.1		
<i>Tauberia gracilis</i> ( <i>polychaeta</i> )			2	0.3									2	1.3	3	0.4				
<i>Terebellidae</i> sp.indet. ( <i>polychaeta</i> )																	2	0.2		
<i>Terebellides stroemi</i> ( <i>polychaeta</i> )	1	1.7	2	0.5					1	0	2	0.7	9	7.2	10	1.5	1	0.1	5	2.9
<i>Tharyx</i> sp.indet. ( <i>polychaeta</i> )	1	1.7									1	0.4			14	2	1	0.1	1	0.3
<i>Thyasira flexuosa</i> ( <i>mollusca</i> )	1	0.9	13	3					47	2.1	1	0.4			13	1.9	19	2		
<i>Tubificoides benedeni</i> ( <i>oligochaeta</i> )			43	9.8	19808	86.4	12	6.7	4	0.2	1	0.2					14	1.5		
<b>Total A (Abundance)</b>	<b>58</b>		<b>432</b>		<b>22929</b>		<b>173</b>		<b>2241</b>		<b>226</b>		<b>119</b>		<b>660</b>		<b>933</b>		<b>157</b>	
<b>Total S (Species richness)</b>	<b>30</b>		<b>64</b>		<b>15</b>		<b>10</b>		<b>53</b>		<b>51</b>		<b>37</b>		<b>72</b>		<b>60</b>		<b>38</b>	
<b>Total B (Biomass)</b>	<b>9.2</b>		<b>45.2</b>		<b>67.2</b>		<b>1.5</b>		<b>30.4</b>		<b>16.8</b>		<b>11.7</b>		<b>38.5</b>		<b>11.9</b>		<b>23.2</b>	

**Appendix 5-5.** Census data and percentages of foraminiferal fauna (> 150 µm) in the topmost centimetre of a 0.1m<sup>2</sup> samples.

Species	Stations	G1		P4		P5		P7		P8.5		P10		J7		M7		T7		V7	
		A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%	A	%
<i>Ammodiscus</i> sp.		0		0		1	4.8			0		0		0		0		1	2.6		0
<i>Bulimina marginata</i>	3	5.9	5	12	3	14			1	13	5	5	1	1.2	1	11	8	21			0
<i>Discammina compressa</i>	3	5.9		0		0				0		0	1	1.2	1	11				0	0
<i>Eggerrella scabra</i>	38	75	15	35	2	9.5			6	75	91	90	74	91	6	67	3	7.9	10		91
<i>Elphidium crispum</i>		0		0		1	4.8			0		0		0		0				0	0
<i>Elphidium excavatum</i>		0		0		0				0	2	2	1	1.2		0				0	0
<i>Elphidium</i> sp.1		0		0		0				0	1	1	1	1.2		0				0	0
<i>Epistominella vitrea</i>		0		0		2	9.5			0		0		0	1	11				0	0
<i>Haplophragmoides</i> sp.		0		0		0				0		0		0		0				0	0
<i>Milionella subrotunda</i>	1	2		0		0				0		0		0		0				0	0
<i>Quinqueloculina seminula</i>		0		0		2	9.5			0	1	1	1	1.2		0		1	2.6		0
<i>Reophax nodolusus</i>		0	6	14	6	29				0		0		0		0	20	53	1		9.1
<i>Reophax</i> sp1.	2	3.9		0		0				0		0	1	1.2		0				0	0
<i>Stainforthia concava</i>	4	7.8	16	37		0				0		0	1	1.2		0		2	5.3		0
<i>Textularia porrecta</i>		0		0		0			1	13	1	1		0		0		3	7.9		0
<i>Textularia sagittula</i>		0		0		1	4.8			0		0		0		0				0	0
Branched foraminifera		0	1	2.3	3	14				0		0		0		0				0	0
<b>Total of censused individuals (A)</b>		<b>51</b>		<b>43</b>		<b>21</b>		<b>0</b>		<b>8</b>		<b>101</b>		<b>81</b>		<b>9</b>		<b>38</b>		<b>11</b>	
<b>Number of species</b>		<b>6</b>		<b>5</b>		<b>9</b>		<b>0</b>		<b>3</b>		<b>6</b>		<b>8</b>		<b>4</b>		<b>7</b>		<b>2</b>	

Comparison of foraminiferal and macrofaunal responses to organic pollution (Scotland)

**Appendix 5-6.** Census data and percentages of foraminiferal fauna (63-150 µm) in the topmost centimetre of a 0.1m<sup>2</sup> samples.

Stations	G1			P4			P5			P7		P8.5		P10			J7			M7		T7		V7		
	A	A*s	%	A	A*s	%	A	A*s	%	A	%	A	%	A	A*s	%	A	A*s	%	A	%	A	%	A	%	
<i>Ammodiscus</i> sp.	1	4	0.6				1	5	0.5					3	15	1.5										
<i>Biloculinella irregularis</i>	2	7	1				3	15	1.4					1	5	0.5										
<i>Bolivina dilatata</i>	2	7	1				2	10	0.9					1	5	0.5	1	2	0.4			4	3.1			
<i>Bolivina pygmaea</i>	2	7	1	1	4	0.5											1	2	0.4							
<i>Bolivina seminuda</i>	12	43	6	50	200	25	49	241	22	1	50			9	44	4.4	38	87	19			39	30	11	31	
<i>Bolivina spathulata</i>	5	18	2.5	1	4	0.5	4	20	1.8					1	5	0.5	1	2	0.4			1	0.8	1	2.9	
<i>Bolivina aenaraiensis</i>	1	4	0.6	4	16	2								3	15	1.5	5	11	2.3	1	11	2	1.6			
<i>Bolivina</i> spp.				4	16	2																1	0.8			
<i>Bulimina marginata</i>	8	28	3.9	21	84	11	7	34	3.1			9	15	6	30	3	9	20	4.3			36	28	3	8.6	
<i>Buliminella elegantissima</i>	1	4	0.6				5	25	2.3			3	4.9	1	5	0.5	1	2	0.4			4	3.1			
<i>Cassidulina crassa</i>	1	4	0.6	3	12	1.5	2	10	0.9																	
<i>Cylogera involvens</i>							3	15	1.4					1	5	0.5						1	0.8			
<i>Eggerella advena</i>	19	68	9.4	5	20	2.5	1	5	0.5			2	3.3	17	84	8.4	12	27	5.7					10	29	
<i>Eggerella scabra</i>	28	100	14	7	28	3.5	6	30	2.7			2	3.3	31	153	15	36	82	17	3	33	1	0.8			
<i>Elphidium albiumbilitatum</i>	59	210	29	27	108	14	40	197	18			4	6.6	25	123	12	31	71	15	1	11	4	3.1	2	5.7	
<i>Elphidium excavatum</i>	24	85	12	11	44	5.5	4	20	1.8					19	94	9.4	15	34	7.2			1	0.8	3	8.6	
<i>Epistominella vitrea</i>	1	4	0.6	14	56	7	20	98	9			11	18	9	43	4.3	5	11	2.3	1	11	19	15	1	2.9	
<i>Haplophragmoides</i> sp.							1	5	0.5																	
<i>Lagena/Fissurina</i> sp.																	2	5	1.1			2	1.6			
<i>Lenticulina</i> sp.																						1	0.8			
<i>Nonionella turgida</i>	21	75	10	7	28	3.5	1	5	0.5					16	79	7.9	3	6	1.3							
<i>Quinqueloculina seminula</i>														1	5	0.5	1	2	0.4							
<i>Quinqueloculina</i> sp.				2	8	1	2	10	0.9													1	0.8			
<i>Reophax nana</i>	1	4	0.6	15	60	7.5	23	113	10			17	28	34	167	17	26	59	13	1	11	2	1.6	4	11	
<i>Reophax nodulosus</i>	3	11	1.5	1	2	0.2								2	10	1	2	5	1.1							
<i>Saccamina</i> sp.					1	0.1	1	3	0.3										1	0.2						
<i>Sigmolopsis</i>																			1	0.2						
<i>Stainforthia concava</i>	2	7	1	14	56	7	29	143	13					11	54	5.4	4	8	1.7			4	3.1			
<i>Stainforthia</i> sp.1	2	8	1.1	3	12	1.5											3	6	1.3			2	1.6			
<i>Textularia agglutinans</i>				1	4	0.5	1	5	0.5																	
<i>Textularia porrecta</i>	3	11	1.5	5	20	2.5	17	84	7.7	1	50	12	20	13	64	6.4	9	21	4.5	1	11	2	1.6			
<i>Textularia sagittula</i>				1	4	0.5						1	1.6								1	11	1	0.8		
Indet. agglutinates	3	11	1.5														2	5	1.1							
Sessil agglutinated				3	11	1.4																1	0.8			
Indet. species				1	4	0.5																				
<b>Total (A)</b>	<b>203</b>	<b>720</b>		<b>201</b>	<b>802</b>		<b>222</b>	<b>1093</b>		<b>2</b>	<b>61</b>	<b>204</b>	<b>1005</b>	<b>206</b>	<b>470</b>	<b>9</b>	<b>129</b>	<b>35</b>								
<b>Number of species (S)</b>	<b>22</b>			<b>24</b>			<b>22</b>		<b>2</b>	<b>9</b>		<b>20</b>		<b>23</b>		<b>7</b>	<b>21</b>	<b>8</b>								
<b>Split (s)</b>	<b>0.3</b>			<b>0.3</b>			<b>0.2</b>		<b>1</b>	<b>1</b>		<b>0.2</b>		<b>0.4</b>		<b>1</b>	<b>1</b>	<b>1</b>								

**Plate 5-1**

1. *Eggerella scabra* (Williamson, 1983).
2. *Epistominella vitrea* (Parker, 1953).
3. *Textularia porrecta* (Brady, 1884).
4. *Textularia sagittula* (Defrance, 1824).
5. *Bolivina seminuda* (Cushman, 1911).
6. *Bulimina marginata* (d'Orbigny, 1826).
7. *Stainforthia concava* (Höglund, 1947).
8. *Elphidium excavatum* (Terquem, 1875).
9. *Elphidium albumbilicatum* (Weiss, 1954).
10. *Eggerella advena* (Cushman, 1922).
11. *Nonionella turgida* (Williamson, 1858).

**Scale bar = 100  $\mu$ m**





**CHAPITRE 6. BENTHIC FORAMINIFERA AS BIO-  
INDICATORS OF DRILL CUTTING DISPOSAL IN  
TROPICAL EAST ATLANTIC OUTER SHELF  
ENVIRONMENTS**

<b>RÉSUMÉ</b> .....	287
<b>6.1 ABSTRACT</b> .....	290
<b>6.2 INTRODUCTION</b> .....	290
<b>6.3 MATERIAL AND METHODS</b> .....	294
<b>6.4 RESULTS</b> .....	296
<b>6.4.1 Grain size analysis</b> .....	296
<b>6.4.2 Sediment organic matter and nutrients contents</b> .....	296
<b>6.4.3 Hydrocarbon and Barium contents</b> .....	297
<b>6.4.4 Redox potential</b> .....	298
<b>6.4.5 Leaching, microtoxicology tests, and biodegradability of     organic matter</b> .....	299
<b>6.4.6 Foraminiferal analyses</b> .....	300
6.4.6.1 Living fauna (> 150 µm fraction).....	300
6.4.6.2 Living fauna (63-150 µm fraction) .....	303
6.4.6.3 Dead fauna .....	304
<b>6.5 DISCUSSION</b> .....	306
<b>6.6 CONCLUSIONS</b> .....	311
<b>6.7 ACKNOWLEDGMENTS</b> .....	312
<b>6.8 REFERENCES</b> .....	312
<b>APPENDICES</b> .....	317
<b>PLATES</b> .....	326





## RÉSUMÉ

Nous présentons une étude sur les foraminifères benthiques de la zone externe du plateau continental Congolais (Afrique de l'Ouest), dans le but de déterminer l'impact des rejets des boues de forages pétroliers imprégnées d'huile sur le fond marin, de juger la capacité régénératrice de l'écosystème benthique ainsi que d'examiner la possibilité de développer une méthode de suivi environnemental pour les environnements ouverts de plateau continental, basée sur les foraminifères benthiques. Nous avons étudié la distribution spatiale et les microhabitats des faunes vivantes ainsi que les faunes mortes, échantillonnées en Avril 2003, 4 années après l'arrêt des activités pétrolières, pour les premiers 3 centimètres du sédiment au niveau de 9 stations (environ 180 m de profondeur). Celles-ci ayant été soumises à différents degrés de pollution par les boues de forages pétroliers de 1993 à 1999.

Nos résultats décrivent une zonation des faunes de foraminifères benthiques dans un rayon de 750 m autour des anciennes stations de rejet. À proximité immédiate des points de rejets (70 m), les faunes sont caractérisées par de faibles densités. Les faunes entre 70 m et 250 m du site de dépôt sont caractérisées par de fortes densités, avec des forts pourcentages (environ 80 %) d'espèces opportunistes comme *Bulimina aculeata*, *Bulimina marginata*, *Textularia sagittula*, *Trifarina bradyi* et *Bolivina* spp. Entre 250 et 750 m, les densités décroissent, et les pourcentages des espèces opportunistes est plus faible (40-60 % d'espèces indicatrices). Ces résultats montrent que 4 ans après l'arrêt des activités pétrolières, un fort impact environnemental est limité à 250 m autour des sites de dépôt. Nous avons utilisé ces données pour développer un indice quantitatif de pollution avec des valeurs fortement corrélées avec la distance des sites de rejet. Cet indice offre la possibilité de quantifier l'impact anthropique dans les environnements de plateau continental, mais sa validité devrait être testée dans d'autres environnements de plateau.

**Mots clés:** Foraminifères benthiques ; plateau externe ; eutrophisation ; bio-indicateur ; boue de forage ; espèces opportunistes.



## CHAPITRE 6. BENTHIC FORAMINIFERA AS BIO-INDICATORS OF DRILL CUTTING DISPOSAL IN TROPICAL EAST ATLANTIC OUTER SHELF ENVIRONMENTS

M. Mojtahid <sup>(1)</sup>, F. Jorissen <sup>(1)</sup>, J. Durrieu <sup>(2)</sup>, F. Galgani <sup>(3)</sup>,  
H. Howa <sup>(1)</sup>, F. Redois <sup>(1)</sup> and R. Camps <sup>(2)</sup>

<sup>(1)</sup> Laboratoire des Bio-Indicateurs Actuels et Fossiles (BIAF) UPRES EA 2644, Université d'Angers. 2, Boulevard Lavoisier, 49045 Angers Cedex, France, and Laboratoire d'Etude des Bio-Indicateurs Marins (LEBIM). Ker Chalon, 85350 Ile D'Yeu, France.

<sup>(2)</sup> TOTAL, département Environnement Opérations. Avenue Larribau, 64018 Pau, France.

<sup>(3)</sup> IFREMER, avenue J.-Monnet, 34203 Sète, France.

Ce chapitre correspond à un article apparu dans la revue *Marine Micropaleontology* (61 (2006), 58–75)

**Keywords:** Benthic foraminifera; outer shelf; eutrophication; bio-indicator; drill mud; opportunistic taxa; oily cuttings.

## 6.1 ABSTRACT

We present a study of benthic foraminiferal faunas from the outer continental shelf off Congo (tropical West Africa), with the aim to determine the impact of the discharge of oily drill cuttings on the sea floor environment, to judge the regenerating capacity of the benthic ecosystem, and to investigate the possibility to develop an environmental monitoring method for open marine continental shelf environments, based on benthic foraminifera. We studied the spatial distribution and microhabitats of living and dead foraminiferal faunas, sampled in April 2003, 4 years after the end of disposal activities, in the upper 3 centimeters of the sediment at 9 stations (about 180 m depth) offshore Congo, that were subject to various degrees of pollution by oily cuttings from 1993 until 1999.

Our results describe a zonation of foraminiferal faunas in the 750 m around the former disposal sites. At the immediate vicinity of the discharge points (within 70 m), faunas are characterised by low foraminiferal densities. Faunas between 70 m and 250 m of the disposal sites have very high foraminiferal densities, with high percentages (about 80 %) of opportunistic taxa such as *Bulimina aculeata*, *Bulimina marginata*, *Textularia sagittula*, *Trifarina bradyi* and *Bolivina* spp. Between 250 and 750 m from the disposal site, foraminiferal densities decrease, and the percentages of opportunistic species are lower (40-60% of indicator species). These results show that 4 years after the cessation of oily cutting disposal, strong environmental impact is limited to the 250 m around the disposal sites. We used these data to develop a quantitative pollution index, values of which are strongly correlated to distance to the disposal site. This foraminiferal index offers the possibility to quantify the impact of anthropogenic eutrophication in continental shelf environments, but its validity must be tested in other continental shelf environments.

## 6.2 INTRODUCTION

Oil well drilling operations generate large quantities of fluids and cuttings; small pieces of rock carried to the surface by the drilling fluid (“mud”) used to lubricate and cool the drill bit, and to maintain well pressure. The drill mud is recycled after the cuttings are separated by physical means (shale shakers, hydrocyclones, etc.). The cuttings are discharged, most often directly into the marine environment, but if oil based muds are used, depending on

local regulations, cuttings may be discharged into the sea, shipped to shore for treatment, or reinjected into wells (*Dalmazzone et al., 2004*).

Since the onset of offshore drilling, drill cuttings and their disposal have received considerable attention, and drilling muds have been developed with increased biodegradability and lower toxicity. However, the impact of cutting discharge on marine ecosystems, and the re-establishment of the marine fauna after cessation of drill cutting disposal, is still badly known, especially in tropical and subtropical environments. Therefore, better methods have to be developed to quantify the environmental impact of drill cutting disposal, and the duration and intensity of the impact after cessation of disposal.

At the N'Kossa field off Congo, two oil operating platforms, NKF1 and NKF2 (Fig. 6-1), were active from November 1993 to April 1999, and have been generating important discharges of cuttings impregnated with oil drill fluids. Two substances, hydrocarbons and barium, are present in important concentrations in these drill cutting discharges, and may pollute the surrounding marine ecosystems.

The cuttings contain a significant quantity of hydrocarbons, and are mixed with the autochthonous sediments by currents and bioturbation. Their discharge may enhance eutrophication and thus increase the ecosystem oxygen demand. Toxic hydrocarbon components may be responsible for additional environmental stress, which may influence faunal abundance. Under stressed conditions, some taxa will disappear, whereas more resistant taxa will increase in abundance, and highly stress-tolerant taxa may appear.

Hydrocarbons are degraded on the seafloor in the oxic environments at the sediment-water interface, and by biologic activity of anaerobic benthic organisms within the sediment. Aerobic organisms burrow into the deeper dysoxic and anoxic sediments and transport some reduced components (such as hydrocarbons) to the oxygenated sediment-water interface.

Hydrocarbon concentrations in the sediment rapidly decrease with increasing distance from the drilling platforms. At the N'Kossa field, in 2003, 4 years after the cessation of drilling activities, values are comparable to normal background values between 100 and 500 m from the disposal site (*Dalmazzone et al., 2004, Durrieu et al., 2004*).

Barium ( $\text{BaSO}_4$ ) is a major component of drilling fluids, and thus an excellent tracer of drill mud disposal. At the N'Kossa field, barium concentrations are high in the direct surroundings of the disposal sites, but strongly increased concentrations (with respect to the background values found at station 2) are found until 750 m from the discharge sites (*Dalmazzone et al., 2004, Durrieu et al., 2004*). High Barium concentrations are found farther away from the discharge area than increased hydrocarbon concentrations (until 250 m from

the disposal site, see Fig. 6-2), suggesting that hydrocarbons tend to be bio-degraded whereas Barium is preserved. For instance, between 250 and 500 m from NKF1, the levels of Ba increase from 2000 (1 year after the end of discharge activities) to 2003, indicative of a spreading of contaminated sediments over time in more distal areas (*Durrieu et al., 2004; Dalmazzone et al., 2004*).

Between 2000 and 2003, Ifremer (French Research Institute for Exploitation of the Sea) in collaboration with TOTAL, organized a research project with two main objectives:

- 1) to evaluate quantitatively the impact on the benthic ecosystem of drill cuttings contaminated by oil-based drilling fluids, and
- 2) to supervise seabed re-colonization after cessation of drill cutting disposal activities.

Foraminifera are among the more abundant protists in marine benthic environments (*Murray, 1991*). Because of their short life cycles, high biodiversity and specific ecological requirements of individual species, foraminifera react quickly to environmental disturbance, and can be successfully employed as bio-indicators of environmental change, such as those brought about by anthropogenic pollution (as defined by *Kramer and Botterweg, 1991*). Foraminiferal assemblages are easy to collect; foraminifera are commonly abundant, providing a highly reliable database for statistical analysis, even when only small sample volumes are available. Furthermore, many foraminiferal taxa secrete a carbonate shell, and leave an excellent fossil record, that may be used to characterise baseline conditions, and to reconstruct the state of the ecosystem prior to sampling.

Studies of the effects of pollution on benthic foraminiferal assemblages, and their possible use as pollution indicators were initiated in the early 1960's by *Resig (1960) and Watkins (1961)*. In the last decennia, foraminifera have been increasingly used to monitor pollution in a wide range of marine environments, such as intertidal mudflats impacted by oil spillages (*Morvan et al., 2004*), harbours affected by heavy metal pollution (*Armynot Du Châtelet et al., 2004*), or eutrophicated continental shelves (*Sharifi et al., 1991; Yanko and Flexer, 1991*).

In April 2003, we sampled benthic foraminiferal faunas at 9 stations (~180 m depth) around two sites off Congo (tropical Africa), where drill cuttings were deposited between November 1993 and April 1999. Due to its location close to the Congo River (discharge volume 40,600 m<sup>3</sup>/s, *Laraque et al., 2001*) and the presence of South-North surface currents

(Benguela current, long-shore drift; *Mounganga, 1999*) on the Congo shelf, the study area receives significant quantities of terrigenous sediments, rich in organic matter and nutrients, as shown by the high organic carbon content (12 % on average). Seasonal upwelling on the outer shelf (*Voituriez and Herbland, 1982; Jansen et al., 1984*) may add to the nutrients in the surface waters.

Nutrient input usually results in increased primary production, contributing to delivery of organic carbon on the sea floor. The oxic degradation of these organic substances by micro-organisms, in particular bacteria, leads to strong oxygen consumption in the benthic ecosystem, often leading to dysoxic to anoxic conditions in pore waters or even at the sea floor. Such natural eutrophication is common on inner shelf environments, e.g. close to the deltas of the Po (*Jorissen, 1987*), and Rhône and Mississippi rivers (*Van der Zwaan and Jorissen, 1991*). The high organic matter concentrations in our study area suggest that shelf areas off Congo are similarly naturally eutrophicated. In recent times, these natural eutrophication phenomena may be significantly amplified by anthropogenic activities in the catchment area, that result in strongly increased nutrient and organic matter concentrations in river waters (e.g. *Rabalais and Turner, 2001*).

In this study of benthic foraminiferal faunas from a naturally eutrophic region impacted by human activities, we concentrate on three aspects:

1) the density and composition of the living fauna. Due to the short life cycle of foraminifera (in general 3 months to 2 years, *Murray, 1991*), these characteristics inform us about the current ecological conditions, and thus, about the adaptation of the faunas to the physico-chemical environmental parameters resulting from the drill cutting disposal, that ended four years before sampling. Our study focuses on 2 different size fractions: the > 150 µm fraction contains the adults of the larger species, whereas the 63-150 µm size fraction contains juveniles of larger species, as well as adult representatives of small, often highly opportunistic taxa. Especially these small opportunistic taxa may have a strong response to eutrophication and/or pollution phenomena;

2) the vertical distribution of the live faunas in the first centimetres of the sediment. This so-called microhabitat varies in function of the zero oxygen level, and the availability of nutritive substances within sediment (*Jorissen et al., 1995*). A better knowledge of the foraminiferal microhabitat may yield complementary information about the degree of ecosystem eutrophication;



3) the composition of subrecent faunas, preserved at several cm depth in the sediment. This subfossil fauna, that can be studied thanks to the preservation of carbonatic foraminiferal shells after the death of the organism, is composed of a mixture of the original, pre impact fauna, alive before the onset of drilling mud disposal, and the faunas that colonized the study area during and after the period of drill mud disposal. The comparison between this subrecent fossil fauna and the living faunas enables us to recognize species indicative of this specific type of human imposed environmental stress. Generally, responsive species show a strong contrast between an absence (or a low density) in the original fauna and a high abundance in the living faunas of the stations close to the drill mud disposal site.

### 6.3 MATERIAL AND METHODS

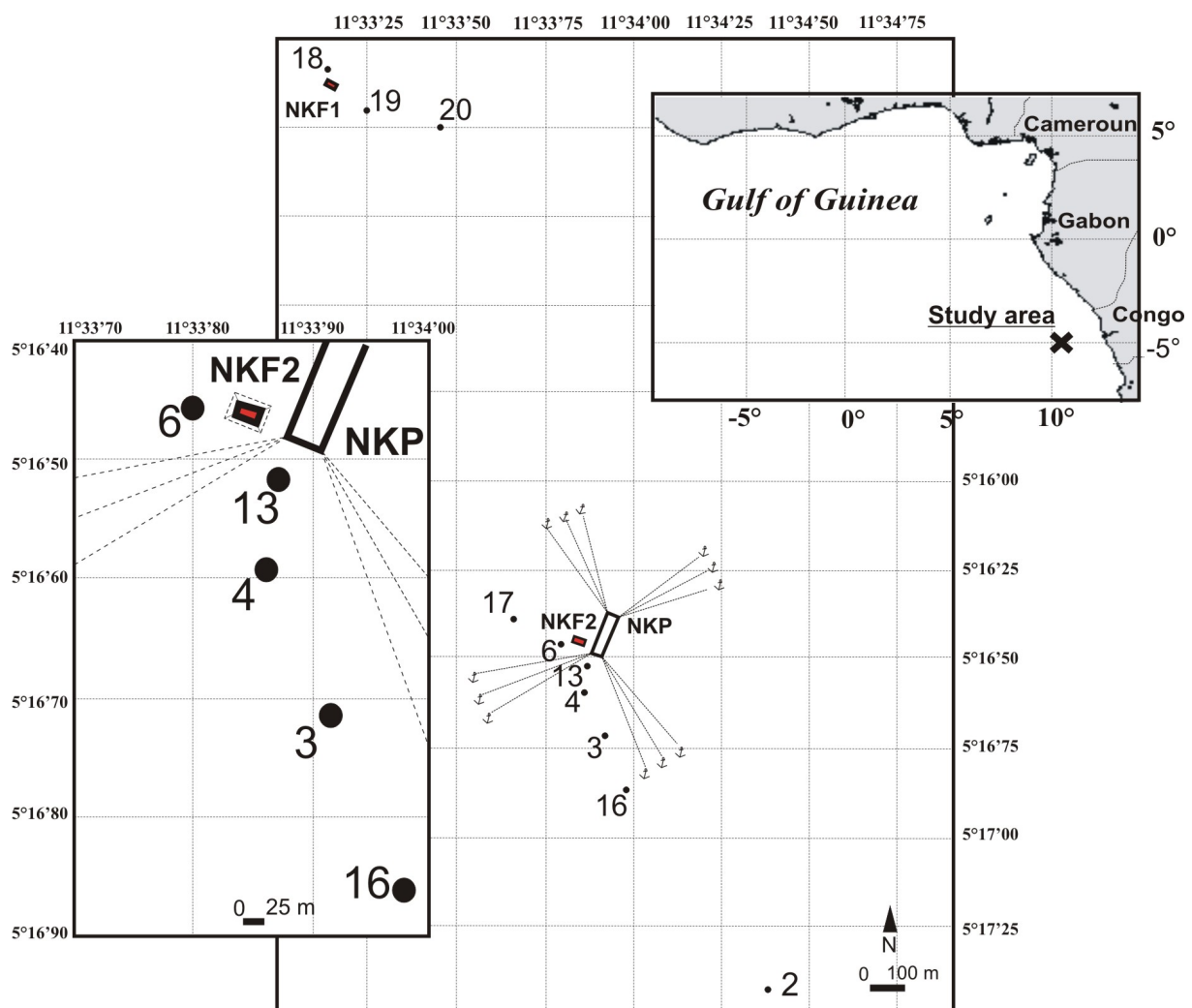


Figure 6-1. Study area and sampling location.

The study area is located in the offshore Congo on the N'Kossa field, 60 km off Pointe Noire, at a water depth of 180 m. Dumpings of LTMBF (Low Toxicity Mineral Oil Base Fluid) cuttings began in November 1993 and ended in April 1999. A study was undertaken after the first period of drilling in 1995, and was followed by 3 monitoring surveys in November 2000, March 2002 and April 2003. In this paper, we present results for the last survey. Samples were collected from the 7<sup>th</sup> to the 18<sup>th</sup> of April 2003 on a radial of 6 points around site NKF2 (the previous surveys from 2000 and 2002 suggest that drill muds were dispersed southward by bottom currents). In 2003, a seventh site was added northwest of the drill rig, and 3 sampling stations were added around the nearby drill cutting disposal site NKF1 (Fig. 6-1, Table 6-1).

Station	Location	Latitude	Longitude	Total hydrocarbons (% d.w.)	Barium (% d.w.)
2	2000m from NKF2 (South)	05°17.419 S	11°34.379 E	< 0.010	0.482
3	470m from NKF2 (South)	05°16.711 S	11°33.916 E	0.076	5.340
4	230m from NKF2 (South)	05°16.588 S	11°33.861 E	8.815	56.300
6	70m from NKF2 (West)	05°16.453 S	11°33.802 E	109.000	94.600
13	100m from NKF2 (South)	05°16.519 S	11°33.874 E	9.970	77.600
16	730m from NKF2 (South)	05°16.839 S	11°33.966 E	0.029	1.530
17	450m from NKF2 (West)	05°16.365 S	11°33.654 E	0.018	3.480
18	70m from NKF1 (North)	05°14.996 S	11°33.131 E	2.667	36.000
19	250m from NKF1 (South)	05°14.901 S	11°33.251 E	0.084	9.760
20	500 m from NKF1 (South-East)	05°15.001 S	11°33.441 E	0.040	1.270

Table 6-1. Geographical position of the sampling stations, and concentrations of total hydrocarbons and Barium in the sediment.

Methodology of measurements of all physico-chemical analyses (Ba, hydrocarbons, grain size, organic matter, nutrients, redox potential and tests of biodegradation) is given in *Dalmazzone et al. (2004)*.

For the analysis of their micropaleontological content (foraminifera), Van Veen grabs with apparently intact sediment surfaces were subsampled with a core with 4 cm inner diameter. The cores were sliced into 0.5 cm levels down to 1 cm and then in 1 cm levels down to 7 cm depth. All samples were preserved in 95% ethanol with 1 g/l Rose Bengal. In the laboratory, the collected samples were sieved over sieves of 63 and 150 µm openings. For the fraction larger than 150 µm, foraminifera of the surface level (A: 0-0.5 cm) and of the 2-3 cm level (D) were picked without any preliminary treatment, under wet conditions (50% ethanol). For the levels B (0.5-1 cm) and C (1-2 cm) as well as for samples of the granulometric

fraction 63-150  $\mu\text{m}$ , living Foraminifera were concentrated by density separation with trichloroethylene ( $D = 1.46$ ). Living as well as unaltered dead foraminifera should be found exclusively in the floated part. A check of the deposited sediment, revealing the absence of live individuals, showed the efficiency of the method. The study of the dead fauna was carried out on level D (2-3 cm). At this depth, most of the non-fossilizing arenaceous foraminifera have disappeared (*Bizon and Bizon, 1985*), and deeper living faunal elements will be correctly represented (*Loubere, 1989*). For the analysis of the dead fauna, samples were dried and split with an Otto microsplitter. Whole splits were counted until a minimum of 200 tests of foraminifera was obtained. All foraminifera selected were determined using taxonomic studies with emphasis on Atlantic Ocean shelf environments (*Phleger, Parker and Pearson, 1953; Kouyoumontzakis, 1982; Schiebel, 1992; Jones, 1994; Fontanier et al., 2002; Duchemin et al., 2005*).

## 6.4 RESULTS

### 6.4.1 Grain size analysis

The natural, unimpacted, sediment (station 2, 2 km south of the deposit site) shows a bimodal grain size distribution with maxima between 6 and 10  $\mu\text{m}$  and between 200 and 400  $\mu\text{m}$  (*Dalmazzone et al., 2004*). Close to the discharge point, an additional granulometric maximum between 20 and 60  $\mu\text{m}$  is present. This fraction is most abundant at station 13 (100 m south of the disposal site). In comparison to the values of 2002, in 2003, the fraction 20-60  $\mu\text{m}$ , that appears to be related to the discharge of cuttings, has a higher concentration at every station, with the exception of station 6 (70 m west of the disposal site), where its concentration slightly decreases (*Dalmazzone et al., 2004*).

### 6.4.2 Sediment organic matter and nutrients contents

The study area is directly influenced by the input of sediment, nutrients and continentally-derived organic matter by the Congo River, and thus is naturally eutrophic (*e.g., Kouyoumontzakis, 1979*). This observation explains the elevated levels of organic matter at all stations (11.0 to 12.8 % dry weight; 18.4 % at station 6, 70 m west of NKF2, the main

disposal site; Table 6-2). Sediment nutrient levels are elevated; 0.14-0.25 % d.w. of nitrogen (0.19% at site 2, farthest away from the drill mud disposal sites) and 0.5-1.5 ‰ d.w. of phosphorus. With the exception of the elevated organic matter content at station 6, levels of organic matter, nitrogen and phosphorus in the areas around the disposal sites are similar to those at the reference station 2. No significant changes in nutrient levels were found between 2002 and 2003 (*Dalmazzone et al., 2004*).

Platforms	Station	Distance from the discharge points (m)	Water content (%)	Organic matter (% d.w.)	Total nitrogen (% d.w.)	total phosphorous (ppm d.w.)
	6	70	35.3	18.4	0.14	778
	13	100	42.5	11.3	0.19	522
	4	230	45.8	11.3	0.19	1020
NKF2	17	380	44.8	12.8	0.16	770
	3	470	49.8	12.5	0.16	863
	16	730	47.9	11.3	0.18	810
	2	2000	48.6	12.9	0.19	1023
NKF1	18	70	48.5	12.0	0.25	824
	19	250	48.4	11.0	0.19	1461

Table 6-2. Water contents, percentage of organic matter and concentrations of nutrients in the sediment.

### 6.4.3 Hydrocarbon and Barium contents

Concentrations of hydrocarbons and Barium in the superficial sediments are presented in figure 6-2 and table 6-1. Four zones can be defined:

- Zone 1 (station 6, ~ 70 m west of NFK2) is characterized by very high hydrocarbon (> 100 ‰ d.w.) and Barium (> 90 ‰ d.w.) concentrations.

- Zone 2 (stations 13 and 4 south of NFK2, station 18, close to NKF1; within 250 m from the disposal sites) is characterised by intermediate hydrocarbon (> 2 ‰ d.w.) and very high Barium (> 30 ‰ d.w.) concentrations.

- Zone 3 (stations 17, 3 and 16 close to site NKF2, 19 and 20 close to site NKF1, between 250 and 750 m from the disposal sites) are characterised by low hydrocarbon values (0.02 and 0.09 ‰ d.w.), but elevated Barium concentrations (1-10 ‰ d.w.).

- Station 2, at 2 km from the main disposal site, supposedly represents baseline conditions, but Barium concentrations are still slightly elevated (about 0.5 ‰ d.w.).

Compared to 2002 (*Dalmazzone et al; 2004*), hydrocarbon and Barium concentrations decreased significantly at station 6, but increased slightly in an area up to 250 m from the disposal site (stations 13 and 4; *Dalmazzone et al., 2004*), probably because cuttings are spread over a larger area by means of the bottom currents. In 2003, increased Barium concentrations were observed as far as 2000 m from the disposal site whereas hydrocarbons were not observed beyond 1000 m.

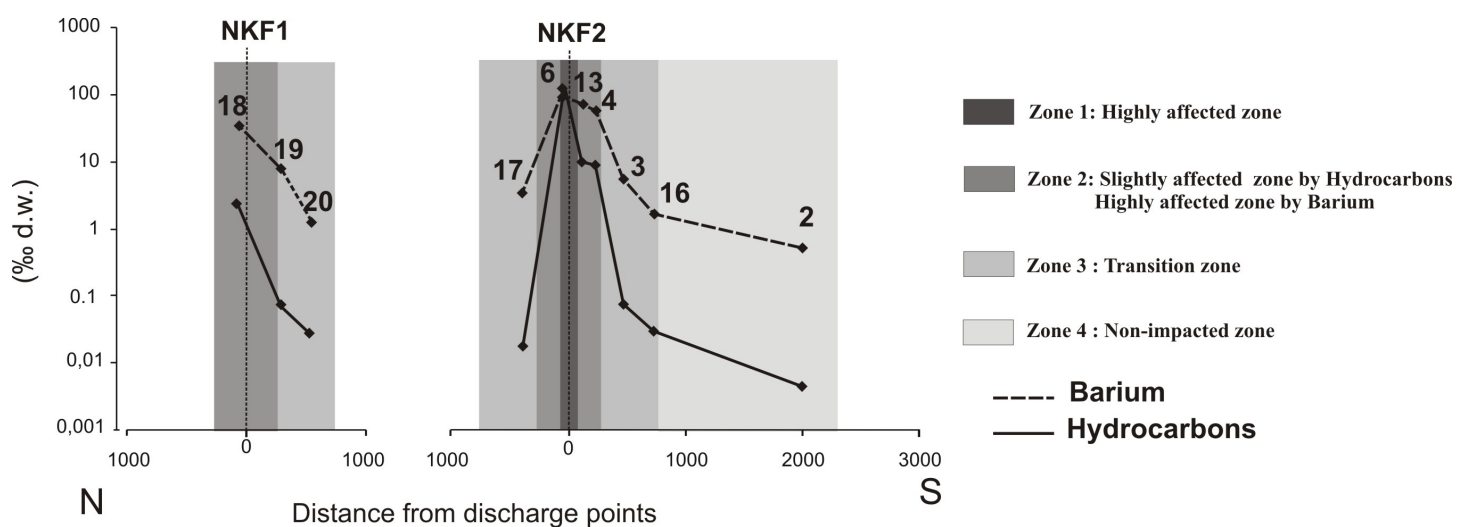


Figure 6-2. Concentration of total hydrocarbons and Barium in the sediment, in function of distance from the oil cutting disposal sites.

#### 6.4.4 Redox potential

At background station 2, the redox potential is +41mV, indicating that the sediment is sufficiently oxygenated to ensure the aerobic degradation of natural organic matter input. The redox potential increases progressively from ~ (-240 mV) at the disposal site NKF1 to ~ (+30 mV) at 730m from the discharge point, correlated closely with the decreasing hydrocarbon concentration in the sediment (*Durrieu and Bouzet, 2004*).

### 6.4.5 Leaching, microtoxicology tests, and biodegradability of organic matter

Stations	TOC (mg/l)	Total hydrocarbons (µg/l)	Microtox I max
2 (2000 m S)	73	16	<threshold
4 (230 m S)	72	90	50
13 (100 m S)	90	111	<threshold
6 (70 m W)	137	107	<threshold

Table 6-3. Results of the leaching tests on sediments containing oily cuttings and of a Microtox test (test of toxicity on marine bacteria). “I max” is the maximum inhibition of bacterial activity in the presence of the maximum concentration in the test tube (leachate diluted at 50%). Minimal threshold of inhibition: 20% (after Dalmazzone *et al.*, 2004).

Stations	Sediment (g)	Degraded hydrocarbons (%)
6 (70 m)	7.6	86*-88**
	6.8	65-71
	6.5	79-82
	6.1	84-87
13 (100 m)	5.8	48-56
	7.4	42-51
	7.3	38-48
4 (230 m)	5.7	79-83
	5.8	73-79
	5.5	79-83
	5.2	73-79

Table 6-4. Results of aerobic biodegradation after 90 days exposure, expressed in percentage of degraded hydrocarbons. Minimum (\*) and maximum (\*\*) values take into account the extraction efficiency from the abiotic sample (after Dalmazzone *et al.*, 2004).

The results from the leaching procedure and microtoxicology essays are presented in Table 6-3. A significant release of hydrocarbons (90–110 µg/l) was observed at stations 6, 13 and 4, within 70, 100 and 230 m of disposal site NKF2 (Table 6-3). The SE values are about 6 times higher than those observed at background station 2. Only at station 4 (230 m from disposal site NKF2), the microtoxicity tests showed a partial inhibition of bacterial activity, which probably is not the result of hydrocarbon pollution, in view of the low hydrocarbon concentrations in the leachate (Dalmazzone *et al.*, 2004). The results of an aerobic organic matter degradation test, performed for the most contaminated stations 6, 13 and 4, are presented in Table 6-4. For sediments collected at station 6 (70 m west of site NKF2), about

75 % of hydrocarbons were degraded after 90 days from the beginning of the experience. At stations 13 (100 m south of NFK2) and 4 (230 m south), these values are about 45 % and 80 %, respectively. These results are variable, but confirm the high biodegradability of the hydrocarbons, at least under aerobic conditions.

## 6.4.6 Foraminiferal analyses

### 6.4.6.1 Living fauna (> 150 µm fraction)

In general, the living faunas are poor in this size fraction, even for the relatively small sediment surface (12.6 cm<sup>2</sup>) sampled, and contain only minimal quantities of deformed tests (Plate 6-1; Appendix 6-2). The total number of individuals found in the uppermost 3 cm of sediment (volume = 37.7 cm<sup>3</sup>) varies between 7 and 215 (Appendix 6-3), corresponding to a density between 1.8 and 57.0 individuals/10 cm<sup>3</sup> (Fig. 6-3a). Samples from stations 2, 3, 6, 17 and 19 contain fewer than 20 live individuals (less than 5.3 individuals/10 cm<sup>3</sup>), so that percentage data are not relevant there. Samples from stations 4, 13, 16 and 18 (Fig. 6-3a, Appendix 6-3) contain more than ~ 50 specimens (more than 13.2 individuals/ 10 cm<sup>3</sup>).

– The fauna at station 13 (100 m south of NFK2; 97 specimens = 25.7 individuals/10 cm<sup>3</sup>) is dominated by species of the genus *Bulimina* (*Bulimina marginata*, 27.8 % of the total living fauna; *Bulimina costata*, 19.6 %; *Bulimina aculeata*, 12.4 %); *Uvigerina peregrina* (13.4 %), *Trifarina bradyi* (12.4 %) and *Textularia sagittula* (7.2 %) are also common.

– The fauna at station 4 (230 m south of NFK2; 215 specimens = 57.0 individuals/10 cm<sup>3</sup>) is dominated by *Amphicoryna scalaris* (20.5 %), *Eggerella* sp.1 (19.5 %), *B. aculeata* (14.9 %) and *B. marginata* (9.3 %). *T. sagittula* (4.7 %), *U. peregrina* (4.7 %) and *Rosalina globularis* (3.7 %) are present.

– The fauna at station 16 (500 m south of NFK2; 49 specimens = 13 individuals/10 cm<sup>3</sup>) is dominated by *Nonion scaphum* (22.4 %) and *U. peregrina* (18.4 %). *B. marginata* (8.2 %) and *Cancris auriculus* (8.2 %) are common.

– The fauna of station 18 (70 m north of NKF1; 85 specimens = 22.5 individuals/10 cm<sup>3</sup>) resembles that at station 4 and it is dominated by *B. aculeata* (20.0 %), *U. peregrina* (15.3 %), *Eggerella* sp.1 (14.1 %), *T. bradyi* (9.4 %), *B. marginata* (8.2 %) and *T. sagittula* (7.1 %). Some specimens of *A. scalaris* (5.9 %) are present.

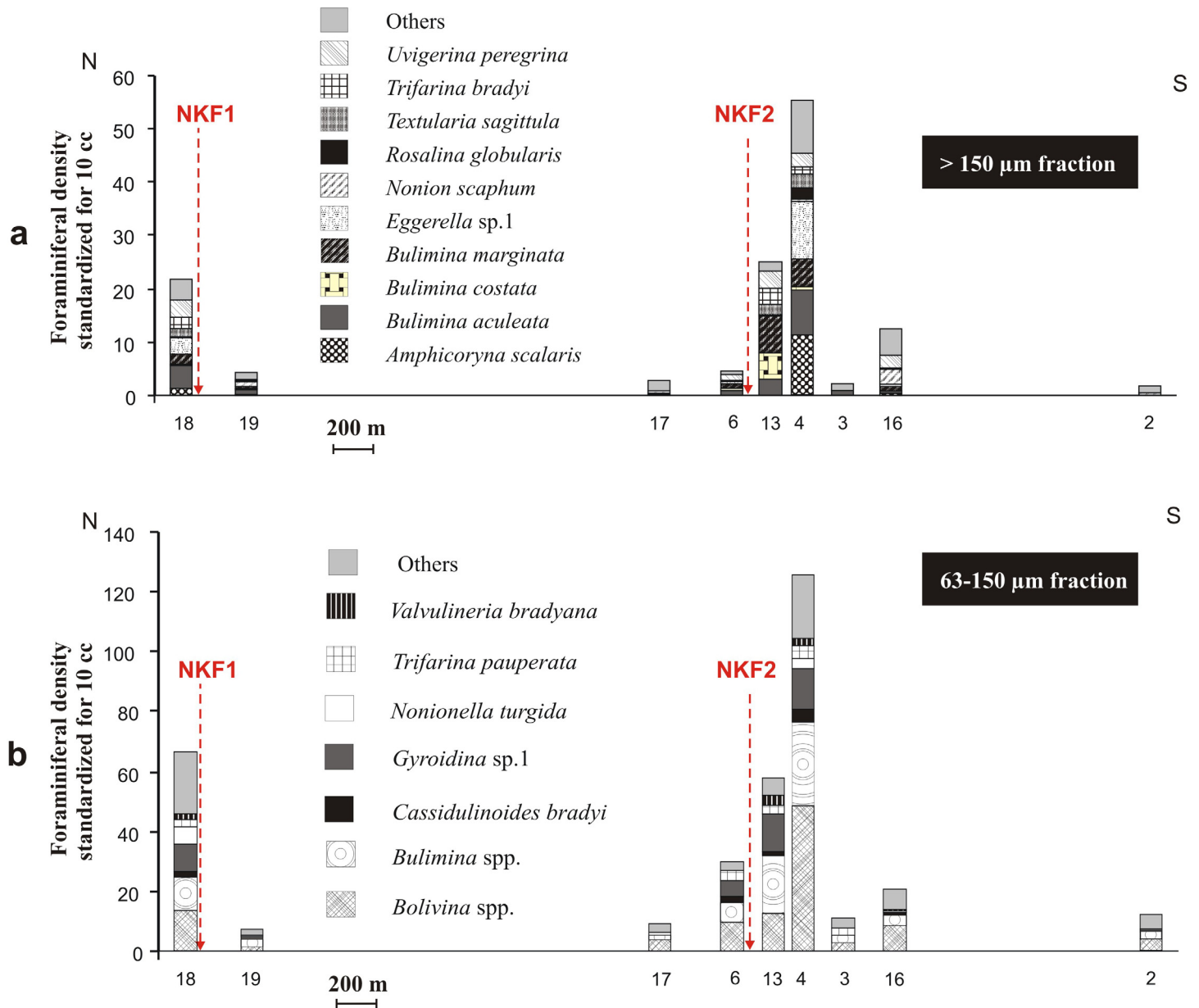


Figure 6-3. (a) Density and composition of the living foraminiferal faunas (> 150 μm fraction observed in the first 3 cm of the sediment) standardized for 10 cm<sup>3</sup> sediment volume. (b) Density and composition of the living foraminiferal faunas (63–150 μm fraction observed in the first 2 cm of the sediment) standardized for 10 cm<sup>3</sup> sediment volume.



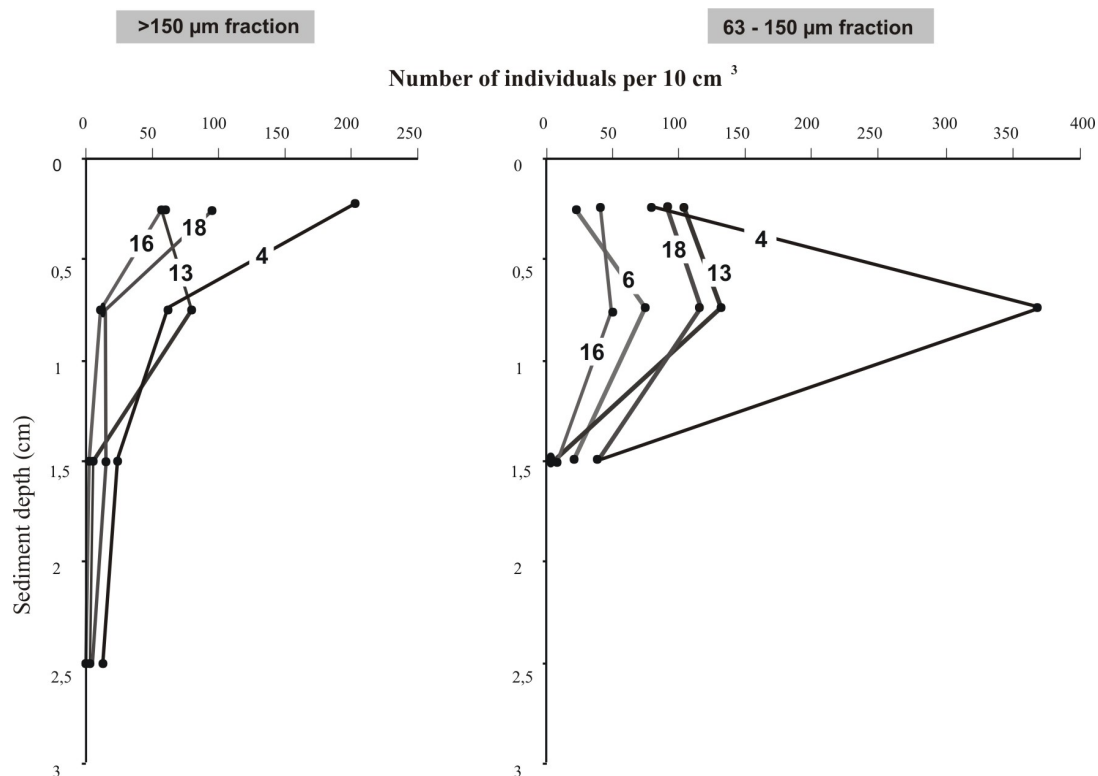


Figure 6-4. Vertical distribution of living benthic foraminifera (>150 µm and 63–150 µm fractions) standardized for 10 cm<sup>3</sup> sediment volume. Stations that are not represented contain less than 30 individuals per 10 cm<sup>3</sup> sediment volume.

Station	2	3	4	6	13	16	17	18	19
<i>(a) Total data (&gt; 150 µm fraction)</i>									
0-0,5 cm	2	1	129	11	36	38	7	60	4
0,5-1 cm	2	0	40	2	50	8	3	7	4
1-2 cm	3	6	30	5	7	3	1	18	1
2-3 cm	0	1	16	0	4	0	0	0	8
<b>Total</b>	<b>7</b>	<b>8</b>	<b>215</b>	<b>18</b>	<b>97</b>	<b>49</b>	<b>11</b>	<b>85</b>	<b>17</b>
<i>(b) Same data, standardized for 10 cm<sup>3</sup> sediment volume</i>									
0-0,5 cm	3	2	205	17	57	60	11	95	6
0,5-1 cm	3	0	63	3	79	13	5	11	6
1-2 cm	2	5	24	4	6	2	1	14	1
2-3 cm	0	1	13	0	3	0	0	0	6

Table 6-5. (a) Total numbers of living benthic foraminifera (>150 µm fraction, not standardized for sediment volume) found in all sampled sediment intervals; (b) Same data, standardized for 10 cm<sup>3</sup> sediment volume.

The fauna is generally concentrated in the upper 1 cm (Table 6-5, Fig. 6-4). At stations 2, 3 and 19, the faunas are too poor to recognize a vertical distribution. At the richest stations (4, 16 and 18), the density of the living benthic foraminifera varies from 57 to 205

individuals/ 10 cm<sup>3</sup> sediment volume in the first half centimetre, decreasing rapidly towards the deeper sediment levels. Only at station 13, the highest density (79 individuals/ 10 cm<sup>3</sup>) is in the 0.5–1 cm level. The deepest studied sediment interval (D: 2–3 cm) contains more than 1 specimen only at stations 4, 13 and 19. The faunas below 1 cm depth are dominated by *B. aculeata* (Appendix 6-2).

#### 6.4.6.2 Living fauna (63-150 µm fraction)

In general, densities in this size fraction (uppermost 2 cm) are rather similar in pattern to those found in the >150 µm fraction, although the faunas tend to be slightly richer (Plate 6-2; Appendix 6-4; Fig. 6-3b, Appendix 6-5), especially at station 6. In all cases, simple species diversity (species richness) is much higher than in the > 150 µm fraction. Faunas at stations 4, 13 and 18 contain 147 to 319 individuals/25.2 cm<sup>3</sup> (39.0 to 84.6 individuals/ 10 cm<sup>3</sup>) are dominated by *Bolivina* spp., *Bulimina* spp. and *Gyroidina* sp.1, with significant *Cassidulina crassa*, *Cassidulinoides bradyi*, *Nonionella turgida*, *Trifarina pauperata* and *Valvulineria bradyana*. The relatively high faunal densities at stations 4, 13 and 18 contrast with the much lower densities at the 6 other stations (18 to 76 individuals for 25.2 cm<sup>3</sup> = 4.8 to 20.1 individuals/10 cm<sup>3</sup>). The faunas contain not only juvenile specimens of taxa found in the >150 µm fraction, such as *B. aculeata*, *B. marginata* and *U. peregrina*, but also several small sized species that occur only in this size fraction, such as the various *Bolivina* species, *Gyroidina* sp.1, *C. bradyi*, *T. pauperata* and *V. bradyana* (Fig. 6-3b, Appendix 6-5). The composition of the faunas at these 6 stations resembles to that at stations 4, 13 and 18. The overall faunal variability is relatively limited. The stations within 230 m of the disposal sites are all rich in *Bolivina* and *Bulimina* species. *Gyroidina* sp.1 and some less frequent taxa, such as *T. pauperata*, *V. bradyana* and *N. turgida*, appear exclusively at these stations. Background station 2 differs from all other stations by the absence of *Bulimina* species. The scarce fauna (30 individuals = 11.9 individuals/10 cm<sup>3</sup>) is dominated by *B. striatula*; the species *Gyroidina* sp.1 is represented by only one specimen. At all stations, the 63-150 µm fauna is concentrated in the second half centimetre (B: 0.5–1 cm), with a density from 21 to 362 individuals/10 cm<sup>3</sup> (Table 6-6, Fig. 6-4), whereas in the first half centimetre of the sediment there are from 2 to 98 individuals/10 cm<sup>3</sup>.

Station	2	3	4	6	13	16	17	18	19
<i>(a) Total data (63–150 <math>\mu\text{m}</math> fraction)</i>									
0-0,5 cm	4	8	47	11	62	23	1	54	3
0,5-1 cm	15	11	228	44	80	27	13	70	11
1-2 cm	11	9	44	21	5	3	9	45	4
<b>Total</b>	<b>30</b>	<b>28</b>	<b>319</b>	<b>76</b>	<b>147</b>	<b>53</b>	<b>23</b>	<b>169</b>	<b>18</b>
<i>(b) Same data, standardized for 10 cm<sup>3</sup> sediment volume</i>									
0-0,5 cm	6	13	75	17	98	37	2	86	5
0,5-1 cm	24	17	362	70	127	43	21	111	17
1-2 cm	9	7	35	17	4	2	7	36	3

Table 6-6. (a) Total numbers of living benthic foraminifera (63-150  $\mu\text{m}$  fraction, not standardized for sediment volume) found in all sampled sediment intervals; (b) Same data, standardized for 10 cm<sup>3</sup> sediment volume.

#### 6.4.6.3 Dead fauna

Specimens not coloured by Rose Bengal consist of a mixture of those that inhabited the area before the start of drill mud disposal, and those living afterwards (Appendix 6-6). The study of these faunas provides a time averaged picture that may inform us about pre-pollution assemblages.

The total number of dead benthic and planktic foraminifera varies strongly. Foraminiferal densities are very low in samples 6, 13, 4 and 18 (Fig. 6-5a, Table 6-7), within 230 m of the disposal sites, probably because of the sediment dilution by drill cuttings. Stations 4, 6 and 18 are also characterized by a low PB-ratio (Table 6-7). The percentages of the most common species in the dead/fossil faunas are presented in Fig. 6-5b and c. At background station 2, stress-indicative species should have a minimal density in the living as well as dead assemblages. All dead faunas are strongly dominated by *U. peregrina*, with significant quantities of the species *Cassidulina carinata*, *B. marginata*, *Cibicides lobatulus*, *N. scaphum* and *Pseudoepionides falsobeccarii*. Such an assemblage is typical of outer continental shelf environments under the influence of abundant organic inputs (Murray, 1991; Fontanier et al., 2002).

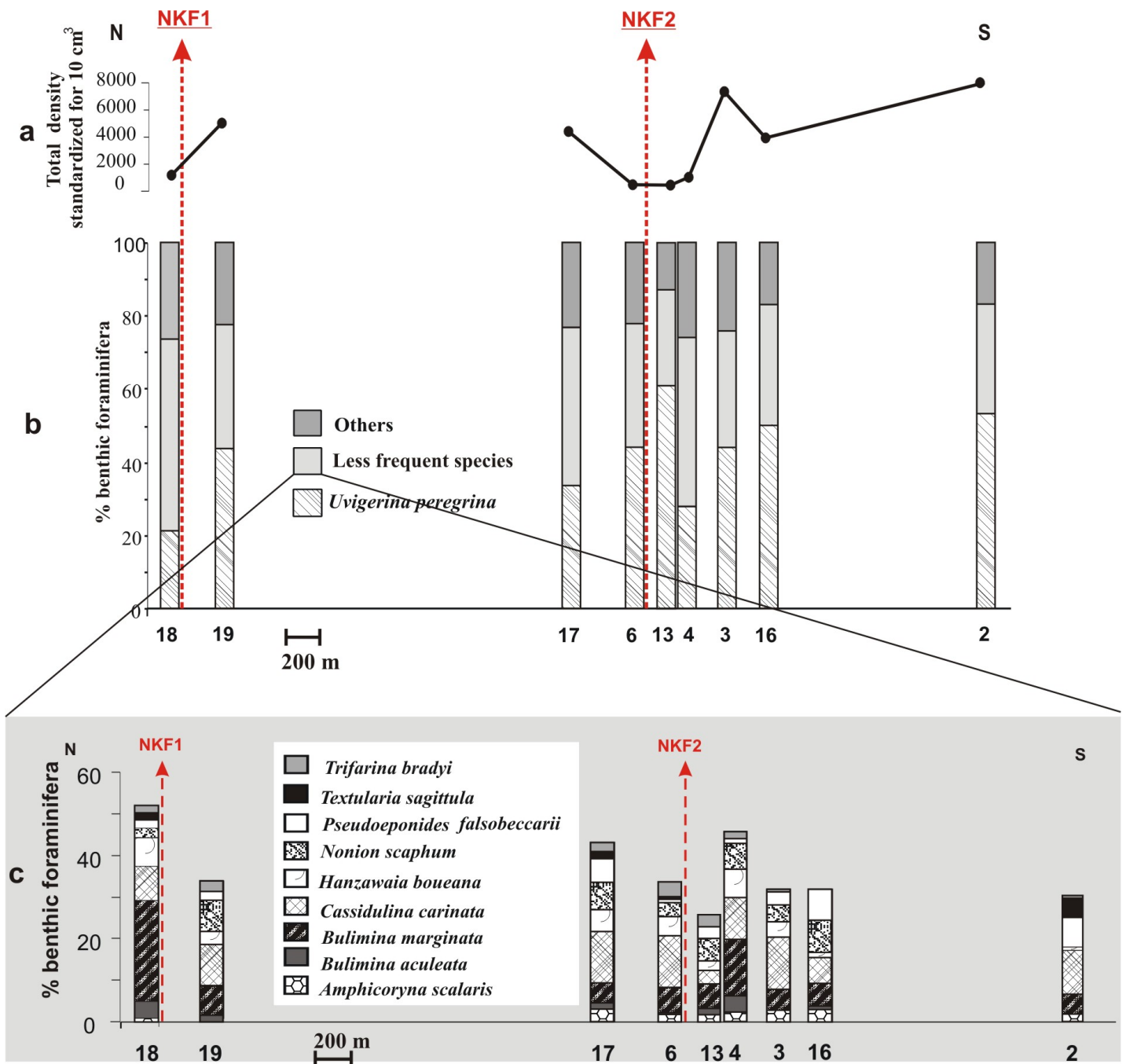


Figure 6-5. (a) Total density of dead fauna (>150  $\mu\text{m}$  fraction observed in the 2–3 cm level) standardized for 10 cm<sup>3</sup> sediment volume. (b) Percentages of *Uvigerina peregrina*. (c) Percentages of less frequent species in the dead faunas.

Despite this overall similarity, faunas at background station 2 differ from all others by the absence of *B. aculeata*, and low percentages of *B. marginata*, *T. bradyi* and *T. sagittula*, species that are typical elements of the live faunas of some of the stations closest to the disposal sites. In comparison with the composition of the living faunas, all dead faunas are

strongly enriched in *U. peregrina*, whereas the percentages of *B. aculeata*, *B. costata* and *B. marginata*, *A. scalaris* and *N. scaphum* are much higher in the richest living assemblages. Finally, the study of the dead faunas revealed important amounts of reworked Pleistocene foraminifera and glauconitic grains at all stations.

Station	2	3	4	6	13	16	17	18	19
<i>(a)</i>									
Total benthic foraminifera	9728	9301	1328	542	555	5077	6176	1543	6336
Total planktonic foraminifera	17250	12843	1195	450	677	7573	7968	903	7232
PB – ratio (% planktonic)	63.9	58.0	47.4	45.4	55.0	59.9	56.3	36.9	53.3
<i>(b)</i>									
Total benthic foraminifera	7721	7382	1054	430	440	4029	4902	1225	5029
Total planktonic foraminifera	13690	10193	948	357	537	6010	6324	717	5740
PB – ratio (% planktonic)	63.9	58.0	47.4	45.4	55.0	59.9	56.3	36.9	53.3

Table 6-7. (a) Total amounts of dead/subfossil foraminifera in level D (2–3 cm), and the PB-ratio (with  $PB=P/(P+B)$ ), expressed as the percentage of planktonic foraminifera within the total foraminiferal assemblage; (b) Same data, standardized for 10 cm<sup>3</sup> sediment volume.

## 6.5 DISCUSSION

The eutrophic nature of the region where our sites are located is documented by the high organic carbon levels, the composition of the total benthic foraminiferal faunas and the presence of a large quantity of faecal pellets in the sediment, but it contrasts with the low densities of the living faunas. The value of about 3 live individuals per 10 cm<sup>3</sup> (> 150 µm fraction) in the topmost cm at background station 2 is about two orders of magnitude lower than values at a 140 m deep station in the Bay of Biscay (Fontanier *et al.*, 2002). Values of about 50–100 individuals/10 cm<sup>3</sup> (sites 4, 13 and 18, within 230 m of the discharge sites) are similar to the values described by Fontanier *et al.* (2002). The low foraminiferal densities in our study area may be the consequence of the presence of strong bottom currents that hamper foraminiferal colonization of the relatively coarse substrate, as corroborated by the very low percentage of clay, and by the important amounts of reworked Pleistocene foraminifera and glauconitic grains. However, the low foraminiferal densities may also be due to a dilution with very high amounts of silty and fine sandy sediments originating from the Congo River. The density and composition of the foraminiferal faunas allow us to subdivide the 9 stations into four groups:

1) Group 1: Station 6, 70 m west of NKF2, contains a rather poor fauna, slightly richer in the 63–150  $\mu\text{m}$  fraction, that is dominated by *Bulimina* spp., *Bolivina* spp., *Gyroidina* sp.1 and *T. pauperata*.

2) Group 2: Stations 4, 13 and 18, < 250 m from the disposal sites, contain abundant foraminiferal faunas. In the >150  $\mu\text{m}$  fraction, *B. marginata* and *B. aculeata* are dominant, and *U. peregrina* is common at stations 13 and 18. In the 63–150  $\mu\text{m}$  fraction, *Bolivina* spp. and *Bulimina* spp. are dominant. These taxa are accompanied by some other species (*Gyroidina* sp.1, *Trifarina pauperata* and *C. bradyi*), that are much less common in the dead faunas, differ between the stations, and that may be considered as indicator species of pollution.

3) Group 3: Stations 2, 3, 17 and 19, >250 m from the disposal sites, are characterized by poor faunas in the >150  $\mu\text{m}$  as well as in the 63–150  $\mu\text{m}$  fraction, without clearly dominant species.

4) Group 4: Station 16, 730 m south of NKF2, contains intermediate numbers of foraminifera in both size fractions; faunas in the >150  $\mu\text{m}$  fraction are dominated by *N. scaphum*, *U. peregrina*, *C. auriculus* and *B. marginata*, whereas the 63-150  $\mu\text{m}$  contains also abundant *Bolivina* spp.

The > 150  $\mu\text{m}$  fauna contains the same taxa as the fossil faunas found at most stations (including background station 2), although the percentage of *U. peregrina* is much lower. Faunas in group 2 show considerable difference between stations. In the living fauna of station 13 (100 m South of NKF2), *B. costata* (20.0 %), *T. bradyi* (12.0 %), *U. peregrina* (13.0 %), *T. sagittula* (7.0 %) and, in the 63-150  $\mu\text{m}$  fraction, *Gyroidina* sp.1 (21.1 %), *V. bradyana* (6.0 %) and *T. pauperata* (5.0 %) are common to abundant. The former three species are rare in the dead fauna. The living fauna of station 4 (230 m south of NKF2) is dominated by *A. scalaris* (20.0 %) and *Eggerella* sp.1 (20.0 %). In the dead faunas, these species are rare. *T. sagittula* (5.0 %), *R. globularis* (4.0 %) and *T. bradyi* (3.0 %) are equally rare in the fossil faunas. *U. peregrina* is present at this station with about 5.0 %. The 63-150  $\mu\text{m}$  fraction contains very high numbers of bolivinids and of the species *Gyroidina* sp.1, *C. bradyi*, *V. bradyana*, *N. turgida* and *T. pauperata*. The living fauna of station 18 (70 m north of NKF1) resembles that of station 4, although the densities of *A. scalaris* and *Eggerella* sp.1

are lower and *T. bradyi*, *T. sagittula* and *U. peregrina* are more common. *N. turgida* is common in the 63-150  $\mu\text{m}$  fraction.

The comparison of the living fauna with the dead/fossil faunas, especially at station 2 (non-impacted site) allows us to recognize groups of species typical for the impact of the oily mud drilling disposals. Dead fauna is at all stations strongly dominated by *U. peregrina*, with *B. marginata/aculeata*, *C. carinata*, *N. scaphum*, *Hanzawaia boueana* and *P. falsobeccarii*. *U. peregrina* is known for its preference of open ocean environments characterized by enhanced organic matter fluxes (e.g. Lutze and Coulbourn, 1984; Lutze, 1986; Hermelin and Shimmiedl, 1990; Mackensen et al., 1995; Fariduddin and Loubere, 1997; Schmiedl and Mackensen, 1997; De Rijk et al., 2000; Kuhnt et al., 1999; Schmiedl et al., 2000; Huang et al., 2002). It has also been described in severely oxygen-depleted areas in the Arabian Sea OMZ (Hermelin and Shimmiedl, 1990; Jannink et al., 1998). Schmiedl et al. (1997) suggest, however, that, in the southern Angola Basin and the Cape Basin, *U. peregrina* avoids strong oxygen depletion, and occurs preferentially in TOC-rich (>1%) sediments from the lower slope, characterized by moderate oxygen deficiency (>2 ml/l). Fontanier et al. (2003) observed, at a 550m deep station in the Bay of Biscay, that this species shows a particularly strong reproductive and growth response to phytodetritus deposits, and is less abundant during periods without a large supply of fresh organic matter. The important difference between our dead faunas, very rich in *U. peregrina*, and our living faunas (much poorer) suggest that in our study area, this species only reproduces during periods of strong primary production, that may be induced by seasonal upwelling events. In the live faunas from stations 4, 13 and 18, *U. peregrina* in the >150  $\mu\text{m}$  fraction consistently co-occurs with *T. sagittula* and *T. bradyi* (Fig. 6-3). The latter species are rare or absent in the fossil fauna, and seem to be characteristic of the eutrophied conditions generated by the drilling disposals.

All stations within 230 m of the disposal points (4, 6, 13 and 18) are characterized, in the >150  $\mu\text{m}$  fraction, by high percentages of *B. aculeata* and *B. marginata*. *B. aculeata* is absent at the reference station 2. High densities of these species have often been considered typical for highly stressed environments, specifically by oxygen depletion (Murray, 1991). *B. costata* is similarly known to survive dysoxic conditions (Jorissen, 1999). Although the P/B-ratios are high for a 180 m deep outer shelf environment (Van der Zwaan et al., 1990), values at stations 4, 13 and 18 are minimal (Table 6-7). This corroborates the thesis of a significant eutrophication of the sea floor at sites, resulting in a strong productivity of benthic foraminifera. *A. scalaris*, *Eggerella* sp.1, and *R. globularis* are abundant in the living faunas

at station 4, present at station 18, but almost absent in the dead faunas. In the literature, these species are not known for their preferences or tolerances for stressed and/or eutrophic environments. *R. globularis* has been described as an epifaunal, often epiphytic species (e.g. Spindler, 1980; Murray, 1991), and we observed several living specimens attached to rock debris in the residues of station 4. Apparently, this species is able to colonize hard substrates, presented by the larger drill cuttings. We suspect that all three species are early colonizers of drill cuttings.

In the 63–150 µm fraction, *Bolivina* spp. and *Bulimina* spp. are dominant elements at all stations. Both genera are known for their preference of food-rich areas, and their tolerance for low-oxygen conditions (e.g. Barmawidjaja et al., 1992). In the stations close to the disposal sites, these taxa are accompanied by other important species that may be considered as pollution indicators. At stations 4, 13 and 18, *Gyroidina* sp.1, *T. pauperata* and *V. bradyana* are always present. Station 6 contains nearly the same species, without *V. bradyana*.

If we compare the living faunas around sites NKF2 and NKF1 with the sub-fossil faunas at background station 2, we can define the extent of the impact of drill cutting disposal (Fig. 6-6) as follows:

- Faunas found in stations 2, 3, 16, 17 and 19 (>250 m from disposal sites) represent faunas, that are not (station 2), or little impacted by the drilling cutting deposits.
- Stations 4, 13 and 18 (between 70 m and 250 m from disposal sites) contain faunas with increased percentages of opportunistic species, indicating eutrophication, as also shown by a significant increase of the faunal density and colonization of deeper sediment intervals.
- Station 6 (70 m from the disposal sites), finally, comprises a rather poor fauna, dominated mainly by species of *Bulimina*, a taxon resistant to oxygen depletion. The absence of foraminifera deeper in the sediment suggests a minimal thickness of the oxygenated layer of the sediment, and anoxic conditions close to the sediment–water interface. Therefore, this site appears to represent the conditions of maximum impact.



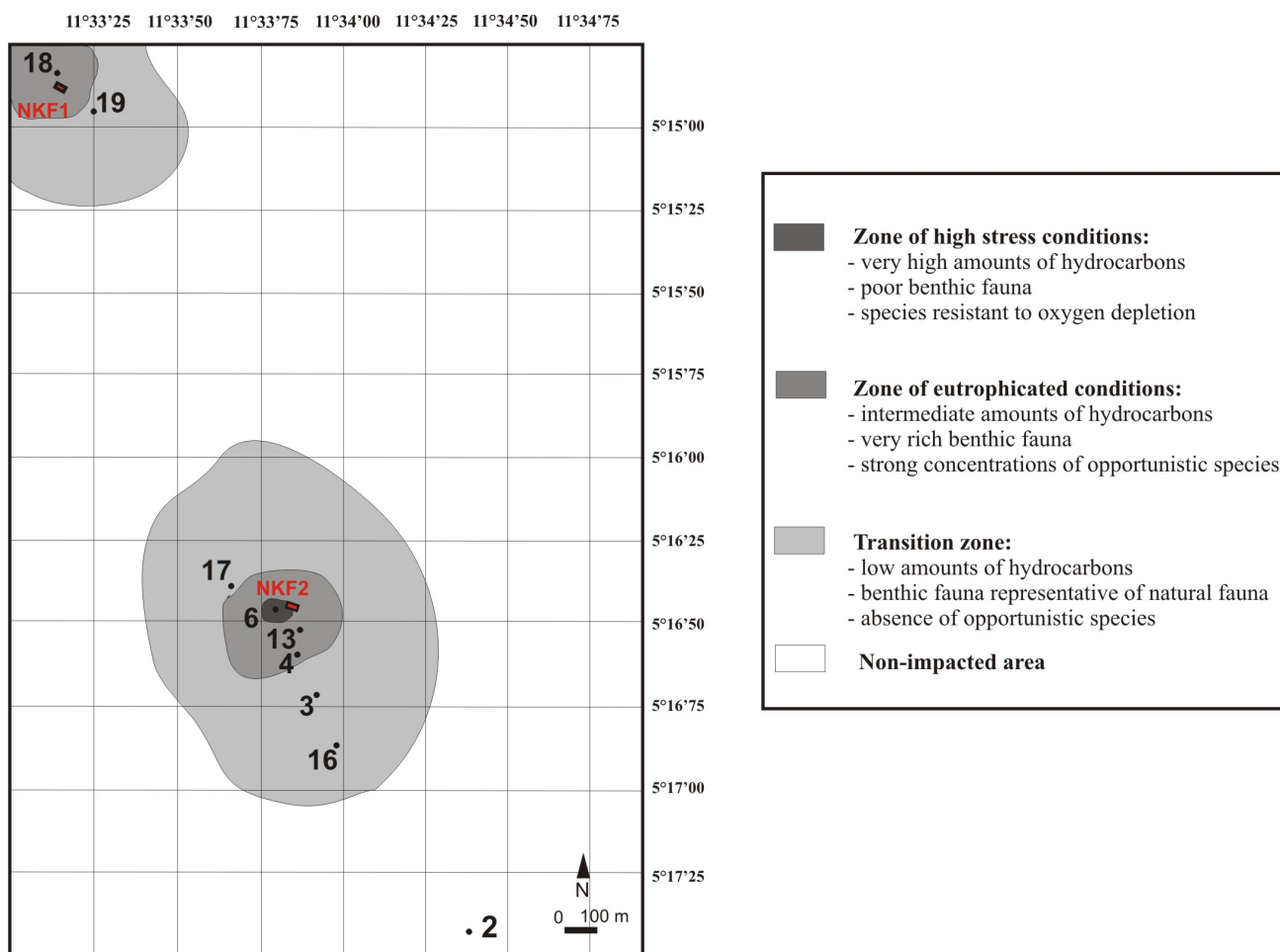


Figure 6-6. Overview map, indicating the succession of faunal zones with decreasing environmental impact at increasing distance from the drill cutting disposal sites.

Summarising, our data present a typical picture, with strongly impoverished faunas closest to the disposal site (Fig. 6-6). This area is surrounded by an aureole of high density faunas with important opportunistic species, that may be tolerant to the dysoxic conditions. This pattern is very similar to the macrofaunal succession described by *Pearson (1985)* around a sludge disposal site in the Firth of Clyde, and to the foraminiferal successions described by *Alve (1995)* around point sources of pollution in estuarine areas.

In order to quantify the impact of pollution due to drill cutting disposal, we developed an index based on the cumulative relative abundance (percentage of the total fauna) of all taxa indicative of stress and/or ecosystem eutrophication. For both size fractions (63-150  $\mu\text{m}$  + >150  $\mu\text{m}$ ), the living faunas in the 0-2 cm interval were added, and percentages were calculated for the total > 63  $\mu\text{m}$  fraction (63-150  $\mu\text{m}$  + >150  $\mu\text{m}$  fraction). Next, percentages for the taxa *A. scalaris*, *B. dilatata*, *B. seminuda*, *B. spathulata*, *Bolivina* sp.1, *Bulimina* spp.,

*Eggerella* sp.1, *Gyroidina* sp.1, *N. turgida*, *R. globularis*, *T. sagittula*, *T. bradyi*, *T. pauperata*, *U. peregrina* and *V. bradyana*, that are considered indicative of conditions of natural or anthropogenic eutrophication and/or stress, have been summed (Fig. 6-7). The cumulative percentage of these taxa is a function of the distance to the disposal sites ( $r^2 = 0.85$ ). This foraminiferal index makes a clear distinction between strongly impacted sites (4, 6, 13 and 18, more than 60% indicator species), weakly impacted sites (3, 16, 17 and 19, 40–60% indicator species), and a non impacted site (station 2) with less than 20% of indicator species.

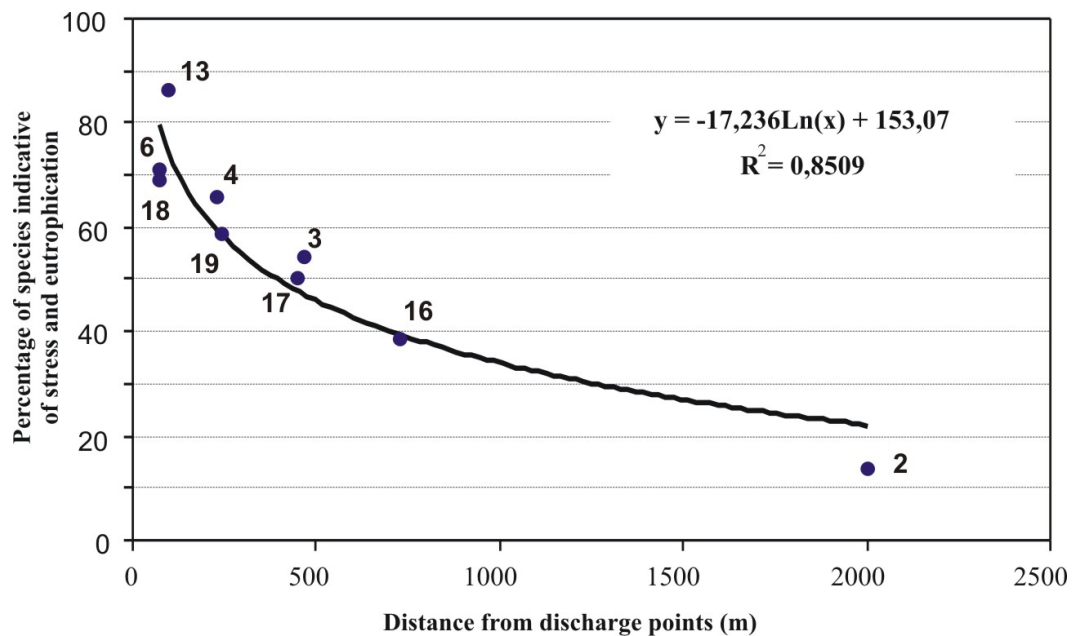


Figure 6-7. Cumulative percentages of all taxa indicative of natural and/or anthropogenic eutrophication and ecosystem stress, in function of distance to the drill cutting disposal sites.

## 6.6 CONCLUSIONS

- We propose to use living benthic foraminiferal faunas as bio-indicators of the impact of disposal of oily drill cuttings in a tropical outer shelf environment. Chemical analyses show 4 years after the end of drill cutting disposal activities, the level of contamination of the sediment by hydrocarbons and barium is still high in an area of 250 m around the discharge points, and decreases progressively further away, with hydrocarbon not perceptible beyond 1000 m.

- Foraminiferal faunas reflect a strong decrease of environmental impact with increasing distance from the disposal sites. Using the density and composition of the benthic foraminiferal faunas, in comparison with a reference site, we can distinguish three zones where faunas are affected:

– a first zone is within 100 m of the disposal site, represented by a single station (6), characterized by a poor fauna composed mainly of species resistant to oxygen depletion;

– a second zone, situated from about 100 to 250 m from the disposal sites (stations, 4, 13 and 18), contains a fauna typical of eutrophicated environments, characterized by a high faunal density and a strong dominance of opportunistic species.

– a third zone (stations 3, 16, 17 and 19), more than 250m, and until 730m away from the disposal site and, appears to present a transitional situation, where the environmental impact is minimal, but still perceptible. Faunal densities are low, but the faunal composition still shows a slight increase of opportunistic taxa.

- A quantitative index based on the proportions of all taxa indicative of natural and/or anthropogenic eutrophication and stress shows a very high correlation with the distance from the disposal sites. These results show that benthic foraminifera are suitable to monitor the impact of oil cutting disposal in the open marine environment. 4 years after cessation of drill cutting disposal, the impact is largely limited to a zone of 250 m around the disposal sites.

## **6.7 ACKNOWLEDGMENTS**

The authors acknowledge the financial support of the Conseil Général de la Vendée for the senior author. We are very grateful to the reviewers Ellen Thomas and Alessandra Asioli, who investigated much time in the correction of the first manuscript, leading to a strongly improved final version.

## **6.8 REFERENCES**

Alve, E., 1995. Benthic foraminiferal response to estuarine pollution: a review. *Journal of Foraminiferal Research*, 25, 190-203.

Armynot du Châtelet, E., Debenay, J.P., Soulard, R., 2004. Foraminiferal proxies for pollution monitoring in moderately polluted harbors. *Environmental Pollution*, 127, 27-40.

Barmawidjaja, D.M., Jorissen, F.J., Puskaric, S., Van der Zwaan, G.J., 1992. Microhabitat selection by benthic foraminifera in the northern Adriatic Sea. *Journal of Foraminiferal Research*, 22, 297-317.

Bizon, G., Bizon, J.J., 1985. Distribution des foraminifères sur le plateau continental du Rhône. ECOMED, pp. 84-94.

Dalmazzone, Ch., Blanchet, D., Lamoureux, S., Dutrieux, E., Durrieu, J., Camps, R., Galgani, F., 2004. Impact of drilling activities in warm sea: recolonization capacities of seabed. *Oil & Gas Science and Technology - Rev. IFP* 59, 625-647.

De Rijk, S., Jorissen, F.J., Rohling, E.J., Troelstra, S.R., 2000. Organic flux control on bathymetric zonation of Mediterranean benthic foraminifera. *Marine Micropaleontology*, 40, 151-166.

Duchemin, G., Jorissen, F.J., Andrieux-Loyer, F., Le Loc'h, F., Hily, C., Philippon, X., 2005. "Living benthic foraminifera from "La grande vasière", French Atlantic continental shelf: faunal composition and microhabitats. *Journal of Foraminiferal Research*, 35 (3), 198-218.

Durrieu, J., Bouzet, Ph., 2004. Seabed recolonisation: N'Kossa case, vol. 86710. Society of Petroleum Engineers Inc. SPE, Calgary. 8 pp.

Fariduddin, M., Loubere, P., 1997. The surface ocean productivity response of deeper water benthic foraminifera in the Atlantic Ocean. *Marine Micropaleontology*, 32, 289-310.

Fontanier, C., Jorissen, F., Licari, L., Alexandre, A., Anschutz, P., Carbonel, P., 2002. Live benthic foraminiferal faunas from the Bay of Biscay: faunal density, composition, and microhabitats. *Deep-Sea Research. Part 1. Oceanographic Research Papers*, 49, 751-785.

Fontanier, C., Jorissen, F.J., Chaillou, G., David, C., Anschutz, P., Lafon, V., 2003. Seasonal and interannual variability of benthic foraminiferal faunas at 550 m depth in the Bay of Biscay. *Deep-Sea Research I*, 50, 457-494.

Hermelin, J.O.R., Shimmield, G.B., 1990. The importance of the Oxygen Minimum Zone and sediment geochemistry in the distribution of recent benthic foraminifera in the Northwest Indian Ocean. *Marine Geology*, 91, 1-29.

Huang, B., Jian, Z., Cheng, X., Wang, P., 2002. Foraminiferal responses to upwelling variations in the South China Sea over the last 220000 years. *Marine Micropaleontology*, 47, 1-15.

Jannink, N.T., Zachariasse, W.J., Van der Zwaan, G.J., 1998. Living (Rose Bengal stained) benthic foraminifera from the Pakistan continental margin (northern Arabian Sea). *Deep-Sea Research. Part 1. Oceanographic Research Papers*, 45 (9), 1483-1513.

Jansen, J.H.F., Van Weering, T.C.E., Gieles, R., Van Iperen, J., 1984. Middle and late Quaternary oceanography and climatology of the Zaire-Congo fan and the adjacent eastern Angola Basin. *Netherlands Journal of Sea Research*, 17, 201-249.

Jones, R.W., 1994. *The Challenger Foraminifera*. Oxford University Press. 149 pp.

Jorissen, F.J., 1987. The distribution of benthic foraminifera in the Adriatic Sea. *Marine Micropaleontology*, 12, 21-48.

Jorissen, F.J., 1999. Benthic foraminiferal microhabitats below the sediment–water interface. In: Sen Gupta, B. (Ed.), *Ecology of Recent Foraminifera*. Kluwer Academic Publishers, pp. 161-179. Chapter 10.

Jorissen, F.J., De Stigter, H.C., Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology*, 26, 3-15.

Kouyoumouzakis, G., 1979. La microfaune benthique du plateau continental congolais. Inventaire, répartition, stratigraphie du Quaternaire supérieur. Rapports avec le milieu sédimentaire. Thèse de Doctorat de spécialité, Aix-Marseille II.

Kouyoumouzakis, G., 1982. Le biotope à *Canceris congolensis* aux abords de l'estuaire du fleuve Congo. *Océanographie Tropicale*, 17 (2), 139-144.

Kramer, Botterweg, 1991. Aquatic biological early warning systems: an overview. In: Jeffrey, D.W., Madden, B. (Eds.), *Bioindicators and Environmental Management*. Academic press, London, pp. 95-126.

Kuhnt, W., Hess, S., Jian, Z., 1999. Quantitative composition of benthic foraminiferal assemblages as a proxy indicator for organic carbon flux rates in the South China Sea. *Marine Geology*, 156 (1-4), 123-158.

Laraque, A., Mahé, G., Orange, D., Marieu, B., 2001. Spatiotemporal variations in hydrological regimes within Central Africa during XXth Century. *Journal of Hydrology*, 245, 104-117.

Loubere, P., 1989. Bioturbation and sedimentation rate control of benthic microfossil taxon abundances in surface sediments: a theoretical approach to the analysis of species microhabitats. *Marine Micropaleontology*, 14, 317-325.

Lutze, G.F., 1986. *Uvigerina* species of the eastern North Atlantic. In: Van der Zwaan, G.J., Jorissen, F.J., Verhallen, P.J.J.M., von Daniels, C.H. (Eds.), *Atlantic-European Oligocene to Recent Uvigerina*. Utrecht Micropaleontological Bulletins, vol. 35, pp. 21-46.

Lutze, G.F., Coulbourn, W.T., 1984. Recent benthic foraminifera from the continental margin of northwest Africa: community structure and distribution. *Marine Micropaleontology*, 8, 361-401.

Mackensen, A., Schmiedl, G., Harloff, J., Giese, M., 1995. Deep-sea foraminifera in the South Atlantic Ocean: ecology and assemblage generation. *Micropaleontology*, 41 (4), 342-358.

Morvan, J., Le Cadre, V., Jorissen, F., Debenay, J.P., 2004. Foraminifera as potential bio-indicators of the «Erika» oil spill in the Bay of Bourneuf: field and experimental studies. *Aquatic Living Resources*, 17, 317-322.

Mouganga, M.D., 1999. Les systèmes flèches-lagunes du littoral gabonais. Rapport partiel de terrain, activités 1998, Laboratoire GEOLITTOMER-BREST, Institut Universitaire Européen de la mer, Université de Bretagne occidentale, Brest. 30 pp.

Murray, J.W., 1991. Ecology and distribution. BENTHOS'90. Tokai University Press, Sendai.

Pearson, T.H., 1985. Benthic ecology in accumulating sludge-disposal site. Proceedings of the Fourth International Ocean Disposal Symposium, pp. 195–200. England, April 1985, Chapter 17.

Phleger, F.B., Parker, F.L., Peirson, J.F., 1953. North Atlantic foraminifera. Reports of the Swedish Deep-Sea Expedition, 7 (1), 1-122.

Rabalais, N.N., Turner, R.E., 2001. Coastal Hypoxia: Consequences for Living Resources and Ecosystems. Coastal and Estuarine Studies Series, vol. 58. American Geophysical Union, Washington, D.C. 463 pp.

Resig, J.M., 1960. Foraminiferal ecology around ocean outfalls off southern California. In: Person, E. (Ed.), Disposal in the Marine Environment. Pergamon Press, London, pp. 104-121.

Schiebel, R., 1992. Rezente benthische Foraminiferen in Sedimenten des Schelfes und oberen Kontinentalhanges im Golf von Guinea (Westafrika), vol. 51. Berichte Geologisch-Paläontologisches Institut und Museum Christian-Albrechts-Universität Kiel, Deutschland. 126 pp.

Schmiedl, G., Mackensen, A., 1997. Late Quaternary paleoproductivity and deep water circulation in the eastern South Atlantic Ocean: evidence from benthic foraminifera. *Palaeogeography, Palaeoclimatology, Palaeoecology* 130, 43-80.

Schmiedl, G., Mackensen, A., Müller, P.J., 1997. Recent benthic foraminifera from the eastern South Atlantic Ocean: dependence of food supply and water masses. *Marine Micropaleontology* 32, 249-287.

Schmiedl, G., De Bovée, F., Buscail, R., Charrière, B., Hemleben, C., Medernach, L., Picon, P., 2000. Trophic control of benthic foraminiferal abundances and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea. *Marine Micropaleontology* 40, 167-188.

Sharifi, A.R., Croudace, I.W., Austin, R.L., 1991. Benthic foraminiferids as pollution indicators in Southampton Water, southern England, UK. *Journal of Micropaleontology* 10 (1), 109-113.

Spindler, M., 1980. The pelagic golfweed *Sargassum natans* as a habitat for the benthic foraminifera *Planorbulina acervalis* et *Rosalina globularis*. *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie, Monatshefte*, 9, 569-580.

Van der Zwaan, G.J., Jorissen, F.J., 1991. Biofacial patterns in rive rinduced shelf anoxia. From Tyson R.V and Pearson T.H., 1991 Modern and ancient continental shelf anoxia. *Geological Society Special*, 58, 65-82.

Van der Zwaan, G.J., et Jorissen, F.J., de Stigter, H.C., 1990. The depth dependency of planktonic/benthic foraminiferal ratios: constraints and applications. *Marine Geology*, 95, 1-16.

Voituriez, B., Herbland, A., 1982. Comparaison des systèmes productifs de l'Atlantique Tropical Est: dômes thermiques, upwellings côtiers et upwelling équatorial. *Rapports et Procès-Verbaux des Reunions - Conseil International Pour l'Exploration de la Mer*, 180, 114-130.

Watkins, J.G., 1961. Foraminiferal ecology around the Orange County, California, ocean sewer outfall. *Micropaleontology*, 7 (2), 199-206.

Yanko, V., Flexer, A., 1991. Foraminiferal benthonic assemblages as indicators of pollution (an example of north-western shelf of the Black Sea). Third Annual Symp. on the Mediterranean Margin of Israel. Haifa-Israel, 5 pp.

**Appendix 6-1.** Taxonomic index.

- Amphicoryna scalaris* (Batsch), 1791. Jones (1994), pl. 63. Figs. 28-31
- Bigenerina nodosaria* (d'Orbigny), 1826. Jones (1994), pl. 44, Figs. 19-24
- Bolivina dilatata* (Reuss), 1850. Lutze (1974b), pl. 5, Figs. 83-85, pl. 6, Fig. 95
- Bolivina spathulata* (Williamson), 1858. Jorissen (1987), pl. 1, Fig. 5
- Bolivina striatula* (Cushman), 1922. Cushman (1937), pl. 18, Figs. 30-31
- Bolivina seminuda* (Cushman), 1911. Barmawidjaja (1992), pl.2, Figs. 1-3
- Bulimina aculeata* (d'Orbigny), 1826. Jones (1994), pl.51, Figs. 7-9
- Bulimina costata* (d'Orbigny), 1852. Van Leeuwen (1989), pl. 8, Figs. 2 and 3
- Bulimina exilis* (Brady),1884. Jones (1994), pl. 50. Fig. 5 (as *Eubuliminella exilis*)
- Bulimina marginata* (d'Orbigny), 1826. Hess (1998), pl. 10, Fig. 7
- Bulimina striata* (d'Orbigny), 1843. Lévy et al. (1995), pl.8, Figs. 1-2
- Cancris auriculus* (Fichtel et Moll),1942. Jones (1994), pl. 106, Fig. 4
- Cassidulina carinata* (Silvestri),1896. Phleger et al. (1953).pl. 9. Figs. 32-37
- Cassidulina crassa* (d'Orbigny), 1839. Jorissen (1987), pl. 1, Fig. 3
- Cassidulina oblonga* (Reuss), 1850. Jorissen (1987), pl. 3. Fig. 11
- Cassidulinoides bradyi* (Norman), 1881. Murray (1971a), pl. 46, figs. 4-7
- Cibicides Iobatulus* (Walker et Jacob), 1798. Jones (1994), pl. 92, Fig. 10
- Cibicides ungerianus* (d'Orbigny), 1846. Jones (1994), pl. 94, Fig. 9
- Cribrostomoides subglobosus* (M.Sars), 1868. Jones (1994), pl. 34, Figs. 8-10
- Cyclogyra involvens* (Reuss), 1850. Cushman (1929), pl. 20, Figs. 6-8
- Eggerella apicularis* (Cushman), 1911. Jones (1994), pl. 46, figs. 17-29 (as *Karrerulina conversa*)
- Eggerella bradyi* (Cushman), 1911. Jones (1994), pl. 47, figs. 4-7
- Eggerella scabra* (Williamson), 1858. Jones (1994), pl. 47, Figs. 15-17
- Elphidium advenum* (Cushman), 1922. Phleger, Parker, and Peirson (1953), pl. 6, Fig. 15
- Epistominella exigua* (Brady), 1884. Schiebel (1992), pl. 5, Fig. 9
- Fissurina orbignyana* (Seguenza), 1862. Cimerman et Langer (1991), pl. 59, Figs. 6-7
- Gavelinopsis praegeri* (Heron-Allen and Earland), 1913. Schiebel (1992), pl. 4, fig. 6
- Glandulina laevigata* (d'Orbigny), 1826. Hottinger et al. (1993), pl. 96, figs. 1-5, 8
- Globobulimina affinis* (d'orbigny), 1839. Phleger, Parker, and Peirson (1953), pl. 6, fig. 32
- Globocassidulina subglobosa* (Brady), 1881. Jones (1994), pl. 54, fig. 17



**Appendix 6-1.** Continued.

- Gyroidina orbicularis* (sensu Parker, Jones and Brady), 1865. Jones (1994), pl. 115, fig. 6
- Gyroidina soldanii* (d'Orbigny, 1826). Phleger, Parker and Pierson (1953), pl. 9, figs. 1-2
- Gyroidina umbonata* (Silvestri), 1898. Parker (1958), pl. 3, fig. 19-20
- Jadammina macrescens* (Brady), 1870. Alve and Murray (1994), pl. 1, figs. 9-11
- Hanzawaia boueana* (d'Orbigny), 1846. Jorissen (1987), pl. 3, fig. 10
- Hoeglundina elegans* (d'Orbigny), 1826. Phleger et al. (1953), pl. 9, figs. 24-25
- Hyalinea balthica* (Schroeter), 1783. Jones (1994), pl. 112, fig. 1-2
- Lenticulina peregrina* (Schwager), 1866. Cushman and McCulloch (1950), pl. 39, fig. 5
- Leptohalysis scottii* (Chester), 1892. Sgarrella et al. (1993), pl. 2, fig. 5
- Miliolinella subrotunda* (Montagu), 1803. Lévy et al. (1995), pl. 4, fig. 7
- Nonion scaphum* (Fitchell and Moll), 1798. Jones (1994), pl. 109, fig. 12
- Nonionella turgida* (Williamson), 1858. Jones (1994), pl. 109, figs. 17-19
- Nouria polymorphinoides* (Heron Allen and Earland), 1914. Loeblich and Tappan (1988), pl. 123, figs. 11-12
- Oolina hexagona* (Williamson), 1848. Cimerman et Langer (1991), pl. 58, figs. 8-9
- Oridorsalis umbonatus* (Reuss), 1851. Van Leeuwen (1989), pl. 17, figs. 1-13
- Pseudoeponides falsobeccarii* (Rouvillois), 1974. Jorissen (1987), pl. 4, fig. 3a
- Pullenia quinqueloba* (Reuss), 1851. Jones (1994), pl. 84, figs. 14 and 15
- Rectuvigerina phlegeri* (Le Calvez), 1959. Schiebel (1992), pl. 3, fig. 10a-d
- Reophax scorpiurus* (Montfort), 1808. Loeblich and Tappan (1988), pl. 44, figs. 1-3
- Rosalina globularis* (d'Orbigny), 1826. Lévy et al. (1995), pl. 9, fig. 11
- Siphotextularia affinis* (Fornasini), 1883. Kohl (1985), pl. 2, fig. 5
- Spiroloculina tenuiseptata* (Brady), 1884. Jones (1994), pl. 10, figs. 5-6
- Textularia agglutinans* (d'Orbigny), 1839. Jones (1994), pl. 43, figs. 1-3
- Textularia porrecta* (d'Orbigny), 1884. Jones (1994), pl. 43, fig. 4
- Textularia sagittula* (DeFrance), 1824. Jorissen (1987), pl. 3, fig. 12
- Trifarina angulosa* (Williamson), 1858. Jones (1994), pl. 74, figs. 17-18
- Trifarina bradyi* (Cushman), 1923. Jones (1994), pl. 67, figs. 1-3
- Trifarina pauperata* (Heron Allen and Earland), 1932. Timm (1992), pl. 6, Fig. 4
- Triloculina trigonula* (Lamarck), 1804. Loeblich et Tappan (1988), pl. 351, figs. 19-21
- Uvigerina bononiensis* (Fornasini), 1888. Lutze (1986), pl. 7, figs. 7-12

**Appendix 6-1.** Continued.

*Uvigerina elongatastriata* (Colom), 1952. Van Der Zwann et al. (1986), pl. 6, figs. 1-8

*Uvigerina peregrina* (Cushman), 1923. Van Der Zwann et al. (1986), pl. 1, figs. 1-6

*Valvulineria bradyana* (Fornasini), 1900. Jorissen (1987), pl. 4, figs. 1 and 2



**Appendix 6-3.** Composition and percentages of living fauna (> 150 µm fraction) for the first 3 cm of the sediment (total sediment volume = 37.7 cm<sup>3</sup>).

Taxa	Stations		2		3		4		6		13		16		17		18		19	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
<i>Ammoscalaria</i> sp.					1	0.5							3	6.1						
<i>Amphicoryna scalaris</i>					44	20.5							2	4.1			5	5.9	1	5.9
<i>Astacolus</i> sp.					1	0.5														
<i>Bigenerina nodosaria</i>																	1	1.2		
<i>Bolivina spathulata</i>					1	0.5											1	1.2		
<i>Bolivina striatula</i>					3	1.4	1	5.6	2	2.1										
<i>Bulimina aculeata</i>			3	37.5	32	14.9	3	16.7	12	12.4	1	2.0	1	9.1	17	20.0	3	17.6		
<i>Bulimina costata</i>					3	1.4	2	11.1	19	19.6					1	1.2	1	5.9		
<i>Bulimina marginata</i>					20	9.3	3	16.7	27	27.8	4	8.2	1	9.1	7	8.2	2	11.8		
<i>Cancris auriculus</i>			1	12.5									4	8.2						
<i>Cassidulina carinata</i>					1	0.5														
<i>Cibicides lobatulus</i>					1	0.5	1	5.6												
<i>Cribrostomoides subglobosus</i>					2	0.9			1	1.0				2	18.2				1	5.9
<i>Cyclogyra involvens</i>									1	1.0							1	1.2		
<i>Cyclammina</i> sp.	1	14.3	1	12.5										1	9.1					
<i>Dentalina</i> sp.					3	1.4														
<i>Eggerella</i> sp. 1					42	19.5			1	1.0	1	2.0			12	14.1				
<i>Glabratella</i> sp.											1	2.0							1	5.9
<i>Globobulimina affinis</i>											2	4.1	1	9.1						
<i>Hanzawaia boueana</i>					1	0.5			1	1.0	2	4.1			1	1.2				
<i>Haplophragmoides</i> sp.					4	1.9								1	9.1	2	2.4			
<i>Jadammina macrescens</i>			3	37.5																
<i>Lagena</i> sp.6	1	14.3																		
<i>Lagena</i> sp.7					1	0.5														
<i>Lenticulina peregrina</i>					1	0.5														
<i>Lenticulina</i> sp. 1					1	0.5					1	2.0			3	3.5				
<i>Martinotiella</i> sp.					1	0.5					1	2.0	1	9.1						
<i>Miliolinella subrotunda</i>																				
<i>Nonion scaphum</i>	2	28.6			2	0.9							11	22.4	1	9.1			3	17.6
<i>Nonionella turgida</i>					1	0.5							1	2.0			1	1.2		
<i>Nonionella</i> sp. 2															2	2.4				
<i>Nouria polymorphinoides</i>	1	14.3											1	2.0			1	1.2	2	11.8
<i>Quinqueloculina</i> sp.					2	0.9														
<i>Reophax</i> sp.																	1	1.2		
<i>Rosalina globularis</i>	0				8	3.7	2	11.1									1	1.2		
<i>Saccamina</i> sp.	2	28.6											1	2.0	2	18.2				
<i>Siphotextularia affinis</i>					2	0.9							1	2.0						
<i>Spiroloculina tenuiseptata</i>					5	2.3	1	5.6					1	2.0						
<i>Textularia agglutinans</i>					2	0.9									1	1.2				
<i>Textularia porrecta</i>					1	0.5														
<i>Textularia sagittula</i>					10	4.7			7	7.2					6	7.1	1	5.9		
<i>Trifarina bradyi</i>					5	2.3	1	5.6	12	12.4	1	2.0			8	9.4				
<i>Trifarina pauperata</i>									1	1.0									1	5.9
<i>Trochammina</i> sp.					4	1.9														
<i>Uvigerina peregrina</i>					10	4.7	4	22.2	13	13.4	9	18.4			13	15.3	1	5.9		
Spec indet													1	2.0						
<b>Total</b>	<b>7</b>	<b>8</b>	<b>215</b>	<b>18</b>	<b>97</b>	<b>49</b>	<b>11</b>	<b>85</b>	<b>17</b>											

**Appendix 6-4.** Living fauna (non-standardized data) in the 63-150 µm fraction.

Stations	Taxa	2A (0-0.5 cm)	2B (0.5-1 cm)	2C (1-2 cm)	2TOT	3A (0-0.5 cm)	3B (0.5-1 cm)	3C (1-2 cm)	3TOT	4A (0-0.5 cm)	4B (0.5-1 cm)	4C (1-2 cm)	4TOT	6A (0-0.5 cm)	6B (0.5-1 cm)	6C (1-2 cm)	6TOT	13A (0-0.5 cm)	13B (0.5-1 cm)	13C (1-2 cm)	13TOT	16A (0-0.5 cm)	16B (0.5-1 cm)	16C (1-2 cm)	16TOT	17A (0-0.5 cm)	17B (0.5-1 cm)	17C (1-2 cm)	17TOT	18A (0-0.5 cm)	18B (0.5-1 cm)	18C (1-2 cm)	18TOT	19A (0-0.5 cm)	19B (0.5-1 cm)	19C (1-2 cm)	19TOT			
	<i>Amniglobigerina</i> sp.																																							
	<i>Amphicoelina scalaris</i>																																							
	<i>Bolivina dilatata</i>																																							
	<i>Bolivina seminuda</i>																																							
	<i>Bolivina striatula</i>	1				1				4	1	2	5	1																										
	<i>Bolivina aculeata</i>																																							
	<i>Bolivina costata</i>																																							
	<i>Bolivina exilis</i>																																							
	<i>Bolivina marginata</i>																																							
	<i>Cassidulina carinata</i>																																							
	<i>Cassidulina crassa</i>																																							
	<i>Cassidulinoides bradyi</i>																																							
	<i>Cibicides lobatulus</i>																																							
	<i>Cribrostomoides</i> sp.																																							
	<i>Dentalina</i> sp.																																							
	<i>Eggerella</i> sp. 1																																							
	<i>Eggerella</i> sp. 2																																							
	<i>Epistominella exigua</i>																																							
	<i>Fursenkohina mexicana</i>																																							
	<i>Gavelinopsis praegeri</i>																																							
	<i>Gyroidina</i> sp1																																							
	<i>Gyroidina</i> sp2																																							
	<i>Glomospira</i> sp.																																							
	<i>Hanzawata boueana</i>																																							
	<i>Lagena</i> sp.																																							
	<i>Leptohyalysis scottii</i>																																							
	<i>Nontion</i> spp.																																							
	<i>Nontion scaphum</i>																																							
	<i>Nontionella turgida</i>																																							
	<i>Ordoersalis umbonatis</i>																																							
	<i>Quinqueloculina</i> sp.																																							
	<i>Recuvoldes</i> sp.																																							
	<i>Rosalina</i> sp.																																							
	<i>Stainforthia</i> sp.																																							
	<i>Textularia porecta</i>																																							
	<i>Textularia sagittula</i>																																							
	<i>Textularia sp.</i>																																							
	<i>Trifarina pauperata</i>																																							
	<i>Trifarina bradyi</i>																																							
	<i>Trochammina</i> sp.																																							
	<i>Vigierina bononiensis</i>																																							
	<i>Vigierina peregrina</i>																																							
	<i>Vavulinierina bradyana</i>																																							
	<i>Spec. Agglutinant indet.</i>																																							
	<i>Spec. Hyalin Indet.</i>																																							
	Total	4	15	11	30	8	11	9	28	47	228	44	319	11	44	21	76	62	80	5	147	23	27	3	53	1	13	9	23	54	70	45	169	3	11	4	18			

**Appendix 6-5.** Composition and percentages of living fauna (63-150  $\mu\text{m}$  fraction) for the first 2 cm of the sediment (total volume= 25.2  $\text{cm}^3$ ).

Taxa	Stations		2		3		4		6		13		16		17		18		19		
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	
<i>Ammoglobigerina</i> sp.					2	0.6															
<i>Amphicoryna scalaris</i>					1	0.3															
<i>Bolivina dilatata</i>					1	0.3	3	3.9	8	5.4	3	5.7					2	1.2	1	5.6	
<i>Bolivina seminuda</i>	2	6.7	4	14.3	29	9.1	3	3.9	4	2.8	4	7.5	8	34.8	11	6.5					
<i>Bolivina spathulata</i>					7	2.2	8	10.5	6	4.1	3	5.7					2	1.2	3	16.7	
<i>Bolivina striatula</i>	8	26.7	3	10.7	86	27.0	11	14.5	14	9.5	12	22.6	2	8.7	19	11.2					
<i>Bulimina aculeata</i>			2	7.1	25	7.8	8	10.5	4	2.7					2	8.7	16	9.5	5	27.8	
<i>Bulimina costata</i>									1	0.7	1	1.9					1	0.6			
<i>Bulimina exilis</i>									2	1.4											
<i>Bulimina marginata</i>			5	17.9	47	14.7	9	11.8	42	28.6	7	13.2	1	4.3	12	7.1	1	5.6			
<i>Cassidulina carinata</i>					1	0.3	1	1.3													
<i>Cassidulina crassa</i>	1	3.3	1	3.6	8	2.5					1	1.9			3	1.8					
<i>Cassidulinoides bradyi</i>	6	20.0			10	3.1	5	6.6	4	2.7	3	5.7			4	2.4					
<i>Cibicides lobatulus</i>									1	0.7											
<i>Cribrostomoides</i> sp.	1	3.3			3	0.9							2	3.8			1	0.6			
<i>Dentalina</i> sp.															1	4.3					
<i>Eggerella apicularis</i>	1	3.3			2	0.6					1	1.9					11	6.5	1	5.6	
<i>Eggerella</i> sp. 1					1	0.3											3	1.8	1	5.6	
<i>Eggerella</i> sp. 2					3	0.9															
<i>Epistominella exigua</i>							1	1.3									2	1.2			
<i>Fursenkoina mexicana</i>					1	0.3											1	0.6			
<i>Gavelinopsis praegeri</i>					3	0.9	2	2.6	4	2.7											
<i>Gyroidina</i> sp. 1	1	3.3			35	11.0	13	17.1	31	21.1			1	4.3	24	14.2	2	11.1			
<i>Gyroidina</i> sp. 2							1	1.3													
<i>Glomospira</i> sp.					1	0.3															
<i>Hanzawaia boueana</i>	1	3.3	1	3.6	3	0.9					1	1.9			5	3.0	1	5.6			
<i>Lagena</i> sp.					1	0.3					1	1.9									
<i>Leptohalysis scottii</i>					1	0.3															
<i>Nonion</i> spp.	1	3.3																			
<i>Nonion scaphum</i>	3	10.0	1	3.6	4	1.3					2	3.8	4	17.4	1	0.6	1	5.6			
<i>Nonionella turgida</i>	1	3.3			8	2.5					1	1.9	2	8.7	14	8.3	1	5.6			
<i>Oridorsalis umbonatis</i>											1	1.9									
<i>Quinqueloculina</i> sp.	1	3.3			3	0.9															
<i>Recurvoides</i> sp.	1	3.3									5	9.4			1	0.6					
<i>Rosalina</i> sp.			1	3.6							1	1.9			2	1.2					
<i>Stainforthia</i> sp.					1	0.3			1	0.7											
<i>Textularia porecta</i>			3	10.7	4	1.3			1	0.7	1	1.9	1	4.3	2	1.2					
<i>Textularia sagittula</i>			1	3.6					3	2.0					3	1.8					
<i>Textularia</i> sp.	1	3.3			2	0.6			4	2.7					2	1.2					
<i>Trifarina pauperata</i>			5	17.9	12	3.8	9	11.8	7	4.8					6	3.6	1	5.6			
<i>Trifarina bradyi</i>							1	1.3							1	0.6					
<i>Trochammina</i> sp.															2	1.2					
<i>Uvigerina bononiensis</i>					1	0.3															
<i>Uvigerina peregrina</i>	1	3.3			7	2.2			1	0.7	2	3.8	1	4.3	4	2.4					
<i>Valvulineria bradyana</i>					5	1.6			9	6.1	1	1.9			5	3.0					
Spec Agglutinant indet.			1	3.6											9	5.3					
Spec. Hyalin indet.					1	0.3	1	1.3													
<b>Total</b>	<b>30</b>		<b>28</b>		<b>319</b>		<b>76</b>		<b>147</b>		<b>53</b>		<b>23</b>		<b>169</b>		<b>18</b>				

**Appendix 6-6.** Composition and percentages of the dead/fossil fauna (D: 2-3 cm) (total sediment volume = 12.6 cm<sup>3</sup>).

Taxa	Species		2		3		4		6		13		16		17		18		19		
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	
<i>Ammoscalaria</i> sp.			1	0.5																	
<i>Amphicoryna scalaris</i>	4	1.8	6	2.8	6	2.4	4	1.7	4	1.9	7	2.9	6	3.1	2	0.9					
<i>Astacolus</i> sp.	1	0.4																			
<i>Astrononion</i> sp.			1	0.5									1	0.5							
<i>Bigenerina nodosaria</i>													1	0.5							
<i>Bolivina dilatata</i>					3	1.2							2	1	1	0.5					
<i>Bolivina spathulata</i>	1	0.4	4	1.8	4	1.6	2	0.8	1	0.5			3	1.6	8	3.7	6	3			
<i>Bolivina striatula</i>					2	0.8							4	2.1	5	2.3	2	1			
<i>Bulimina aculeata</i>					9	3.6	1	0.4	3	1.4	2	0.8	3	1.6	9	4.1	3	1.5			
<i>Bulimina costata</i>	6	2.6	5	2.3	7	2.8	11	4.6	7	3.4	5	2.1	3	1.6	3	1.4	7	3.5			
<i>Bulimina exilis</i>					1	0.4	2	0.8							4	1.8					
<i>Bulimina marginata</i>	11	4.8	11	5	34	13.7	15	6.3	12	5.8	13	5.5	9	4.7	53	24.4	14	7.1			
<i>Cancris auriculus</i>	1	0.4	7	3.2	1	0.4	1	0.4				2	0.8		2	0.9					
<i>Cassidulina carinata</i>	24	10.5	27	12.4	25	10	29	12.2	7	3.4	15	6.3	24	12.4	18	8.3	20	10.1			
<i>Cassidulina crassa</i>					3	1.2					1	0.4	1	0.5			1	0.5			
<i>Cassidulina oblonga</i>	1	0.4			2	0.8	1	0.4													
<i>Cassidulinoides bradyi</i>															2	0.9					
<i>Chilostomella oolina</i>					2	0.8	3	1.3			1	0.4									
<i>Cibicides lobatulus</i>	13	5.7	10	4.6	7	2.8	9	3.8	6	2.9	10	4.2	3	1.6	6	2.8	8	4			
<i>Cibicides ungerianus</i>							1	0.4	1	0.5											
<i>Cyclogyra involvens</i>					1	0.4									1	0.5					
<i>Dentalina</i> sp.					1	0.4									2	0.9	1	0.5			
<i>Eggerella bradyi</i>							1	0.4													
<i>Eggerella scabra</i>											1	0.4									
<i>Eggerella</i> sp.1			3	1.4											4	1.8	2	1			
<i>Elphidium advenum</i>			1	0.5									3	1.6	1	0.5					
<i>Elphidium</i> sp.			1	0.5																	
<i>Fissurina orbignyana</i>											1	0.4									
<i>Gavelinopsis praegeri</i>									1	0.5					1	0.5					
<i>Glandulina laevigata</i>											1	0.4									
<i>Globobulimina affinis</i>					1	0.4	2	0.8	1	0.5	2	0.8			1	0.5	1	0.5			
<i>Globocassidulina subglobosa</i>					1	0.4	2	0.8													
<i>Gyroidina orbicularis</i>			1	0.5						3	1.4	2	0.8	3	1.6	1	0.5	2	1		
<i>Gyroidina soldanii</i>					1	0.4															
<i>Gyroidina umbonata</i>					1	0.4							1	0.5	2	0.9	1	0.5			
<i>Hanzawaia boueana</i>	2	0.9	8	3.7	17	6.8	11	4.6	5	2.4	3	1.3	10	5.2	15	6.9	6	3			
<i>Haplophragmoides</i> sp.			1	0.5																	
<i>Hoeglundina elegans</i>	1	0.4	5	2.3	2	0.8	1	0.4			2	0.8	2	1	1	0.5	2	1			
<i>Hyalinea balthica</i>			1	0.5	1	0.4							1	0.5	1	0.5					
<i>Lagena</i> sp.1	1	0.4	1	0.5	2	0.8	1	0.4											1	0.5	
<i>Lagena</i> sp.2					1	0.4	1	0.4	1	0.5											
<i>Lagena</i> sp.3					1	0.4					1	0.4									
<i>Lagena</i> sp.4					1	0.4					1	0.4	1	0.5					1	0.5	

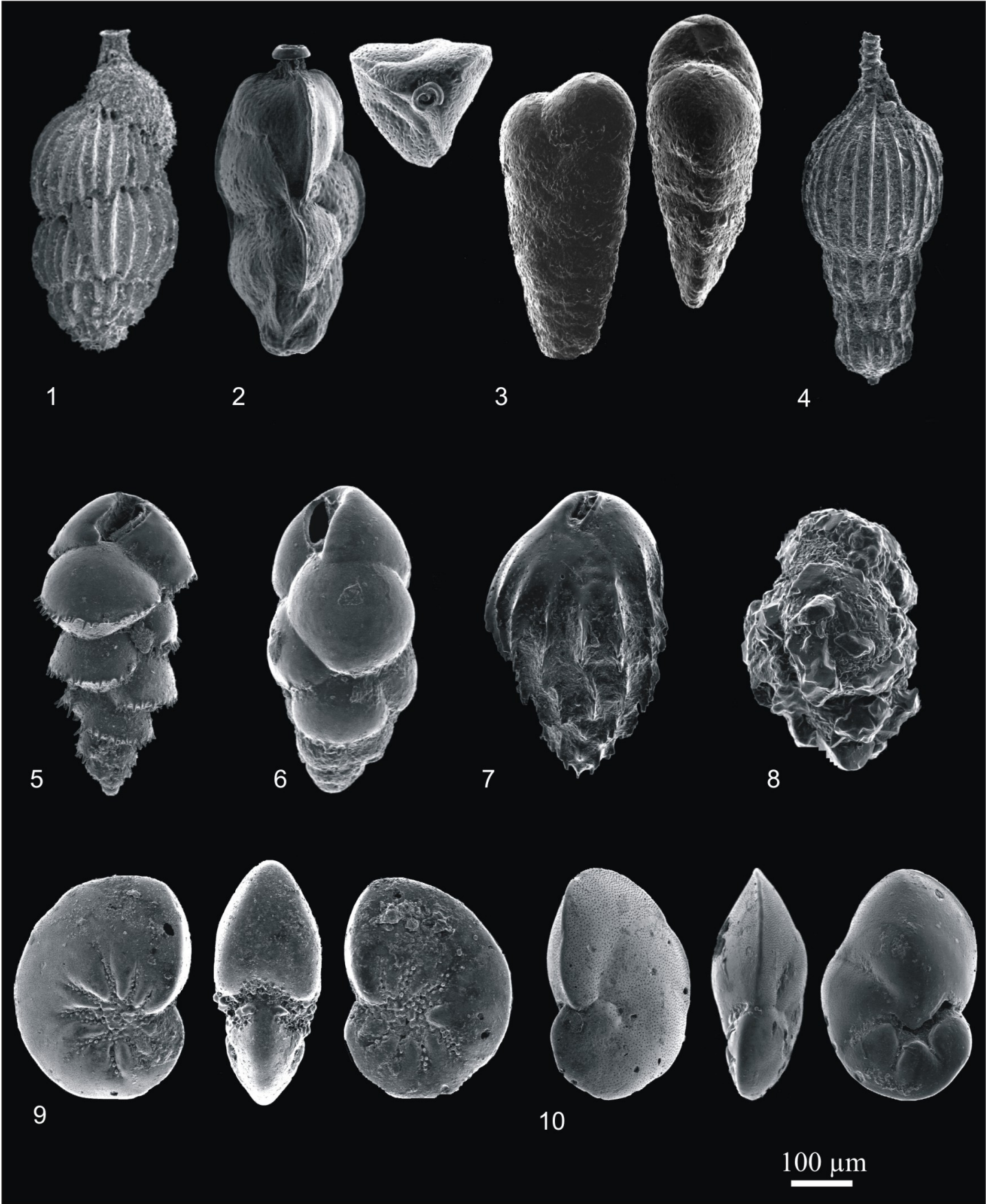
Appendix 6-6. Continued.

Taxa	Species		2		3		4		6		13		16		17		18		19	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
<i>Lagena</i> sp.5					1	0.4														
<i>Lagena</i> sp.6			1	0.5					1	0.4	1	0.5	1	0.4					1	0.5
<i>Lagena</i> sp.7									1	0.4			1	0.4						
<i>Lenticulina peregrina</i>	1	0.4	1	0.5	1	0.4	1	0.4					1	0.4						
<i>Lenticulina</i> sp. 1	2	0.9	1	0.5							2	1			2	1				
<i>Lenticulina</i> sp. 2			1	0.5											2	1				
<i>Nonion scaphum</i>	16	7	9	4.1	16	6.4	8	3.4	11	5.3	18	7.6	13	6.7	5	2.3	15	7.6		
<i>Nonionella</i> sp.					4	1.6	2	0.8						3	1.6					
<i>Nonionella turgida</i>					1	0.4	1	0.4												
<i>Oolina hexagona</i>														1	0.5					
<i>Oridorsalis umbonatus</i>	2	0.9	1	0.5	1	0.4	2	0.8						1	0.5				2	1
<i>Pseudoepionides falsobeccarii</i>	11	4.8	7	3.2	3	1.2	2	0.8	6	2.9	18	7.6	11	5.7	4	1.8	4	2		
<i>Pullenia quinqueloba</i>												1	0.4			1	0.5	1	0.5	
<i>Quinqueloculina</i> sp.							1	0.4												
<i>Rectuvigerina phlegeri</i>					1	0.4	1	0.4						1	0.5				1	0.5
<i>Reophax scorpiurus</i>			2	0.9															1	0.5
<i>Rosalina globularis</i>					1	0.4										2	0.9			
<i>Rosalina</i> sp.							1	0.4												
<i>Saccamina</i> sp.	2	0.9			2	0.8								2	1	1	0.5			
<i>Siphotextularia affinis</i>					1	0.4														
<i>Sphaeroidina bulloides</i>																1	0.5			
<i>Spiroloculina tenuiseptata</i>									1	0.5										
<i>Spiroplectammina</i> sp.			1	0.5			1	0.4					1	0.4						
<i>Textularia agglutinans</i>	2	0.9	1	0.5	3	1.2	2	0.8	1	0.5	5	2.1	1	0.5	3	1.4	2	1		
<i>Textularia sagittula</i>							2	0.8					3	1.6	4	1.8				
<i>Trifarina angulosa</i>	1	0.4																		
<i>Trifarina bradyi</i>	1	0.4	1	0.5	4	1.6	8	3.4	6	2.9				4	2.1	4	1.8	5	2.5	
<i>Triloculina tricarinata</i>																1	0.5			
<i>Triloculina trigonula</i>												1	0.4			1	0.5			
<i>Uvigerina elongatastriata</i>					1	0.4														
<i>Uvigerina peregrina</i>	121	53.1	96	44	71	28.5	104	43.9	127	61.1	120	50.4	65	33.7	46	21.2	87	43.9		
<i>Valvulineria bradyana</i>			1	0.5									2	1	1	0.5	1	0.5		
<i>Valvulineria</i> sp.	2	0.9										1	0.4							
Spec. Indet.	1	0.4	1	0.5	1	0.4	1	0.4	1	0.5				1	0.5					
<b>Total of counted benthic foraminifera</b>	<b>228</b>		<b>218</b>		<b>249</b>		<b>237</b>		<b>208</b>		<b>238</b>		<b>193</b>		<b>217</b>		<b>198</b>			
<b>Number of species</b>	<b>24</b>		<b>32</b>		<b>43</b>		<b>36</b>		<b>21</b>		<b>29</b>		<b>34</b>		<b>36</b>		<b>28</b>			
<b>Split used for benthic foraminifera</b>	<b>0.023</b>		<b>0.023</b>		<b>0.188</b>		<b>0.438</b>		<b>0.375</b>		<b>0.047</b>		<b>0.031</b>		<b>0.141</b>		<b>0.031</b>			
<b>Total benthic foraminifera (estimated)</b>	<b>9728</b>		<b>9301</b>		<b>1328</b>		<b>542</b>		<b>555</b>		<b>5077</b>		<b>6176</b>		<b>1543</b>		<b>6336</b>			
<b>Split used for planktonic foraminifera</b>	<b>0.016</b>		<b>0.023</b>		<b>0.188</b>		<b>0.438</b>		<b>0.375</b>		<b>0.047</b>		<b>0.031</b>		<b>0.141</b>		<b>0.031</b>			
<b>Counted planktonic foraminifera</b>	<b>276</b>		<b>301</b>		<b>224</b>		<b>197</b>		<b>254</b>		<b>355</b>		<b>249</b>		<b>127</b>		<b>226</b>			
<b>Total planktonic foraminifera (estimated)</b>	<b>17250</b>		<b>12843</b>		<b>1195</b>		<b>450</b>		<b>677</b>		<b>7573</b>		<b>7968</b>		<b>903</b>		<b>7232</b>			
<b>PB-ratio (% planktonic)</b>	<b>63.9</b>		<b>58</b>		<b>47.4</b>		<b>45.4</b>		<b>55</b>		<b>59.9</b>		<b>56.3</b>		<b>36.9</b>		<b>53.3</b>			



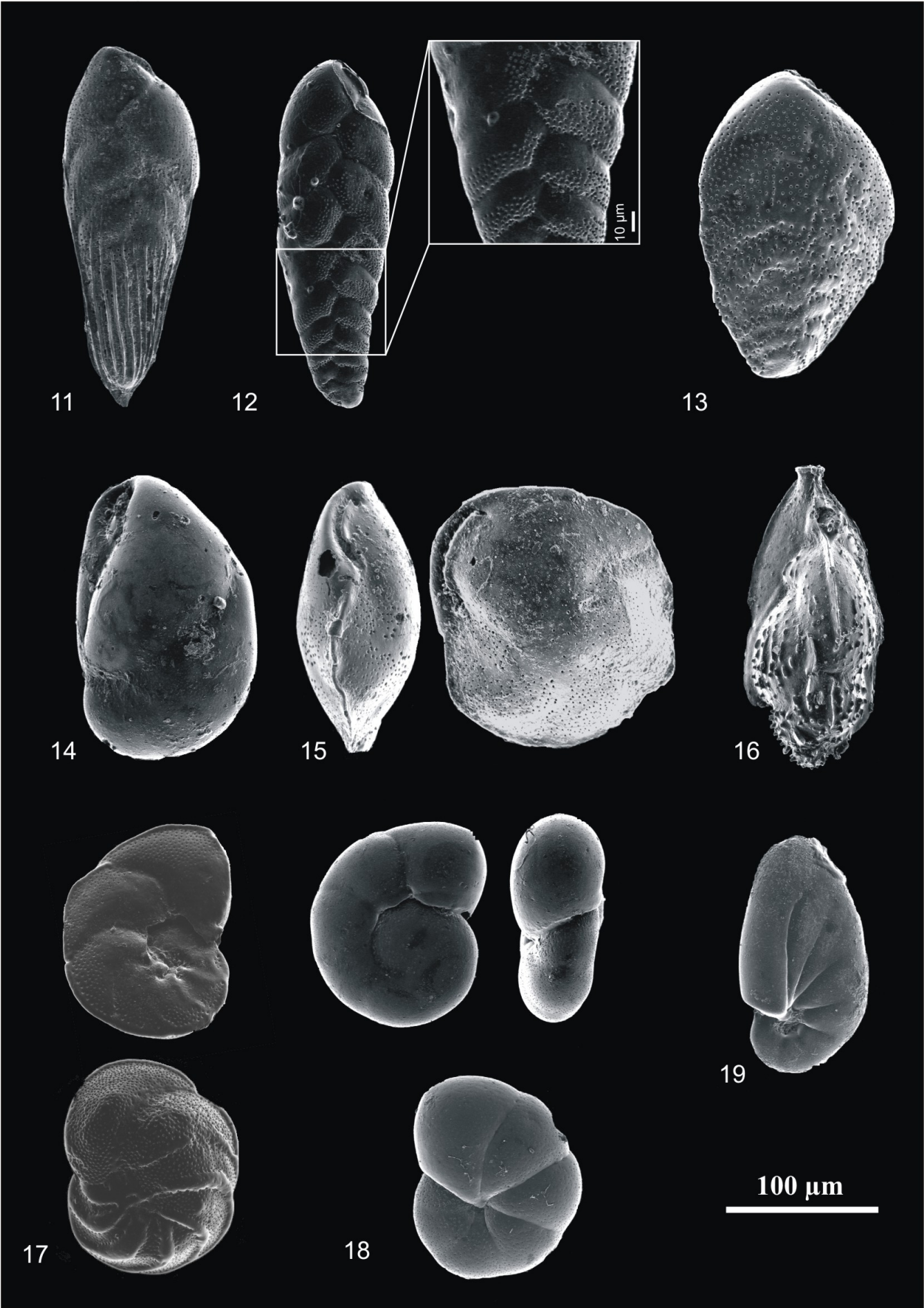
**Plate 6-1**

1. *Uvigerina peregrina* (Fornasini, 1888).
2. *Trifarina bradyi* (Cushman, 1923).
3. *Textularia sagittula* (DeFrance, 1824).
4. *Amphicoryna scalaris* (Batsch, 1791).
5. *Bulimina marginata* (d'Orbigny, 1826).
6. *Bulimina aculeata* (d'Orbigny, 1826).
7. *Bulimina costata* (d'Orbigny, 1852).
8. *Eggerella* sp.1
9. *Nonion scaphum* (Fitchell and Moll, 1798).
10. *Cancris auriculus* (Fichtel et Moll, 1942).



**Plate 6-2**

11. *Bolivina striatula* (Cushman, 1922).
12. *Bolivina seminuda* (Cushman, 1911)
13. *Bolivina spathulata* (Williamson, 1858)
14. *Cassidulinoides bradyi* (Norman, 1881)
15. *Cassidulina carinata* (Silvestri, 1896)
16. *Trifarina pauperata* (Heron Allen and Earland, 1932)
17. *Hanzawaia boueana* (d'Orbigny, 1846)
18. *Gyroidina* sp.1
19. *Nonionella turgida* (Williamson, 1858)





## **CHAPITRE 7. AGED DRILLED CUTTINGS OFFSHORE GABON: NEW METHODOLOGY FOR ASSESSING THEIR IMPACT**

<b>RÉSUMÉ</b> .....	333
<b>7.1 ABSTRACT</b> .....	336
<b>7.2 INTRODUCTION</b> .....	336
<b>7.3 DESCRIPTION</b> .....	337
<b>7.4 MATERIAL AND METHODS</b> .....	338
<b>7.5 RESULTS</b> .....	341
<b>7.5.1 Physico-chemical analyses</b> .....	341
7.5.1.1 Particle size analysis.....	341
7.5.1.2 Redox potential .....	342
7.5.1.3 Organic matter.....	342
7.5.1.4 Total hydrocarbon and Barium .....	343
<b>7.5.2 Toxicity tests</b> .....	343
<b>7.5.3 Macrobenthos analyses</b> .....	344
7.5.3.1 General composition.....	344
7.5.3.2 General structure.....	345
<b>7.5.4 Benthic foraminiferal fauna</b> .....	346
<b>7.6 DISCUSSION</b> .....	349
<b>7.7 CONCLUSION</b> .....	352
<b>7.8 ACKNOWLEDGMENTS</b> .....	354
<b>7.9 REFERENCES</b> .....	354
<b>APPENDICES</b> .....	356



## RÉSUMÉ

Durant les activités pétrolières, et en particulier durant les activités de décharge des boues et déblais de forages pétroliers, les conditions de vie de la flore et la faune sur le fond marin peuvent être perturbées. Ce chapitre décrit l'étude menée dans le but de déterminer l'impact actuel de ces opérations, la capacité régénératrice de l'écosystème benthique et les processus de recolonisation à long terme basée sur des mesures in-situ. Une précédente étude effectuée sur des boues de forages récemment déversées sur la côte Congolaise a mesuré l'étendue spatiale de l'impact de ces activités et le temps nécessaire à la réhabilitation de l'écosystème benthique. Afin de valider ces résultats, nous avons effectué une étude similaire dédiée à l'impact d'anciennes décharges de boues de forage sur la côte Gabonaise. Le processus standard de suivi des effets biologiques de ces boues de forages comprend plusieurs approches et notamment l'étude de la macrofaune benthique (> 1 mm de taille), les analyses physicochimiques du sédiment ainsi que les tests écotoxicologiques. Une des particularités de notre étude est de joindre, à ce processus, l'étude des foraminifères benthiques (0.1 to 1 mm).

Les analyses effectuées ont démontré que, 12 ans après l'arrêt des activités pétrolières, nous trouvons de faibles concentrations d'hydrocarbures originaires des déblais de forages, une faible toxicité du sédiment, l'absence d'altération de la macrofaune benthique ainsi que l'absence de changement dans les communautés actuelles de foraminifères benthiques (meiofaune). Enfin, l'étude de la meiofaune benthique atteste de la qualité du milieu et des conclusions effectuées sur sa santé actuelle.

**Mots clés:** Foraminifères benthiques; anciens déblais de forages pétroliers; macrobenthos; tests de toxicité; hydrocarbures; fleuve « Ogoué ».





## CHAPITRE 7. AGED DRILLED CUTTINGS OFFSHORE GABON: NEW METHODOLOGY FOR ASSESSING THEIR IMPACT

J. Durrieu <sup>(2)</sup>, M. Mojtahid <sup>(1)</sup>, L. Cazes <sup>(4)</sup>, F. Galgani <sup>(3)</sup>,

F. Jorissen <sup>(1)</sup>, D. Tran <sup>(3)</sup> and R. Camps <sup>(2)</sup>

<sup>(1)</sup> Laboratoire des Bio-Indicateurs Actuels et Fossiles (BIAF) UPRES EA 2644, Université d'Angers. 2, Boulevard Lavoisier, 49045 Angers Cedex, France, and Laboratoire d'Etude des Bio-Indicateurs Marins (LEBIM). Ker Chalon, 85350 Ile D'Yeu, France.

<sup>(2)</sup> TOTAL, département Environnement Opérations. Avenue Larribau, 64018 Pau, France.

<sup>(3)</sup> IFREMER, avenue J.-Monnet, 34203 Sète, France.

<sup>(4)</sup> AJILON Engineering, 1, avenue Didier Daurat, 31700 Blagnac, France.

Ce chapitre correspond à un article apparu dans la revue *Society of Petroleum Engineers* (SPE 98414 (2006), 8 pp.)

**Keywords:** Benthic foraminifera; aged drilled cuttings; macrobenthos; toxicity tests; hydrocarbons; “Ogoué” River.

## 7.1 ABSTRACT

During E&P (Exploration and Production) offshore activities, and in particular during drilling operations, the living conditions of the flora and fauna on the seabed may be disturbed. The chapter describes the study made for assessing the actual impact of the discharged cuttings, the regenerating capacity of the ecosystem and the medium and long-term recolonisation processes, based on in situ measurements. A previous study undertaken on cuttings recently discharged offshore Congo measured kinetics of space and time restoration of the drilling site. To validate the results, we carried out a similar study dedicated on aged cuttings offshore Gabon. Usual process for monitoring biological effects of cuttings includes several approaches such as benthic macrofauna (> 1 mm size) studies, physicochemical analysis of sediment and ecotoxicological tests. One of the key features of our study was to add, to this process, a study of the benthic foraminifera (0.1 to 1 mm size).

Experiments conducted demonstrated that, 12 years after the cessation of the drilling activities, there is very low concentrations of hydrocarbons stemming out from the cuttings, a very low toxicity of sediment, no benthic macrofauna community alteration, no change in the communities of actual foraminifera (= the meiofauna) and, last but not least, that the study of the benthic meiofauna improves the quality of the assessment made.

## 7.2 INTRODUCTION

In order to study the way the benthic fauna regenerates and recolonises the seabed after the discharge of cuttings in a warm water context, a project was conducted in 2 phases between 2003 and 2004 off Congo with different objectives:

- To validate an experimental protocol for monitoring re-colonization of aged cuttings. We focused on the impact of oily cuttings.
- To assess the impact of cuttings contaminated by oil based drilling fluids, and the capacity of regeneration of the environment over time (*Dalmazzone et al., 2004; Durrieu and Bouzet, 2004*)

Off Congo, the last survey was realized 4 years after the end of cuttings discharge. To validate the Congo results we carried out a similar study but on aged dumped oil based cuttings (12 years after cessation of the disposal activities) offshore Gabon.

### 7.3 DESCRIPTION

The site is located off Gabon at the offshore Anguille Marine field, some 50 km off Port Gentil, under a water depth of 30 m. Cuttings discharge began in 1986 and ended in 1992 but in 2003 an additional well was drilled with high biodegradable base oil. We present in this paper the results from the survey performed in June 2004.

The sampling plan comprises 12 stations (Table 7-1) located between 70 and 11400 m from the discharge point of cuttings (Fig. 7-1).

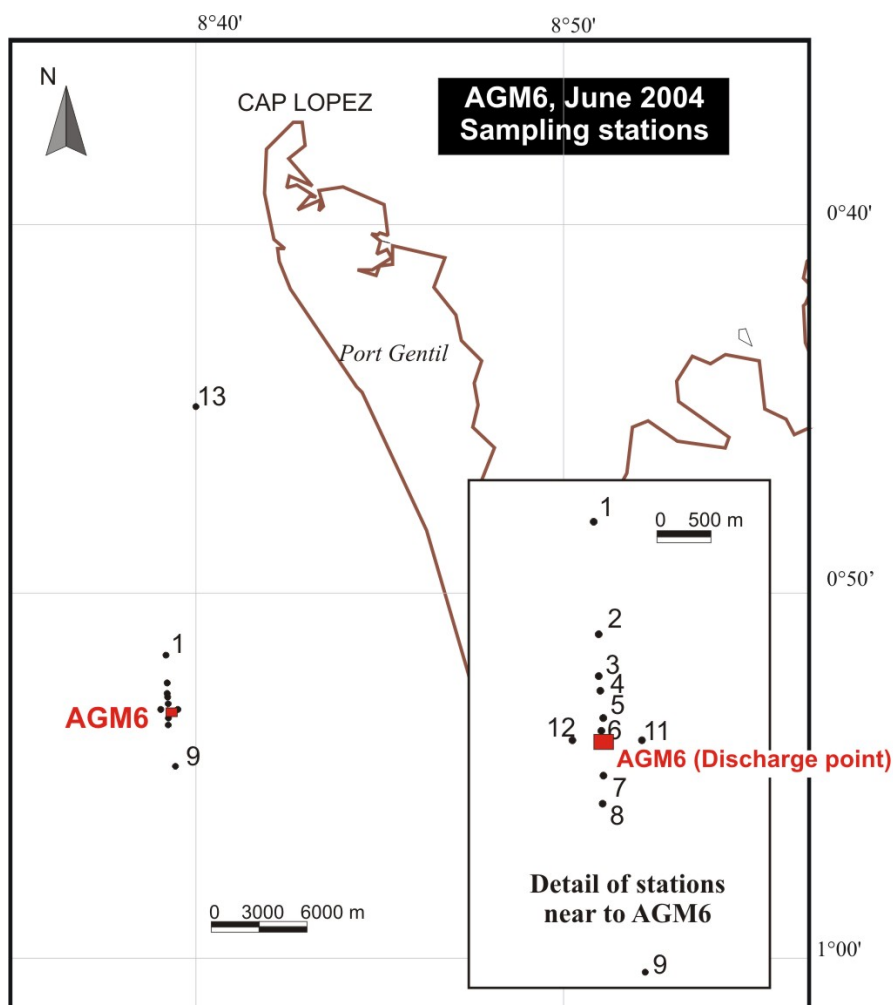


Figure 7-1. Map of sampled stations.

The study area is situated north of the south extensions of the “Ogouué” River. This is the principal river in Gabon with an annual discharge from 4300 m<sup>3</sup>/s to 7600 m<sup>3</sup>/s. This river transports enormous amounts of muddy sediments characteristic of the Gabonese basement. This erosion material is discharged in the ocean and transported by the currents until the study

area. It is noteworthy that previous oceanographic surveys demonstrated a residual circulation oriented to the north, spreading the runoff products of the large river “Ogooué” into the direction of our study area. Indeed, at 30 m water depth, the study area is directly influenced by the southnorthern cold surface Benguela current, tidal currents and waves (southnorthern long-shore drift) (*Mounganga, 1999*).

<b>Station</b>	<b>Distance (m)</b>	<b>Depth (m)</b>
<b>1</b>	2000 m North	29
<b>2</b>	1000 m North	30
<b>3</b>	750 m North	30
<b>4</b>	500 m North	30
<b>5</b>	250 m North	30
<b>6</b>	70 m North	30
<b>7</b>	250 m South	30
<b>8</b>	500 m South	30
<b>9</b>	2000 m South	30
<b>11</b>	250 m East	30
<b>12</b>	250 m West	30
<b>13</b>	11400 m North	30

*Table 7-1. Sampling plan.*

## 7.4 MATERIAL AND METHODS

The methods used included physico-chemical analyses, toxicity tests on sediments, benthic fauna and foraminiferal analysis at different sampling stations located along a transect on the same isobath (30 m) around the discharge site (Fig. 7-1).

Sampling was carried out by means of a Van Veen grab that allows the sampling of an area of about 0.1 m<sup>2</sup> of sediment. At each station, 4 full grabs were taken for physico-chemical analyses, toxicity, and for the analysis of benthic communities (macrofauna and foraminifera). In the specific case of benthic macrofauna studies, samples from 3 grabs were put into a barrel and mixed until a homogeneous suspension was obtained. Then, samples were sieved over a 1 mm stainless steel mesh sieve. After sea water flushing, the oversize was put into a plastic bag with formalin 7-8 % in sea water. For foraminifera, the sediment was sliced in 0.5 cm slices down to 10 cm depth and stored in a solution of 95 % ethanol with 1 g/l Rose Bengal.

**Physico-chemical analyses on sediment.**

The different physico-chemical analyses performed and methods of their measurements on the sediment are listed in Table 7-2.

Tests	Methods	Detection limit
Laser granulometry	Laser Coulter LS230	0.4 µm
Organic matter	Pr EN 12879	0.1 % dry weight
Water content	NF ISO 11465	-
Total nitrogen	NF ISO 11261	0.01 % dry weight
Total phosphorus	NF EN 1189	0.01 % dry weight
Mineralization for barium titration	Total attack in acid medium	
Heavy Metals (Ba, Cd, Cu, Pb, Zn and Hg)	ICP	5 mg/kg dry weight
Total hydrocarbon	XP T 90-114	10 mg/kg dry weight
Redox potential	Potentiometer	

Table 7-2. Physico-chemical analyses.

Total hydrocarbons and Barium were used as tracers of drilling and production activities. The oxido-reduction potential (redox) was measured immediately on the ship during sampling with a potentiometer connected to a platinum electrode and an "AgCl<sub>2</sub>" reference electrode. The redox value is the balance between the oxygen inflow from the circulating waters at the sediment surface and the oxygen consumed by bacteria in the biodegradation of organic matter.

**Toxicity tests.**

Toxicity of sediment was measured using the OSPAR test on the amphipod *Corophium arenarium* (sediment reworker) (Pawliszyn, 1997), and tests on larvae of molluscs (Ospar, 1995)

**Abundance and diversity of benthic macrofauna.**

All the species were identified under a binocular microscope and numbered. For all stations, the density of each species, the specific richness (number of species), the total density (total number of individuals/m<sup>2</sup>), the diversity (Shannon-Wiener index) and the equitability (Pielou index) were calculated.

The Shannon-Wiener diversity index  $H$  (expressed in bits) and the Pielou equitability index  $J$  (expressed in %) were calculated as follows:

$$H = -\sum_{i=1}^s [n_i / N \log_2 (n_i / N)]$$

$$J = H/H_{\max}$$

where  $s$  is the total number of species,  $N$  is the total number of individuals,  $n_i$  is the number of individuals of each species  $i$  and  $H_{\max} = \log_2 s$ . High diversity and equitability indicate a state of equilibrium.

Macrobenthos feeding behaviour can be used to model the community response to organic enrichment. For each species, the trophic group was determined to calculate the trophic index. The different trophic groups are the following (*Word, 1990*):

- Group 1: suspension-feeders
- Group 2: detritivorous feeders or carnivorous
- Group 3: deposit-feeders
- Group 4: anaerobic sediments-feeders

The formula for obtaining the trophic index is the following:

$$TI = 100 - [33.33((0n_1 + 1n_2 + 2n_3 + 3n_4)/(n_1 + n_2 + n_3 + n_4))]$$

where  $n_1$ ,  $n_2$ ,  $n_3$  and  $n_4$  correspond to the respective abundance of trophic groups 1 to 4. Hence, three intervals can be identified to determine the level of settlement:

- $TI > 60$ : normal settlement, characterized by a domination of suspension-feeding species (absence of accumulation of organic matter in the sediment).
- $30 < TI < 60$ : settlement submitted to organic matter inputs (presence of deposit-feeders species).
- $TI < 30$ : settlement submitted to perturbation factors (settlement dominated by deposit-feeders and anaerobic sediments-feeders species, showing a high accumulation of organic matter in the sediment).

### **Foraminifera.**

The samples are preserved, directly after collection, in 95 % ethanol with 1 g/l of Rose Bengal, which colors the cytoplasm of the cells, allowing to distinguish the living specimens from the empty tests and thus to facilitate their observation under the binocular microscope (*Walton, 1952*). In the laboratory, the collected samples were washed (distilled water) and

sieved using 63 and 150  $\mu\text{m}$  meshes. Next, live foraminiferal fauna was inventoried at different depth levels in the sediment; all specimens were identified at a species level and counted.

## 7.5 RESULTS

### 7.5.1 Physico-chemical analyses

#### 7.5.1.1 Particle size analysis

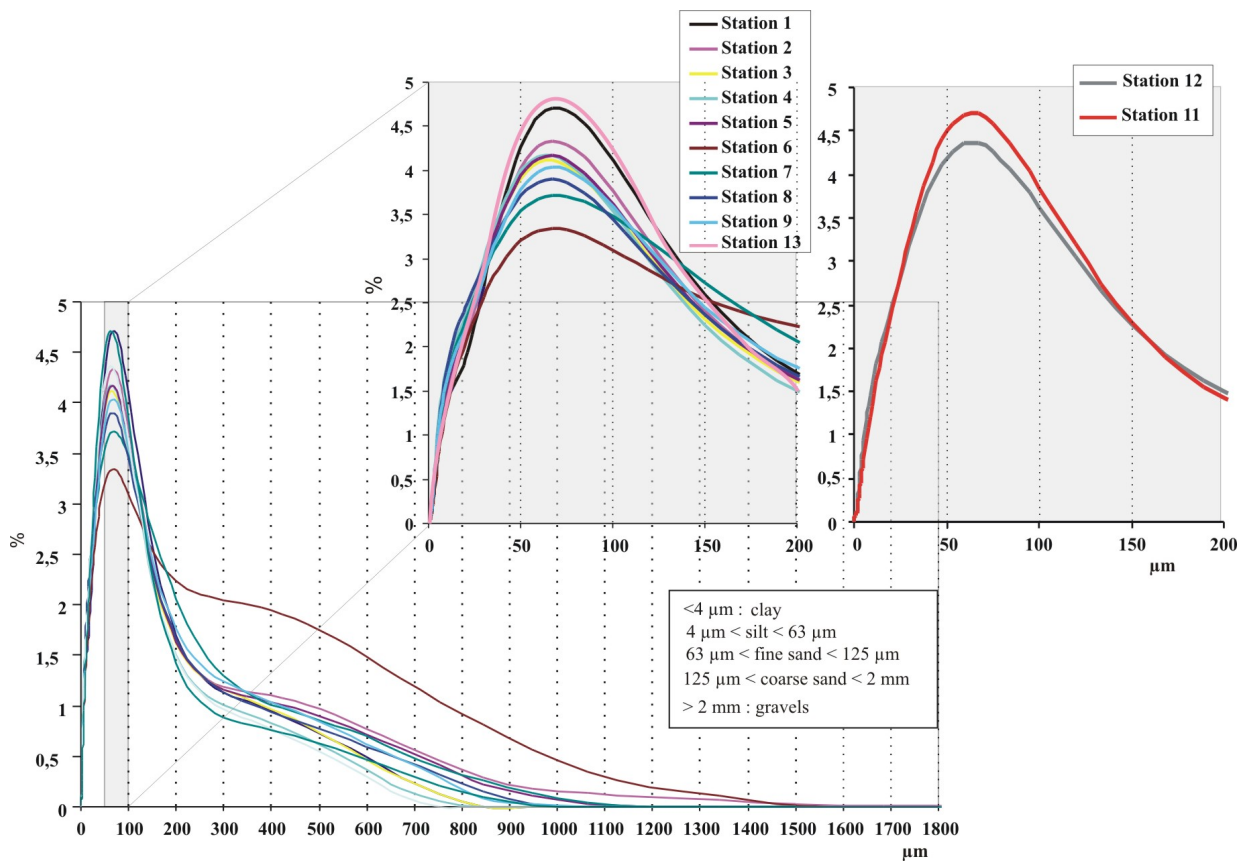


Figure 7-2. Grain size distribution.

Following the grain-size profiles (Fig. 7-2), the sediment presents, at all stations, a principal coarse-silty/fine-sandy mode except for station 6, located in the vicinity of the discharge point, which presents an additional coarse sandy mode. The grain size of the sediment at station 6 can be explained by the recent discharge of cuttings.



### 7.5.1.2 Redox potential

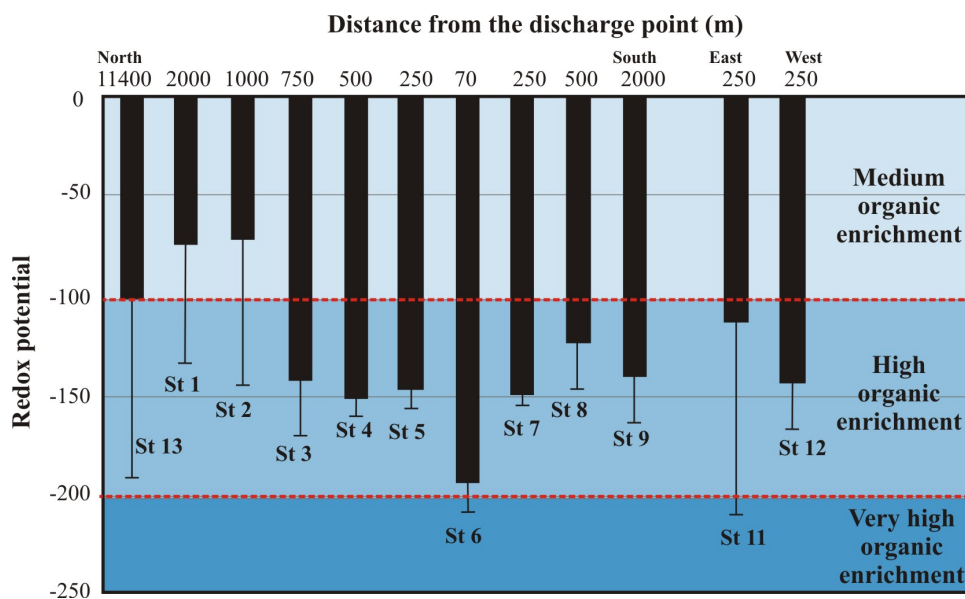


Figure 7-3. Redox potential in the surficial sediment.

Figure 7-3 shows that, at all stations, the redox potential is negative. The redox values decrease progressively while approaching the discharge point. The generally low redox potentials are probably due to the organic input from the “Ogooué” River. The even lower value recorded at station 6 shows the influence of the recent cutting discharges.

### 7.5.1.3 Organic matter

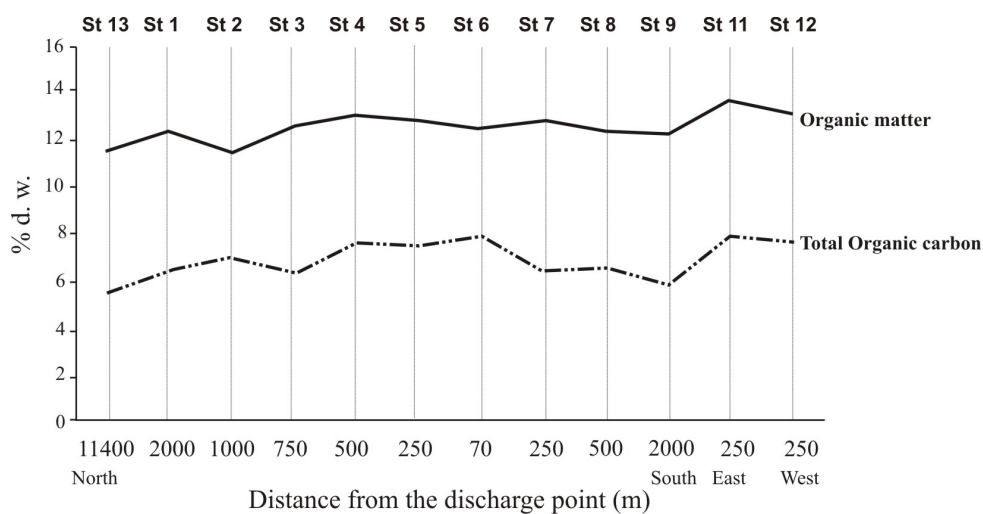


Figure 7-4. Total organic matter-Total organic carbon.

Whatever the distance from the discharge point, levels of organic matter, are quite similar at all stations (Fig. 7-4). The high levels of organic matter (~ 12 %) are directly linked to the "Ogooué" River input (eutrophic zone typical of coastal environment).

#### 7.5.1.4 Total hydrocarbon and Barium

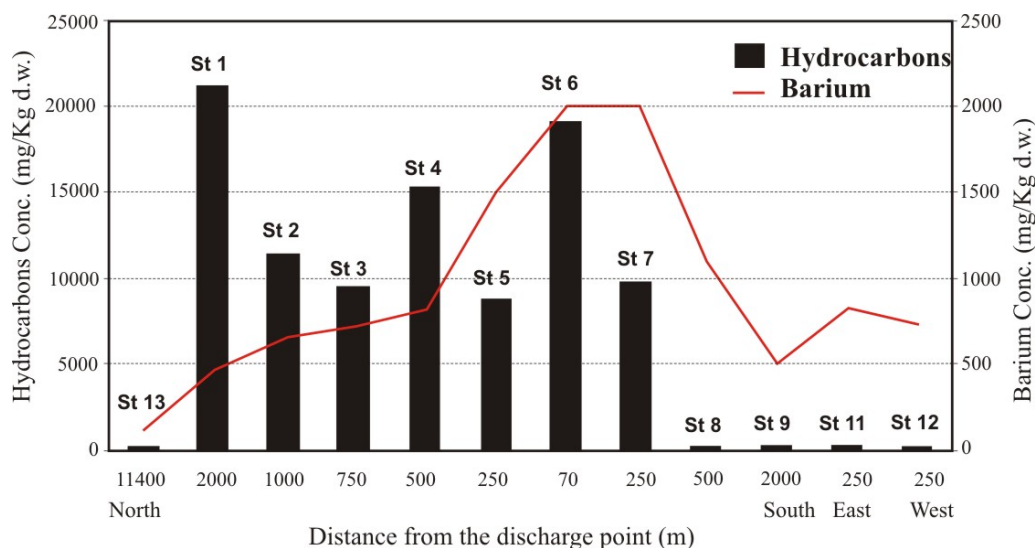


Figure 7-5. Hydrocarbon and Barium content

Station 1, considered as the reference station, and station 6 are the most contaminated stations (Fig. 7-5). Hydrocarbons present at station 6 (~ 19000 mg/Kg d.w.) corresponds to the oil based mud (high levels of Barium are recorded at station 6 ~ 2000 mg/Kg d.w.) whereas the hydrocarbon pattern of station 1 (Hydrocarbons ~ 21000 mg/Kg d.w.; Ba ~ 500 mg/Kg d.w.) suggests a completely different origin.

#### 7.5.2 Toxicity tests

Tests performed on sediment reworker *Corophium arenarium* show a low toxicity in the sediment close to the discharge point (Station 6; 51.9 %) and in a lower extent at station 1 (26.1 %) (Table 7-3). Usually, at recently dumped sites, sometimes 100 % of these reworkers are abnormal.

The tests on larval development of molluscs (oysters) are more sensitive and the highest percentage of anomalies can be observed at the discharge point (station 6; 23.2 %) and also in a lower extent at the station 1 (16.2 %) (Table 7-3).

Station	Distance	<i>(Corophium arenarium)</i>		Oyster bioassay	
		NPA (2 replicates)	EC20	NPA (5 replicates)	EC10
1	2000 m N	26.1	83.1*	16.2	12.8
2	1000 m N	15.7	>100	13.8	24.3
3	750 m N	5.4	>100	12.8	22.3
4	500 m	0.0	>100	8.6	76.0
5	250 m N	0.2	>100	7.0	19.6
6	70 m N	51.9	32.2*	23.2	6.6
7	250 m S	0.2	>100	15.4	63.9
8	500 m S	0.0	>100	8.0	96.3
9	2000 m S	10.5	>100	10.2	95.2
11	250 m E	5.4	>100	0.2	>100
12	250 m W	10.6	>100	3.0	>100
13	11400 m N	10.6	>100	15.6	78.6

Table 7-3. Results of toxicity tests (*Corophium arenaria* and larvae of oyster). NPA: net percentage of anomalies for 100 % elutriate. EC 20: concentration of elutriate causing 20 % abnormalities during development. EC 10: concentration of elutriate causing 10 % abnormalities during development. \*: significantly different ( $p < 0.05$ ).

### 7.5.3 Macrobenthos analyses

#### 7.5.3.1 General composition

Considering all the samples from the stations investigated in our study, 114 species have been identified. The repartition of species by phylum is the following:

- 54 Polychaetes
- 21 Crustaceans
- 4 Sipunculidae
- 1 Nemerte
- 1 Chaetognathe
- 25 Molluscs
- 7 Cnidairae
- 1 Echinodermata
- 1 Phoronidien
- 2 fish

### 7.5.3.2 General structure

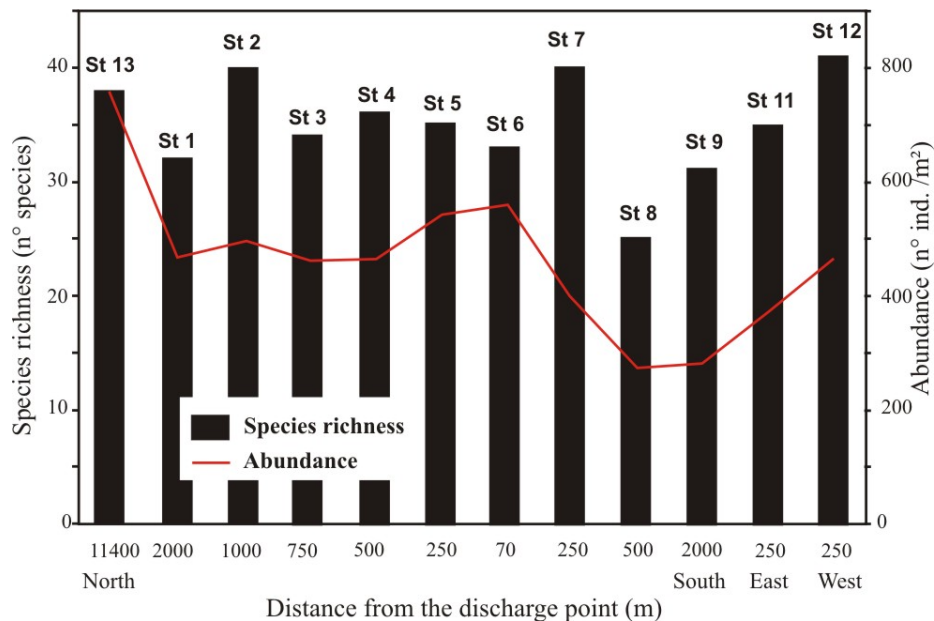


Figure 7-6. Species richness and Abundance.

The spatial evolution of the macrobenthic population is characterised by a slight heterogeneity of the mean faunal density, with minimum values observed at stations 8 and 9 (~ 270 ind. /m²) and maximal values observed at station 13 (~ 770 ind. /m²). The number of species fluctuates between 25 at station 8 and 41 at station 12 (Fig. 7-6). There is no evidence for an environmental impact of E&P activities.

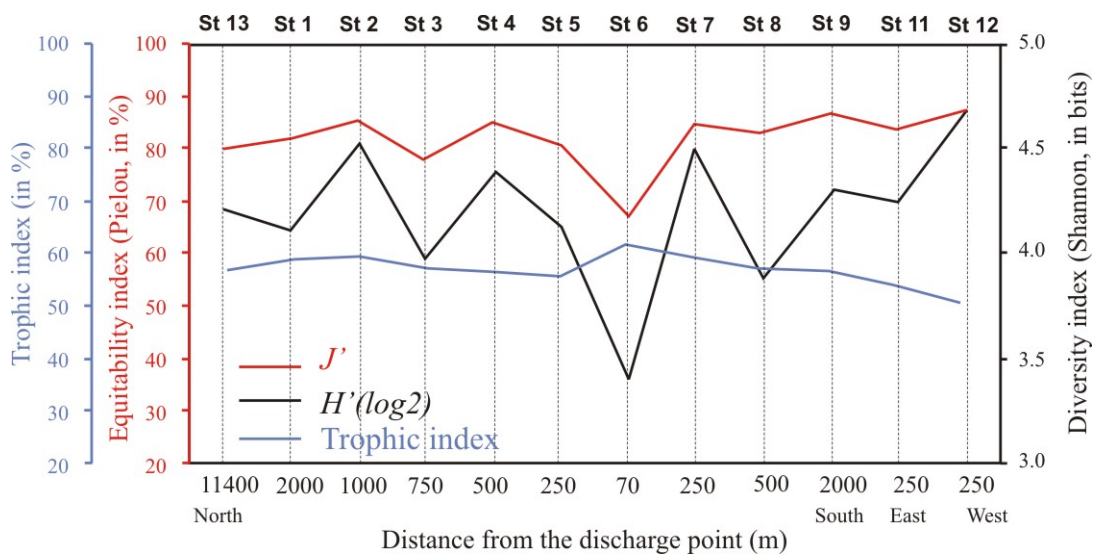


Figure 7-7. Equitability ( $J'$ ), Diversity index ( $H'$ ) and Trophic index.

The Shannon  $H'$  ( $\sim 4.0-4.5$ ) and Pielou  $J$  ( $\sim 80-85\%$ ) indices present normal values at all stations except for station 6 that presents a Shannon index of 3.4 and a Pielou index of 67% (Fig. 7-7).

At all stations, the trophic index presents values from 50 to 60% (Fig. 7-7) translating an environment submitted to organic matter input. In such environments, the presence of deposit feedings species is common.

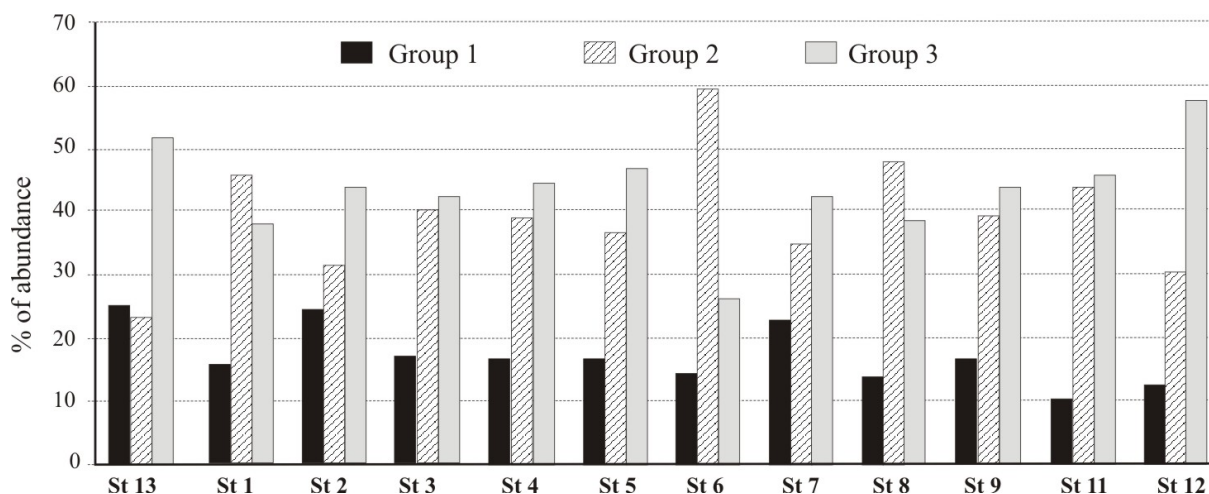


Figure 7-8. Trophic group pattern. Group 1: Suspension feeders; Group 2: Detritivorous feeders or carnivorous, Group 3: Deposit-feeders.

The fauna is dominated at all stations by deposit feeders, detritivorous feeders and carnivorous species. Suspension feeders are also present but in lower abundances. Station 6, where the redox potential is minimal, is different because of the very high percentage of detritivorous feeders and carnivorous (60%).

#### 7.5.4 Benthic foraminiferal fauna (appendices 7-1 ; 7-2)

Our results (Figs. 7-9 and 7-10) indicate that, at all stations, the living fauna in the top 3 cm of the sediment is poor in the larger size fraction ( $> 150\ \mu\text{m}$ ). The faunal density varies from 0 (stations 2 and 12) to about 80 ind./ 50 cc (stations 4 and 7). In the small size fraction (63-150  $\mu\text{m}$ ), the living fauna is richer, with densities varying from about 25 ind./ 50 cc (station 2) to about 2250 ind./50 cc (station 7).

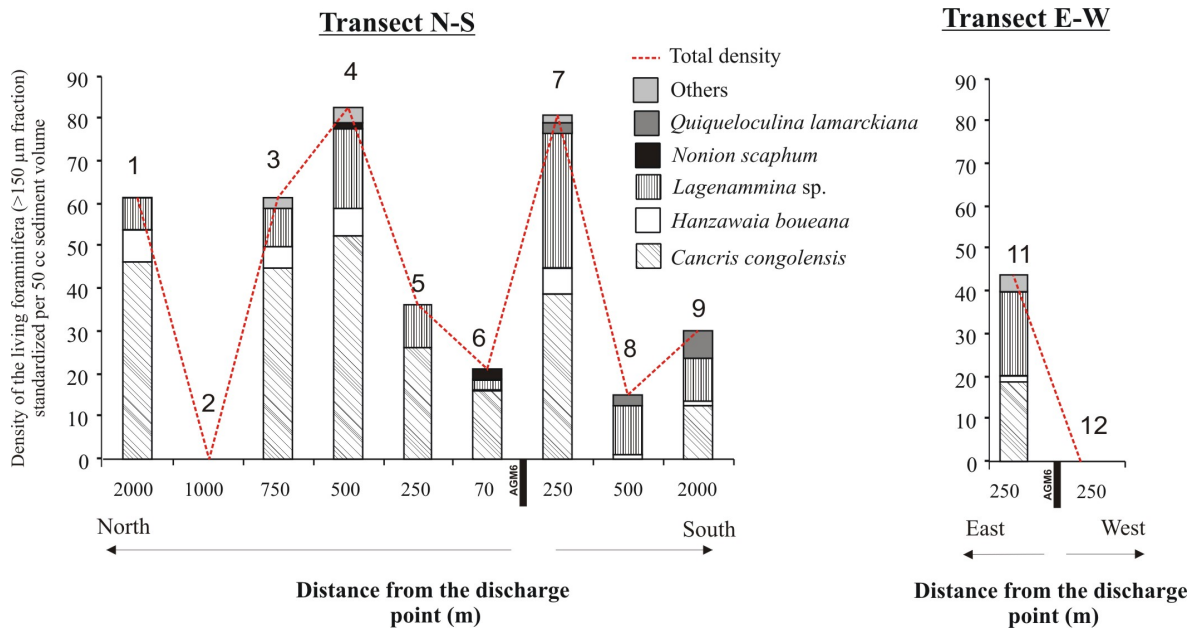


Figure 7-9. Composition and density of the living foraminiferal fauna (> 150 μm fraction observed in the first 3 cm of the sediment standardized per 50 cc sediment volume).

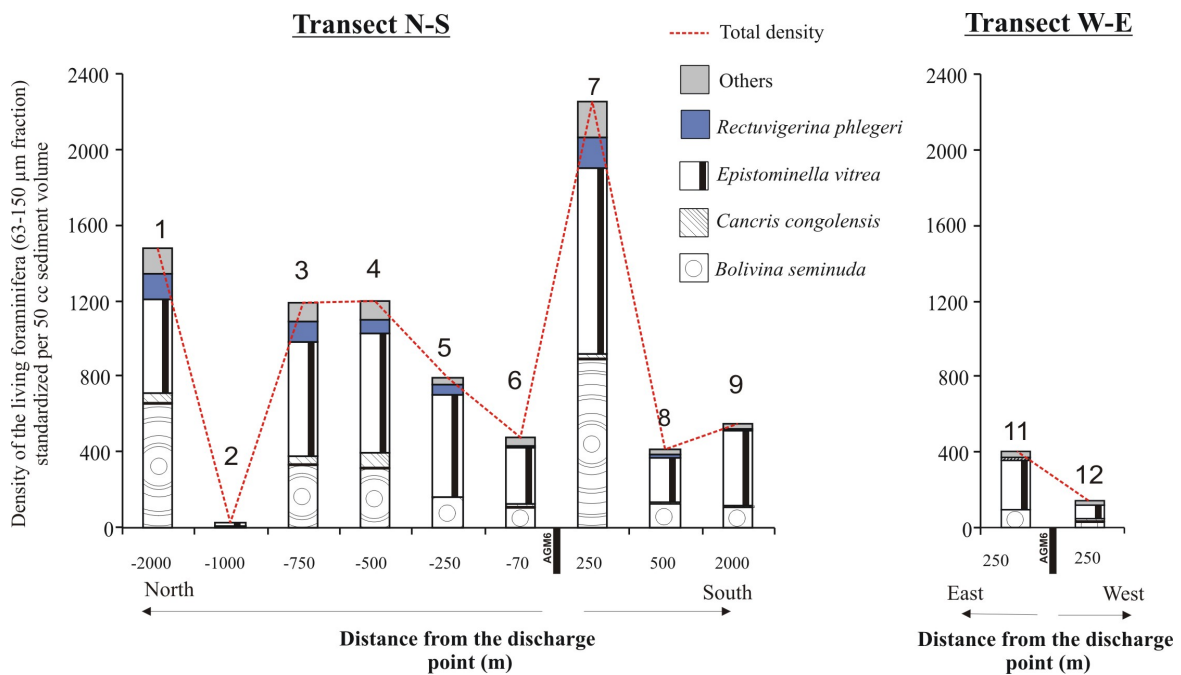


Figure 7-10. Composition and density of the living foraminiferal fauna (63-150 μm fraction observed in the first 2 cm of the sediment standardized per 50 cc sediment volume).

Also, the number of species is more important in the 63-150 μm fraction (4 species at station 2 to 21 species at station 1) than in the > 150 μm fraction (from 0 at stations 2 and 11 to 6 species at stations 4 and 7).

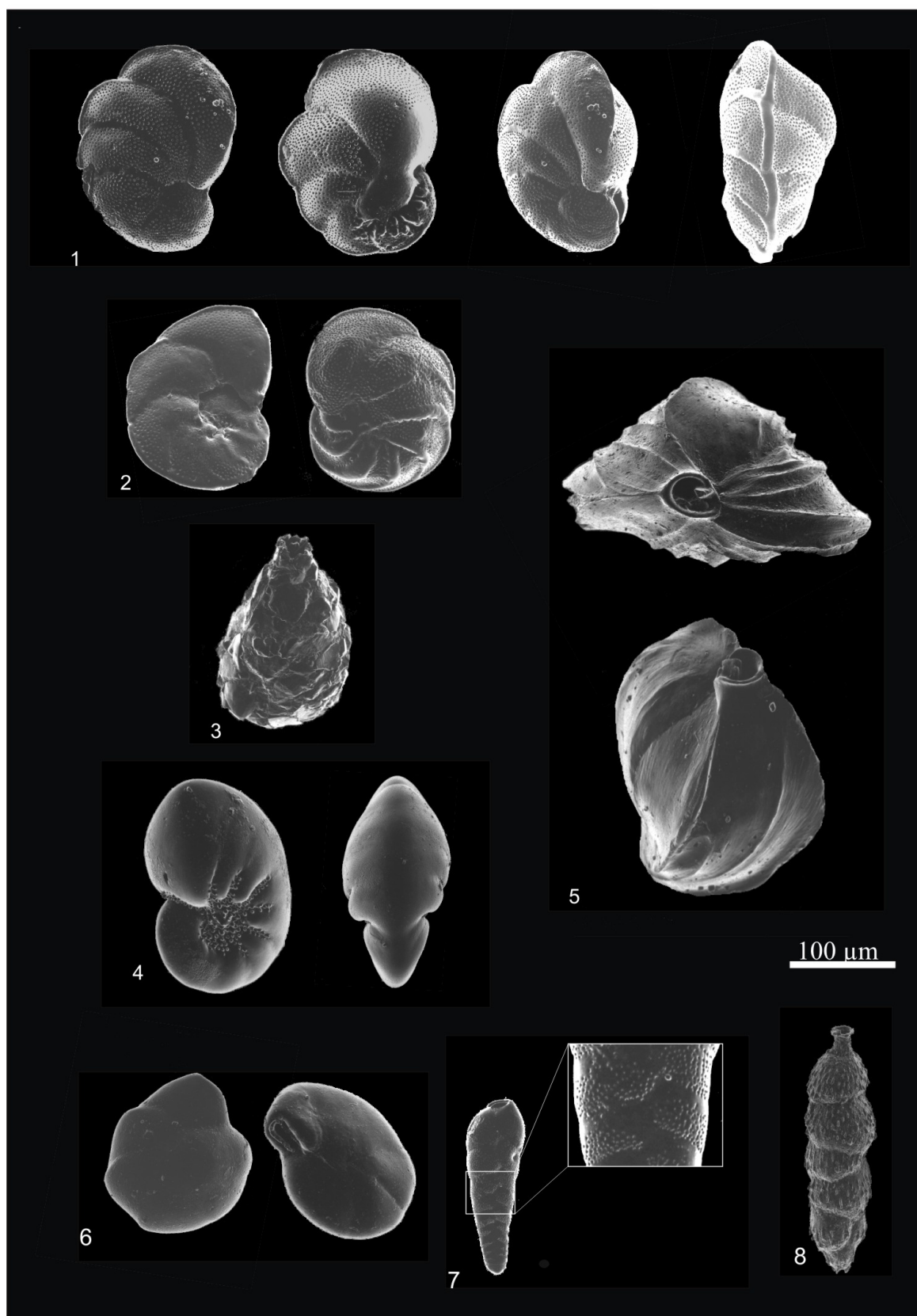


Plate 7-1. SEM images. 1, *Cancris congolensis*; 2, *Hanzawaia boueana*; 3, *Lagenammina* sp.; 4, *Nonion scaphum*; 5, *Quinqueloculina lamarckiana*; 6, *Epistominella vitrea*; 7, *Bolivina seminuda*; 8, *Rectuvigerina phlegeri*.

The specific composition varies very slightly along the transects on both sides of the discharge point. *Cancris congolensis*, *Lagenammina* sp. and *Hanzawaia boueana* are the three dominant species in the > 150 µm fraction. In the 63-150 µm fraction, *Epistominella vitrea* and *Bolivina seminuda* dominate and are generally accompanied by *Rectuvigerina phlegeri* and *Cancris congolensis* (Plate 7-1).

At stations 2 and 12, living foraminifera are present in very low quantities (even absent in the > 150 µm fraction) in comparison with the values obtained at the other stations. We suspect that these low values are due to the fact that the Van Veen grab did not adequately sample the sediment surface.

The spatial distribution of the living foraminifera can be summarized as follows:

- The stations located immediately north (stations 6 and 5), west (station 12) and east (station 11) of the discharge point present low living foraminiferal densities.
- Further away from the discharge point, northward as well as southward, the faunal density increases to maximum values at stations 7, 4 and 3, followed by a decreasing value at station 8.

## 7.6 DISCUSSION

### **Toxicity tests.**

Undoubtedly, toxicity tests demonstrated a very low toxicity of sediments collected in the immediate vicinity of the dumping site (station 6) and to a lesser extent at station 1. It clearly indicates a poor extent of toxicity of sediments from the discharge point after 12 years when compared to recently dumped sites where sometimes 100 % of larvae are abnormal (*Blanchet et al., 2002; Durrieu and Bouzet, 2004; Dalmazonne et al., 2004*). In the more general context of aged cuttings impact, the toxicity results give strong arguments for an almost complete recovery of the site.

### **Macrofaunal analyses.**

The analysis of the different samples shows a quite rich fauna which does not express a marked contamination. The fauna is characteristic of a marine environment influenced by river output causing a naturally strong organic enrichment. Except for station 6, all stations are relatively homogeneous. By statistical analyses (MDS and Bray-Curtis Dissimilarity), it has shown that station 6 which is the closest to the platform (70 m north) is slightly different



notably in grain sizes and benthic community composition. The measured hydrocarbon concentrations only seem to have a minor effect on the benthic communities of station 6. The presence of the estuary and the strong bottom current are responsible for the enrichment with organic matter and a rapid dispersal of potential contaminants.

The environment around the production fields is clearly influenced by the output of the “Ogoué” River. These outputs cause a permanent natural eutrophication of the local environment. In this context, the impact of cuttings disposal is limited and the rehabilitation of the site is facilitated and rapid. Indeed, the encountered fauna is typical for delta influenced area and is well adapted to frequent variations of the environment. Therefore, the recolonisation of the area is very efficient and decontamination will be completed more easily.

### **Foraminiferal analyses.**

Foraminifera are among the most abundant protists in marine benthic environments (*Murray, 1991*). Because of their short life cycles, high biodiversity and the specific ecological requirements of individual species, foraminifera react quickly to environmental disturbance, and can be efficiently employed as bio-indicators of environmental change, such as those brought about by anthropogenic pollution (*Kramer and Botterweg, 1991*). Foraminiferal assemblages are easy to collect; foraminifera are commonly abundant, providing a highly reliable database for statistical analysis, even when only small sample volumes are available. Furthermore, many foraminiferal taxa secrete a carbonate shell, and leave an excellent fossil record, that may be used to characterise baseline conditions, and to reconstruct the state of the ecosystem prior to sampling.

In our samples, the number of living benthic foraminifera is particularly significant in the 63-150  $\mu\text{m}$  fraction (reaching about 2400 individuals per 50 cc at station 7). The proliferation of small size-test organisms is generally thought to be a consequence of unstable and generally eutrophic environmental conditions (*Levinton, 1970; Pianka, 1970*). So called r-strategists allocate most of their energy budget to fast reproduction generating a rich offspring, contrary to K-strategists, that prevail in stable and generally oligotrophic environments, leading to a dominance of large-size forms with a slower reproduction rate. The presence of an important quantity of small-size individuals all along our sampling transects is indicative of a natural eutrophication, due to the input of important amounts of nutrients and continental organic matter by the large “Ogoué” River.

The dominant species found in the study area (Plate 1) are all known in the literature to

be opportunistic and/or tolerant to important eutrophic conditions:

- *Epistominella vitrea*: Previous studies carried out in various environments indicate that this species as well as the closely related species *Epistominella exigua*, are opportunist and respond quickly to significant input of labile organic phytodetritus causing an eutrophication of the benthic ecosystem (Barmawidjaja et al., 1992; Gooday and Rathburn, 1999).

- *Bolivina seminuda*: This species belongs to the benthic foraminiferal assemblage from the northern part of the Adriatic Sea that is strongly enriched in organic matter and is naturally eutrophicated (Barmawidjaja et al., 1992).

- *Rectuvigerina phlegeri*: This species proliferates in front of the Rhône delta, under dysoxic conditions typical for this continental shelf mud flat (Bizon and Bizon, 1985).

- *Cancris congolensis*: Studies, carried out on the continental shelf (about 40 m water depth) in front of the estuary of the Congo River, confirm the existence of a benthic foraminiferal biotope with a strong dominance of *Cancris congolensis*. This species that was first described by Kouyoumontzakis (1982) is distinguished from other species of the genus by the presence of a strongly inflated basal extension of the last chamber. This particular morphology could constitute an adaptation to the extreme physico-chemical conditions generated by the Congo River input, constituted of great quantities of fine-grained sediments rich in organic matter (Kouyoumontzakis, 1982).

The faunal composition is constant along the transects. The fact that the benthic environment is naturally eutrophicated (about 7 % of organic Carbon) suggests that the observed living foraminiferal fauna constitutes the natural background fauna, adapted to natural conditions of environmental stress. Nevertheless, the density shows a slight variability (Figs 7-10; 7-11), that could be indicative of an added ecological stress due to the disposal activities:

- Close to the disposal site (< 250 m), the fauna's density is very low. This could be the consequence of the drilling mud discharges that could accentuate the natural environmental dysoxic conditions by adding organic matter (hydrocarbons) to the benthic ecosystem.
- The increased densities observed at stations 4 and 7, could be indicative of the presence of eutrophicated conditions slightly further away, where the impact of local dysoxia is no longer perceptible.

Beyond these stations, no signs of environmental impact are perceptible. In conclusion, our foraminiferal analyses show that, 12 years after drilled cuttings discharge, the impact is very minor, or even completely absent. This suggests that currently, the toxicity of the bio-

available components of these hydrocarbons is minimal. Therefore, benthic foraminiferal faunas underline the absence of a long-term benthic ecosystem impact. In a similar environmental survey Off Congo (*Mojtahid et al., 2006*), 4 years after the cessation of drilling activities, the foraminiferal fauna clearly reflected the impact of drill mud disposal, until about 500 m from the disposal site. Using the density and the composition of the benthic foraminiferal fauna, we could distinguish a typical picture with strongly impoverished faunas close to the disposal site composed mainly of species resistant to oxygen depletion, surrounded by an aureole of high faunal density with important opportunistic species typical of eutrophicated environments that may be tolerant to the dysoxic conditions. Beyond, the fauna comes back gradually to natural assemblages.

## 7.7 CONCLUSION

- The methodology used in this study is suitable to differentiate sites in terms of environmental impact. It could find numerous applications with the frame work of monitoring programs.

- In the context of aged oil based drill cuttings, it was possible to demonstrate the absence of significant long-term alteration of the area. Although we observed slightly elevated amounts of hydrocarbons and a low remaining toxicity, the benthic macrofauna and foraminifera both demonstrated the homogeneity of the area in terms of benthic ecology. The fauna composition appears to be affected by the naturally eutrophic conditions of this area. Residual hydrocarbons in the sediment have lost most of their toxicity, but may still accentuate the natural eutrophication, without seriously modifying the ecosystem structure, or the taxonomic composition of the fauna. The combination of benthic communities' analysis (macrobenthos and foraminifera), toxicity results and hydrocarbon contents enabled us to distinguish three areas, very similar from an ecological point of view (Fig. 7-11):

- Between 0 and 70 m, the environmental impact is very low. In spite of the remaining hydrocarbons, the toxicity is limited and the fauna is indicative of slightly emphasized naturally eutrophicated conditions.
- Between 70 m and 250 m, an ecotonic area

- Beyond 250 m, no more impact is perceptible. The fauna is similar to baseline fauna and there is no toxicity.

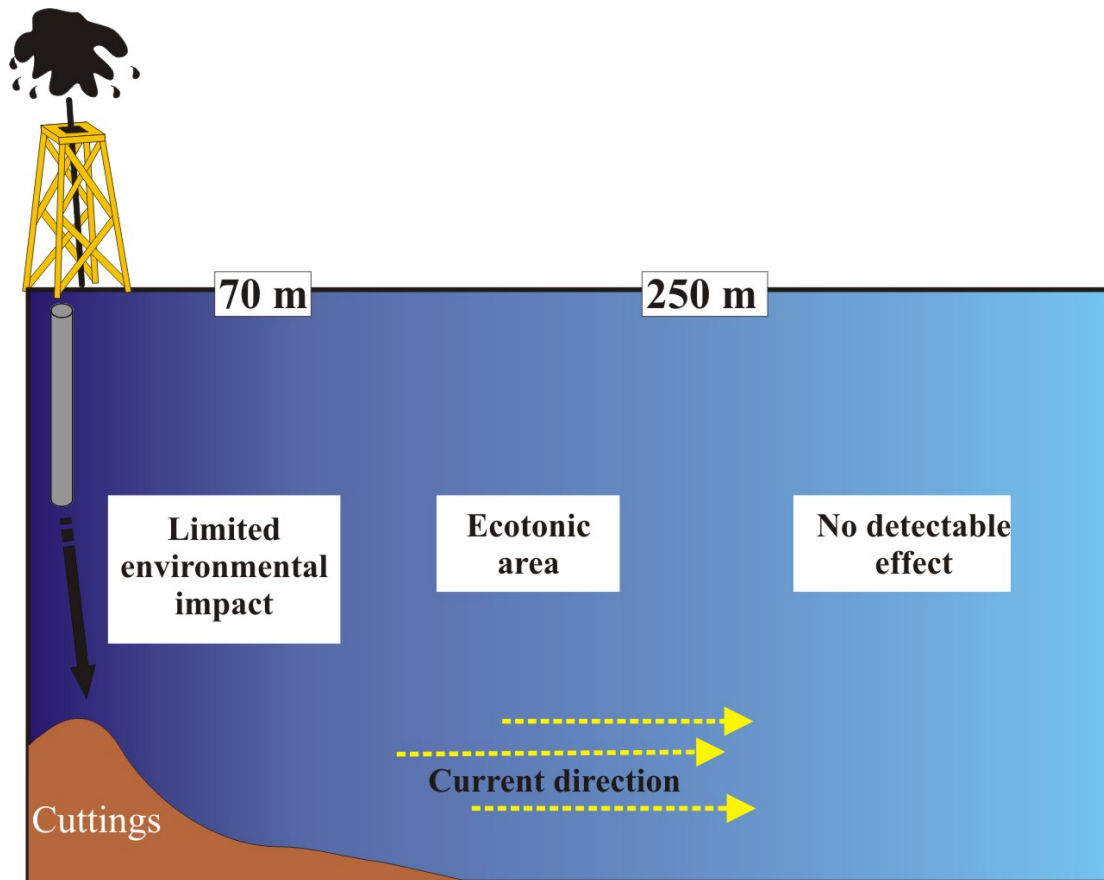


Figure 7-11. Overview of the area

- We conclude that the environmental impact is minimal at this site characterized by natural eutrophication due to significant input of nutrients and organic matter by the “Ogouué” River.

- Overall results clearly demonstrate the recovery over time of this disposal site of oil based drill cuttings in a naturally eutrophicated context.

- In terms of methodology, the multiparametric approach is very promising. The results of the different methods gave similar interpretation. They validate the different methodologies used in the context of aged cuttings impacts. This is one of the first applications of foraminifera in a E&P monitoring survey. This new approach has the following advantages:

- It can be performed on small sediment volumes
- It yields high numbers of individuals, increasing the significance of results
- The comparison of living and dead fauna gives valuable information about the temporal evolution of the ecosystem.

## 7.8 ACKNOWLEDGMENTS

This work was supported by TOTAL and TOTAL E&P NORGE AS. We thank TOTAL GABON (V. ROGANDJI and J. BIGNOUMBA) for logistical assistance. Melissa GAULTIER is sincerely thanked for her technical assistance.

## 7.9 REFERENCES

Barmawidjaja, D.M., Jorissen F. J., Puskaric, C. and Van Der Zwaan, G.J., 1992. Microhabitat selection by benthic foraminifera in the northern Adriatic sea. *Journal of Foraminiferal Research*, 22(4), 297-317.

Bizon G. et J.J. 1985. Distribution des foraminifères sur le plateau continental du Rhône. *ECOMED*. 84-94.

Blanchet, D., Camps, R., Dalmazzone, C., Dutrieux, E., Durrieu, J., His, E., le Minter, P., Senia, J., Galgani, F., 2002. Impact of Drilling Activities: Seabed Recolonization. A French Experiment. SPE paper 77471, SPE ATCE, San Antonio (Tx).

Dalmazzone, C. ; D. Blanchet, S. Lamoureux, J. Durrieu, R. Camps, F. Galgani, 2004. Impact of Drilling Activities in Warm Sea: Seabed Re-Colonization, SPE paper 90100 , Houston (Tx).

Durrieu, J., Bouzet, Ph., 2004. Seabed Recolonisation: N'Kossa Case, SPE paper 86710, SPE HSE in Oil and Gas Exploration and Production, Calgary (Canada).

Gooday, A. J. and A. E. Rathburn. 1999. "Temporal variability in living deep-sea foraminifera: a review." *Earth-Science Reviews*, 46, 187-212.

His E., Beiras R., Seaman M.N.L., 1999. The Assessment of Marine Pollution - Bioassays with Bivalve Embryos and Larvae. *Advances in Marine Biology*, 37, 1-178.

Kouyoumontzakis, G., 1982. Le biotope à Cancris congolensis aux abords de l'estuaire du fleuve Congo. *Océanographie tropicale*, 17 (2), 139-144.

Kramer, K.J. and Botterweg, J., 1991. Aquatic biological early warning systems: an overview. In: Jeffrey, D.W., Madden B. (eds) *Bioindicators and environmental management*. Academic press, London, 95-126.

Levinton, J.S., 1970. The paleoecological significance of opportunistic species. *Lethaia* 3: 69-78.

Mojtahid, M., Jorissen, F., Durrieu, J., Galgani, F., Howa, H., Redois, F., Camps, R. 2006. Benthic foraminifera as bio-indicators of drill cutting disposal in tropical east Atlantic outer shelf environments. *Marine Micropaleontology*, 61, 58-75.

Mouganga, M.D., 1999. Les systèmes flèches-lagunes du littoral gabonais. Rapport partiel de terrain, activités 1998, Laboratoire GEOLITTOMER-BREST, Institut Universitaire Européen de la mer, Université de Bretagne occidentale, Brest : 30 pp.

Murray, J.W., 1991. Ecology and distribution. BENTHOS'90, Sendai, Tokai University Press.

OGP, 2003. Environmental aspects of the use and disposal of non aqueous drilling fluids associated with offshore oil and gas operations, Report n° 342.

OSPAR, 1995. Part A: A sediment bioassay using an amphipod *Corophium* sp., in PARCOM protocols on methods for the testing of chemicals used in the offshore industry.

Pianka, E. R., 1970. On r and K selection. *American Naturalist* 104: 592-597. (Reprinted in 1978 in T. H. Clutton-Brock and P. H. Harvey (eds.) *Readings in Sociobiology*. Freeman. Selected as "This Week's Citation Classic" in *Current Contents*, volume 10 (number 47): page 10.

UKOOA, 2001. Drill cuttings Initiative Final report, December 2001, 57 pp.

Walton, W.R., 1952. Techniques for recognition of living foraminifera. *Contr. Cushman Foundation Foraminiferal Research* 3 (2), 56-64.

Word, J.Q., 1990. The infaunal trophic index, a functional approach to benthic community analyses, PhD Thesis, University of Washington, 297 pp.

**Appendix 7-1.** Living foraminifera (>150 µm fraction, non-standardized taxa).

STATIONS	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina</i> spp.	0	0	0	0	0	0	1	0	0	0	0
<i>Cancris congolensis</i>	22	0	21	30	10	10	22	0	10	0	12
<i>Cibicides lobatulus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Hanzawaia boueana</i>	1	0	1	5	0	0	4	1	1	0	0
<i>Karrerriella</i> sp.	0	0	0	0	0	0	0	0	0	0	0
<i>Lagenammina</i> sp.	5	0	5	14	5	1	20	7	8	0	12
<i>Nonion scaphum</i>	0	0	0	0	0	2	0	0	0	0	0
<i>Quinqueloculina lamarckiana</i>	0	0	0	0	0	0	0	1	3	0	0
<b>Total</b>	<b>28</b>	<b>0</b>	<b>27</b>	<b>49</b>	<b>15</b>	<b>13</b>	<b>47</b>	<b>9</b>	<b>22</b>	<b>0</b>	<b>24</b>

*Appendix 7-1a . Number of living individuals of benthic foraminifera (> 150 µm fraction) found in level A (0-0.5 cm).*

STATIONS	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina</i> spp.	0	0	1	0	0	0	0	0	0	0	1
<i>Cancris congolensis</i>	9	0	7	7	9	3	7	0	0	0	3
<i>Cibicides lobatulus</i>	0	0	0	1	0	0	0	0	0	0	0
<i>Hanzawaia boueana</i>	4	0	0	0	0	0	1	0	0	0	1
<i>Karrerriella</i> sp.	0	0	0	1	0	0	0	0	0	0	0
<i>Lagenammina</i> sp.	1	0	2	1	3	1	5	2	0	0	4
<i>Nonion scaphum</i>	0	0	0	1	0	0	0	0	0	0	0
<i>Quinqueloculina lamarckiana</i>	0	0	0	0	0	0	2	1	2	0	0
<b>Total</b>	<b>14</b>	<b>0</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>4</b>	<b>15</b>	<b>3</b>	<b>2</b>	<b>0</b>	<b>9</b>

*Appendix 7-1b . Number of living individuals of benthic foraminifera (> 150 µm fraction) found in level B (0.5-1 cm).*

STATIONS	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina</i> spp.	0	0	0	0	0	0	0	0	0	0	0
<i>Cancris congolensis</i>	1	0	2	1	2	0	0	0	0	0	0
<i>Cibicides lobatulus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Hanzawaia boueana</i>	1	0	2	0	0	0	0	0	0	0	0
<i>Karrerriella</i> sp.	0	0	0	0	0	0	0	0	0	0	0
<i>Lagenammina</i> sp.	0	0	0	0	0	0	0	0	0	0	0
<i>Nonion scaphum</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Quinqueloculina lamarckiana</i>	0	0	0	0	0	0	0	0	0	0	0
<b>Total</b>	<b>2</b>	<b>0</b>	<b>4</b>	<b>1</b>	<b>2</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>

*Appendix 7-1c . Number of living individuals of benthic foraminifera (> 150 µm fraction) found in level c (1-2 cm).*

STATIONS	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina</i> spp.	0	0	0	0	0	0	0	0	0	0	0
<i>Cancris congolensis</i>	5	0	6	4	0	0	2	0	0	0	0
<i>Cibicides lobatulus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Hanzawaia boueana</i>	0	0	1	0	0	0	0	0	0	0	0
<i>Karrerriella</i> sp.	0	0	0	0	0	0	0	0	0	0	0
<i>Lagenammina</i> sp.	0	0	0	0	0	0	0	0	0	0	0
<i>Nonion scaphum</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Quinqueloculina lamarckiana</i>	0	0	0	0	0	0	0	0	0	0	0
<b>Total</b>	<b>5</b>	<b>0</b>	<b>7</b>	<b>4</b>	<b>0</b>	<b>0</b>	<b>2</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>

*Appendix 7-1d . Number of living individuals of benthic foraminifera (> 150 µm fraction) found in level D (2-3cm).*

## Aged drilled cuttings offshore Gabon

STATIONS	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina</i> spp.	0	0	1	0	0	0	1	0	0	0	1
<i>Cancris congolensis</i>	37	0	36	42	21	13	31	0	10	0	15
<i>Cibicides lobatulus</i>	0	0	0	1	0	0	0	0	0	0	0
<i>Hanzawaia boueana</i>	6	0	4	5	0	0	5	1	1	0	1
<i>Karrerriella</i> sp.	0	0	0	1	0	0	0	0	0	0	0
<i>Lagenammina</i> sp.	6	0	7	15	8	2	25	9	8	0	16
<i>Nonion scaphum</i>	0	0	0	1	0	2	0	0	0	0	0
<i>Quinqueloculina lamarckiana</i>	0	0	0	0	0	0	2	2	5	0	0
<b>Total</b>	<b>49</b>	<b>0</b>	<b>48</b>	<b>65</b>	<b>29</b>	<b>17</b>	<b>64</b>	<b>12</b>	<b>24</b>	<b>0</b>	<b>33</b>

Appendix 7-1e . Number of living individuals of benthic foraminifera (> 150  $\mu\text{m}$  fraction) found in the first 3 cm of the sediment (A+B+C+D).



## Appendix 7-2. Living foraminifera (63-150 µm fraction, non-standardized taxa).

	Splits (A)	1	1	2	2	1	1	4	1	1	1	1
	Stations	1	2	3	4	5	6	7	8	9	12	11
<i>Ammonia tepida</i>		2					2	1		1		
<i>Ammonia</i> sp.								1				
<i>Bolivina dilatata</i>					1						1	
<i>Bolivina</i> spp.		1										
<i>Bolivina seminuda</i>		140	0	69	68	35	37	91	57	39	15	31
<i>Cancris congolensis</i>		18	1	6	14	1	1	2	3	5	0	0
<i>Discammina compressa</i>		2										
<i>Epistominella vitrea</i>		93	5	91	97	114	114	86	86	151	17	76
<i>Fursenkoïna</i> sp.		4		1	2	2	2	1		3	1	1
<i>Gyroidina umbonata</i>										1		
<i>Hanzawaia boueana</i>				2	4	1						
<i>Hopkinsina pacifica</i>										1		
<i>Quinqueloculina aspera</i>					2			1			1	
<i>lagen</i> sp.									1			
<i>Lagenammina</i> sp.		1		1	3		1	3	5	3	1	1
<i>Melonis barleanus</i>								1				
<i>Nonionella turgida</i>		2		1	2	1	9	5	1		2	2
<i>Nonion depressulum</i>				1								
<i>Nonion scaphum</i>		4		5	2					2		
<i>Nouria polymorphinoïdes</i>				2								
<i>Rectuvigerina phlegeri</i>		37	0	23	14	9	0	14	6	2	0	4
<i>Rosalina</i> sp.										2		
<i>Stainfortia fusiformis</i>				2				4	5			
<i>Trifarina pauperata</i>								1				
<i>Valvulineria</i> sp.				7								1
<b>Total censé (B)</b>		<b>304</b>	<b>6</b>	<b>211</b>	<b>209</b>	<b>163</b>	<b>166</b>	<b>211</b>	<b>164</b>	<b>210</b>	<b>38</b>	<b>116</b>
<b>Total estimé= A*B</b>		<b>304</b>	<b>6</b>	<b>422</b>	<b>418</b>	<b>163</b>	<b>664</b>	<b>844</b>	<b>164</b>	<b>210</b>	<b>38</b>	<b>116</b>

## Appendix 7-2a . Number of living individuals of benthic foraminifera (63-150 µm fraction) found at level A (0-0.5 cm).

	Stations	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina</i> spp.		6		1				4				1
<i>Bolivina seminuda</i>		201	1	31	26	44	17	86	7	9	1	15
<i>Cancris congolensis</i>		10		3	10	2	6	6		1		1
<i>Cibicides lobatulus</i>					1							
<i>Discammina compressa</i>		2										
<i>Epistominella vitrea</i>		89	2	83	97	128	36	130	23	28	14	41
<i>Fursenkoïna</i> sp.		4		1	3			1			1	1
<i>Gyroidina umbonata</i>												
<i>Hanzawaia boueana</i>		4		2	1	2	1	1	1			1
<i>Hopkinsina pacifica</i>												
<i>Quinqueloculina aspera</i>					1			2	1	2		
<i>Karrerriella</i> sp.					1							
<i>lagen</i> sp.		2		1		3	2					
<i>Lagenammina</i> sp.		1		2	1	3	1	5	2	0		1
<i>Melonis barleanus</i>					1							
<i>Nonionella turgida</i>		6		3	2	2	4				2	
<i>Nonion depressulum</i>												
<i>Nonion scaphum</i>					1							4
<i>Nouria polymorphinoïdes</i>		6		2	1			6				
<i>Rectuvigerina phlegeri</i>		28		4	9	16	2	24	3	2	1	1
<i>Rosalina</i> sp.		1										
<i>Stainfortia fusiformis</i>		2		2								
<i>Paratrochamina</i> sp.												
<i>Pullenia</i> sp.		4										
<i>Trifarina pauperata</i>		8		5	6	2	1	4				1
<i>Valvulineria</i> sp.					2							
<b>Total censé</b>		<b>374</b>	<b>3</b>	<b>140</b>	<b>163</b>	<b>202</b>	<b>70</b>	<b>269</b>	<b>37</b>	<b>42</b>	<b>19</b>	<b>67</b>

## Appendix 7-2b . Number of living individuals of benthic foraminifera (63-150 µm fraction) found at level B (0.5-1 cm).

## Aged drilled cuttings offshore Gabon

Stations	1	2	3	4	5	6	7	8	9	12	11
<i>Bolivina seminuda</i>	7		7	5	6	3	24	3	7	1	3
<i>Cancris congolensis</i>	3	1	8	3		2			1	9	
<i>Discammina compressa</i>											1
<i>Epistominella vitrea</i>	79	2	56	45	43	9	49	17	33	7	25
<i>Fursenkoïna sp.</i>	2		1				2				1
<i>Hanzawaia boueana</i>	2	1									
<i>Quinqueloculina aspera</i>	1				2					1	
<i>Lagenamina sp.</i>			1				1				
<i>Melonis barleanus</i>	1										
<i>Nonionella turgida</i>	2				1		2				
<i>Nonion scaphum</i>							1				
<i>Nouria polymorphinoïdes</i>	1										
<i>Rectuvigerina phlegeri</i>	5		8	2	3	2	3				1
<i>Stainfortia fusiformis</i>											1
<i>Trifarina pauperata</i>			1	2	1		2				
<i>Uvigerina sp.</i>	1										
<b>Total censé</b>	<b>104</b>	<b>4</b>	<b>82</b>	<b>57</b>	<b>56</b>	<b>16</b>	<b>84</b>	<b>20</b>	<b>41</b>	<b>18</b>	<b>32</b>

Appendix 7-2c . Number of living individuals of benthic foraminifera (63-150 µm fraction) found at level C (1-2 cm).

Stations	1	2	3	4	5	6	7	8	9	12	11
<i>Ammonia tepida</i>	2					2	4		1		
<i>Ammonia sp.</i>							4				
<i>Bolivina dilatata</i>				2						1	
<i>Bolivina spp.</i>	7		1				4				1
<i>Bolivina seminuda</i>	348	1	176	167	85	57	474	67	55	17	49
<i>Cancris congolensis</i>	31	2	23	41	3	9	14	3	7	9	1
<i>Cibicides lobatulus</i>				1							
<i>Discammina compressa</i>	4										1
<i>Epistominella vitrea</i>	261	9	321	336	285	159	523	126	212	38	142
<i>Fursenkoïna sp.</i>	10		4	7	2	2	7		3	2	3
<i>Gyroidina umbonata</i>									1		
<i>Hanzawaia boueana</i>	6	1	6	9	3	1	1	1			1
<i>Hopkinsina pacifica</i>									1		
<i>Quinqueloculina aspera</i>	1			5	2		6	1	2	2	
<i>Karrerriella sp.</i>				1							
<i>lagen sp.</i>	2		1		3	2		1			
<i>Lagenamina sp.</i>	2		5	7	3	2	18	7	3	1	2
<i>Melonis barleanus</i>	1			1			4				
<i>Nonionella turgida</i>	10		5	6	4	13	22	1		4	2
<i>Nonion depressulum</i>			2								
<i>Nonion scaphum</i>	4		10	5			1		2		4
<i>Nouria polymorphinoïdes</i>	7		6	1			6				
<i>Rectuvigerina phlegeri</i>	70		58	39	28	4	83	9	4	1	6
<i>Rosalina sp.</i>	1								2		
<i>Stainfortia fusiformis</i>	2		6				16	5			1
<i>Pullenia sp.</i>	4										
<i>Trifarina pauperata</i>	8		6	8	3	1	10				1
<i>Uvigerina sp.</i>	1										
<i>Valvulineria sp.</i>			14	2							1
<b>Total</b>	<b>782</b>	<b>13</b>	<b>644</b>	<b>638</b>	<b>421</b>	<b>252</b>	<b>1197</b>	<b>221</b>	<b>293</b>	<b>75</b>	<b>215</b>

Appendix 7-2d. Number of living individuals of benthic foraminifera (63-150 µm fraction) found in the first 2 cm of the sediment (A+B+C).



## **SYNTHÈSE ET PERSPECTIVES**



## SYNTHÈSE ET PERSPECTIVES

### Rappels des objectifs de la thèse

L'intérêt général de cette étude concerne l'utilisation des foraminifères benthiques comme bio-indicateurs d'eutrophisation provenant d'une source anthropique ou naturelle. Dans ce contexte, les objectifs de cette thèse peuvent être énumérés comme suit :

1. Étudier la répartition spatiale des foraminifères benthiques dans des zones affectées par une eutrophisation naturelle, plus particulièrement dans les écosystèmes de plateau continentale sous l'influence d'une décharge fluviale.

2. Comparer la réponse des foraminifères benthiques obtenue à la suite d'une eutrophisation naturelle à celle qu'ils développent dans des régions affectées par une pollution organique de source anthropique (rejets de boues de forages pétroliers, rejets de boues d'épuration).

3. Suivre l'évolution de la faune des foraminifères benthiques vivants le long d'un gradient d'enrichissement organique croissant, accompagnée ou non d'un appauvrissement en oxygène de l'écosystème benthique.

4. Examiner les paramètres physicochimiques (oxygène, matière organique, pH, salinité, température, turbidité, hydrodynamisme...) qui puissent être responsables de cette réponse faunistique.

5. Utiliser la thanatocénose des foraminifères benthiques afin d'en extraire des renseignements écologiques qui permettront d'affiner notre compréhension de la réponse de la faune aux phénomènes d'eutrophisation.

6. Comparer la réponse des foraminifères à une pollution organique à celle de la macrofaune benthique.

Ces questions ont été abordées à l'aide d'études multiparamétriques incluant des mesures physicochimiques du sédiment, des analyses faunistiques ainsi que des analyses statistiques.

### **Synthèse des résultats des différentes zones d'étude**

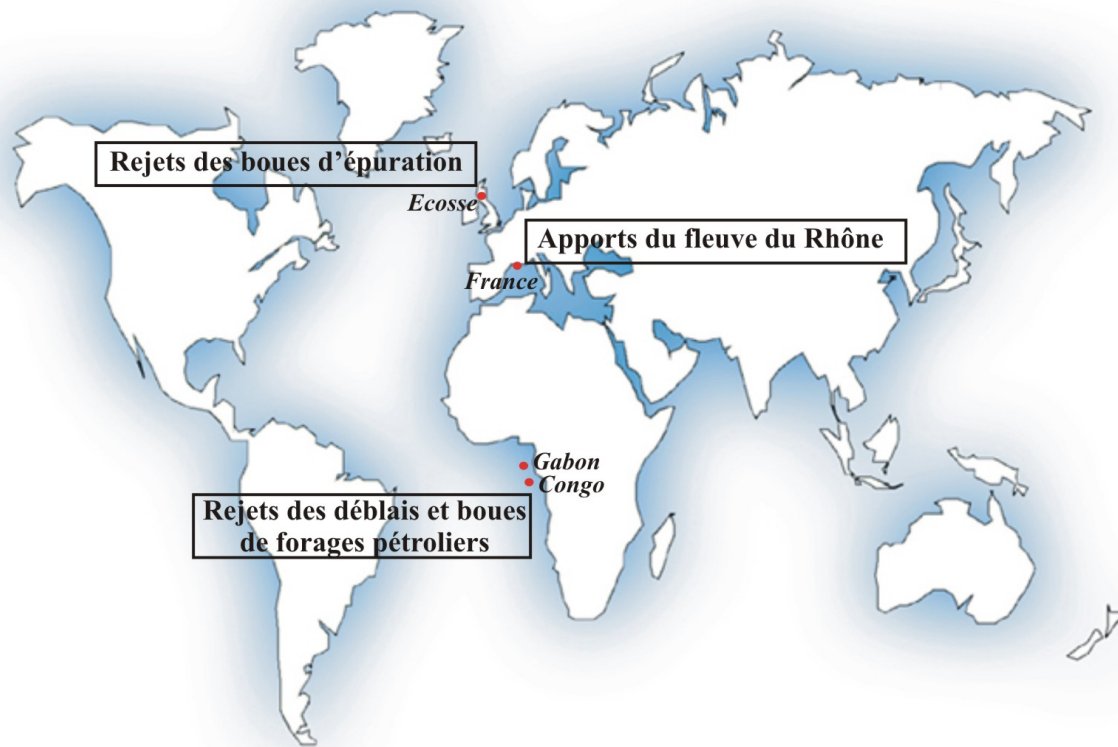


Figure s-1. Carte de localisation des zones d'étude

### **Exemple d'eutrophisation naturelle : Le prodelta du Rhône (France)**

#### Distribution spatiale des foraminifères benthiques vivants (Fig. s-2)

Dans le prodelta du Rhône, le sédiment est riche en carbone organique (0.8-1.9 %) et la pénétration d'oxygène dans le sédiment est très limitée (1-8 mm seulement). Par conséquent, la faune de foraminifères benthiques est composée d'espèces typiques des environnements eutrophiés et des conditions d'hypoxie. En dépit de ce schéma général, il a été possible de faire une subdivision des faunes en 4 assemblages représentant 4 différents biofaciès qui reflètent l'étendue de l'impact des apports du fleuve. L'influence du fleuve sur la faune est la composante d'un complexe de plusieurs paramètres environnementaux, tels que la salinité, la turbidité, l'apport et la qualité de la matière organique ainsi que la pénétration de l'oxygène dans le sédiment. Puisque ces paramètres ont en majorité tendance à covarier, il est extrêmement difficile, voire impossible, d'identifier des facteurs individualisés responsables de la réponse des foraminifères. Il est d'ailleurs probable que la réponse faunistique constitue

une réaction à l'ensemble de ces paramètres. Dans le cas du prodelta du Rhône, les paramètres les plus évidents qui changent en fonction des apports du fleuve sont la quantité et la qualité de la matière organique. À proximité de l'embouchure du fleuve, d'importantes quantités de carbone organique principalement d'origine continentale sont présentes. En s'éloignant de l'embouchure, la quantité de carbone organique arrivant sur le fond marin diminue légèrement et la signature de cette matière organique devient progressivement plus marine et moins continentale.

Les analyses statistiques (PCA = Principal Component Analysis et Analyse cluster) ont permis de classer les faunes selon un gradient décroissant de l'influence fluviale, des stations les plus proches aux stations les plus éloignées de l'embouchure du Rhône. Une faune de faibles densité et biodiversité est observée à proximité immédiate de l'embouchure du fleuve. Cette faune est composée essentiellement d'espèces tolérantes aux conditions de stress présentes dans cette zone. Dans une direction sud-ouest, suivant le principal couloir sous l'influence du panache du fleuve (pendant l'échantillonnage en Juin 2005), la faune est composée essentiellement d'espèces à comportement opportuniste. De très fortes densités de ces espèces sont observées aux extrémités de cette zone. En se dirigeant vers l'Est et vers les stations les plus profondes, la biodiversité augmente. Au niveau de ces stations, les faunes sont caractérisées par des densités intermédiaires et comportent des espèces typiques de la partie externe de la zone d'enrichissement organique (Fig. s-2).

À proximité de l'embouchure du fleuve et dans la direction sud-ouest suivant le panache du fleuve, les conditions environnementales semblent être stressantes pour la faune de foraminifères benthiques. En effet, à proximité de l'embouchure du Rhône, le stress environnemental pourrait être dû à la faible salinité, à la forte turbidité, à la faible pénétration d'oxygène dans le sédiment où encore à la composition de la matière organique, avec une signature continentale très marquée, et donc probablement peu labile. Les taxons *Adelosina longirostra*, *Fursenkoina fusiformis*, *Reophax scottii*, *Bulimina aculeata*, *Quinqueloculina seminula* f. *longa*, *Elphidium macellum* et *Ammonia beccarii* f. *inflata* sont les plus résistants à ce stress. Au niveau des stations sud-ouest du delta, influencées par le panache du fleuve, le fort apport organique d'origine principalement terrestre (plus réfractaire) est le facteur stressant le plus probable pour plusieurs espèces ayant besoin d'une matière organique de qualité essentiellement labile. Dans cette zone, *Nonion scaphum*, *Nonionella turgida* et *Rectuvigerina phlegeri* sont présentes avec des densités relativement faibles par rapport au fort apport en carbone organique. À la périphérie de cette zone, où la quantité de carbone organique demeure toujours aussi importante, le mélange de la matière organique continentale



et marine pourrait devenir plus favorable à la prolifération de *Nonion scaphum*, *Nonionella turgida* et *Rectuvigerina phlegeri* qui montrent des densités élevées, témoignant ici d'un comportement fortement opportuniste. Dans les stations à l'abri d'une forte influence fluviale (stations profondes et la zone Est de l'embouchure), le stress environnemental semble être moins important et le développement de la faune semble être favorisé par une matière organique plus labile. *Cassidulina carinata*, *Epistominella vitrea*, *Nonionella iridea/bradyi*, *Valvulineria bradyana*, *Bolivina spathulata/dilatata*, *Textularia porrecta/agglutinans*, *Recurvoides trochaminiformis* et *Adercotryma glomeratum* sont les espèces les plus adaptées à ces conditions (Fig. s-2).

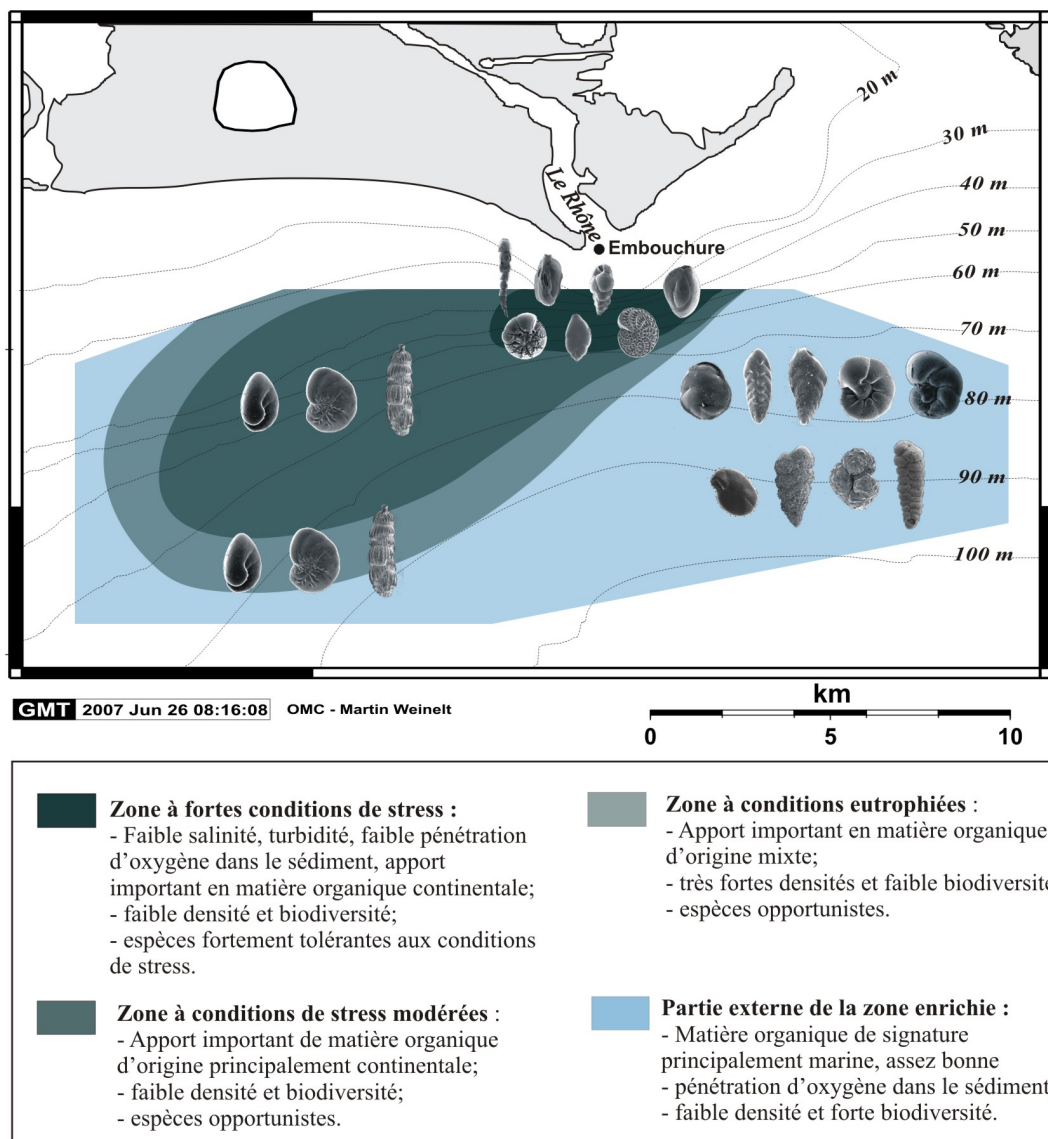


Figure s-2. Carte représentative des successions faunistiques des foraminifères benthiques vivants dans le prodelta du Rhône.

Pour résumer, la répartition spatiale des foraminifères benthiques présente un schéma typique des zones de plateforme continentale sous l'influence d'apports fluviaux, engendrant une eutrophisation du milieu (comme décrit par *Van der Zwaan et Jorissen, 1991*). À l'embouchure, les faunes sont fortement appauvries et sont composées exclusivement d'espèces tolérantes aux différents facteurs de stress environnemental culminant à cet endroit. La zone sous l'influence du panache du fleuve apparaît toujours quelque peu stressée, les faunes y sont toujours présentes avec de faibles densités. Ce secteur est entouré d'une auréole faunistique présentant une forte densité et est dominée par les mêmes espèces opportunistes. Cette faune change graduellement vers une dominance d'une faune composée d'espèces moins opportunistes à la partie externe de la zone d'enrichissement organique avec de plus faibles densités et une forte biodiversité.

#### *Microhabitat des foraminifères benthiques vivants dans le prodelta du Rhône*

Les stations sous l'influence directe des apports du Rhône sont riches en espèces « potentiellement/préférentiellement endopéliques ». Une dominance des espèces endopéliques est un phénomène commun dans les environnements à forte productivité et/ou à faible teneur en oxygène (*Sen Gupta and Machain-Castillo, 1993*). La forte dominance des espèces « potentiellement/préférentiellement endopéliques » dans les stations directement influencées par les apports du fleuve pourrait être expliquée par deux phénomènes : (1) une faible teneur en oxygène à la surface du sédiment, non tolérée par des espèces que l'on trouve usuellement dans les niches à l'interface eau-sédiment et/ou (2) une matière organique faiblement métabolisable ; à cause de leur habitat habituel à l'intérieur du sédiment, les espèces endopéliques sont plus tolérantes à une matière organique de faible qualité que les espèces vivant à l'interface eau-sédiment.

Dans notre zone d'étude, où la concentration en oxygène à l'interface eau-sédiment est relativement élevée au niveau de toutes les stations (210-260  $\mu\text{mol/l}$ ), cette dominance d'espèces endopéliques ne peut pas être expliquée par une disparition des taxons superficiels à cause d'une faible teneur en oxygène. Le fait que toutes les espèces « préférentiellement superficielles » apparaissent aussi systématiquement dans le sédiment anoxique trouvé au delà du premier demi-centimètre du sédiment, suggère fortement que la concentration en oxygène n'explique pas leur préférence pour la surface. Nous proposons donc que la séparation entre les faunes superficielles et potentiellement/préférentiellement endopéliques soit principalement déterminée par leur différente tolérance en ce qui concerne la qualité de la

matière organique. Au niveau des stations directement exposées aux apports du fleuve, le carbone organique terrestre de qualité généralement plus réfractaire domine, tandis que la matière organique marine labile est relativement rare. Par conséquent, les faunes endopéliques, ayant une tolérance plus élevée à cette nourriture de moins bonne qualité, dominant fortement l'assemblage. Aux stations les moins influencées par les apports du Rhône, les espèces préférant la surface du sédiment sont largement dominantes. Nous suggérons que les fortes densités de ces faunes soient une réponse à une meilleure qualité de la matière organique labile d'origine marine ; cette dernière est dominante dans les parties distales du prodelta et dans celles à l'abri du panache du fleuve. Cependant, à ces stations plus distales, la minéralisation bactérienne du carbone organique de mauvaise qualité en profondeur dans le sédiment, qui est un processus relativement lent, continue à fournir la nourriture aux faunes endopéliques moins fréquentes, et retrouvées plus profondément dans le sédiment.

*Comparaison entre la faune morte et vivante des foraminifères benthiques du prodelta du Rhône*

La comparaison entre la faune vivante et la faune morte, trouvée à environ 4 cm de profondeur dans le sédiment, a permis de voir que cette approche est non seulement importante pour améliorer le potentiel de reconstitution d'un paléo-environnement sur la base des faunes de foraminifères benthiques mais peut également fournir d'importantes informations écologiques. Dans le prodelta de Rhône, les assemblages faunistiques sont bien préservés et ne semblent pas souffrir d'une perte taphonomique importante.

Notre étude a prouvé que les apports fluviaux ont un fort impact sur les faunes des foraminifères benthiques. Dans ce contexte, la distribution des foraminifères benthiques aussi bien morts que vivants décrit trois principales zones. (Le biofaciès à l'Est de l'embouchure et celui regroupant les stations profondes, déterminés par les faunes vivantes, ont été décrits comme une seule zone représentant la partie à l'abri des apports du fleuve) : le premier assemblage des foraminifères morts (*Ammonia beccarii* f. *inflata*, *Elphidium advenum*, *Nonionella turgida*, *Quinqueloculina seminula* f. *longa* et *Adelosina longirostra*) et son équivalent dans les faunes vivantes (*Ammonia beccarii* f. *inflata*, *Elphidium macellum*, *Nonionella turgida* et *Quinqueloculina seminula* f. *longa*) dominant l'écosystème benthique en face de l'embouchure du Rhône. Ces espèces semblent tolérer la superposition de plusieurs facteurs stressants présents dans cette zone. Le second assemblage de foraminifères morts

(*Nonion scaphum*, *Pseudoepionides falsobeccarii*, *Rectuvigerina phlegeri*, *Valvulineria bradyana*, *Pyrgo elongata* et *Eggerella scabra*) et l'assemblage équivalent dans les faunes vivantes (*Nonion scaphum* et *Rectuvigerina phlegeri*) dominent les écosystèmes benthiques situés sous le panache du fleuve. Cette faune semble répondre au fort apport organique d'une signature principalement continentale qui est probablement le principal facteur de stress dans cette zone. Le troisième assemblage de foraminifères morts (*Bulimina aculeata*, *Bulimina marginata*, *Cassidulina carinata* et *Hyalinea balthica*) et les 2 assemblages vivants se trouvant dans les stations profondes (*Bulimina aculeata*, *Cassidulina carinata*, *Melonis barleaanus*, *Recurvoides trochaminiformis*) et dans la partie Est du prodelta (*Adercotryma glomeratum*, *Eratidus foliaceus* et *Textularia agglutinans*) dominent principalement les stations se trouvant à l'abri de l'influence du Rhône. Dans cette partie du prodelta, le stress environnemental semble être moins important (forte biodiversité) et les faunes répondent principalement à l'apport dans le milieu de matière organique avec une signature plus marine, probablement de meilleure qualité.

L'étude des assemblages de foraminifères morts, nous renseignant approximativement sur la dernière décennie, suggère que, moyenné sur une telle période, le panache prend une direction vers l'ouest à sa sortie du fleuve. Cette image ne correspond pas à la répartition faunistique vivante au moment de l'échantillonnage, qui semble plutôt répondre à une direction de propagation vers le sud-ouest. De plus, les foraminifères vivants nous renseignent sur une plus importante expansion du panache du Rhône dans les mois avant l'échantillonnage. Ces différences entre la situation enregistrée par la faune vivante (échantillonnée en juin 2005, environ deux mois après un fort débit du fleuve) et la faune morte (enregistrant les conditions moyennées) suggèrent donc que les apports fluviaux sont préférentiellement transportés vers l'ouest, à l'exception des périodes (surtout printanières) connaissant un fort débit et pendant lesquelles le panache se propage dans une direction préférentiellement sud-ouest. Ces spéculations restent à confirmer par une étude de photos satellitaires pendant plusieurs périodes de l'année. La comparaison entre la faune morte et la faune vivante a permis également de confirmer le comportement opportuniste des espèces *Nonion scaphum* et *Rectuvigerina phlegeri* qui sont beaucoup plus abondantes dans la faune vivante que dans la faune morte. Ce décalage ne peut que s'expliquer par une forte reproduction dans les mois après un haut débit du fleuve. Ces espèces montrent donc une forte réponse aux apports importants du fleuve au printemps.

**Exemple d'eutrophisation d'origine anthropique : Firth of Clyde (Écosse)**

Dans cette étude, nous avons employé une nouvelle approche écologique en comparant la réponse des foraminifères benthiques à celle de la macrofaune benthique dans le but d'étudier l'impact de la décharge des boues d'épuration dans le Firth of Clyde (Écosse). La comparaison entre ces deux groupes faunistiques, appuyée par des analyses physico-chimiques du sédiment et des eaux de fond, a permis de se prononcer sur l'état de santé de l'environnement marin benthique environnant. Aussi, cette approche nous a permis de juger de l'applicabilité des foraminifères benthiques en tant que bio-indicateurs d'une perturbation environnementale au même degré que le macrobenthos ; ce dernier étant le groupe faunistique le plus utilisé pour ce type de suivi environnemental.

Le contenu sédimentaire en carbone organique (> 10 %) et en azote (> 1 %) est très élevé à proximité du lieu de dépôt et diminue progressivement en s'en éloignant. Les faibles valeurs du potentiel redox à proximité de la décharge, à la surface du sédiment ainsi que dans le sédiment le plus superficiel, sont indicatives de conditions fortement réductrices provoquées par la dégradation de grandes quantités de matériel organique. De plus, la concentration en métaux est très élevée à proximité du lieu de déversement des eaux usées et le pH y est également minimal (7.2).

Dans l'ensemble, l'analyse faunistique a montré une succession écologique assez comparable pour les deux groupes de bio-marqueurs étudiés (macrofaune et foraminifères). Cette succession faunistique est typique des environnements fortement eutrophiés (Fig. s-3). En combinant les réponses des deux groupes faunistiques, une succession commune se dégage, du site le plus impacté vers la zone la plus éloignée du site de déversement :

1) une zone à proximité des dépôts qui connaît des conditions de stress sévères et où les densités et la biodiversité sont très faibles. La faune dans cette zone contient seulement quelques espèces qui sont tolérantes à de faibles concentrations en oxygène.

2) une deuxième zone comprend une faune typique des conditions enrichies, caractérisée par une densité élevée et une forte dominance d'un nombre limité d'espèces opportunistes.

3) une troisième zone semble décrire une situation transitoire, où l'impact environnemental est minimal, mais encore perceptible. Les densités sont encore élevées et la composition faunistique est caractérisée par un pourcentage légèrement élevé d'espèces opportunistes en comparaison avec la station de référence. Ces espèces opportunistes sont accompagnées d'espèces typiques des environnements non impactés.

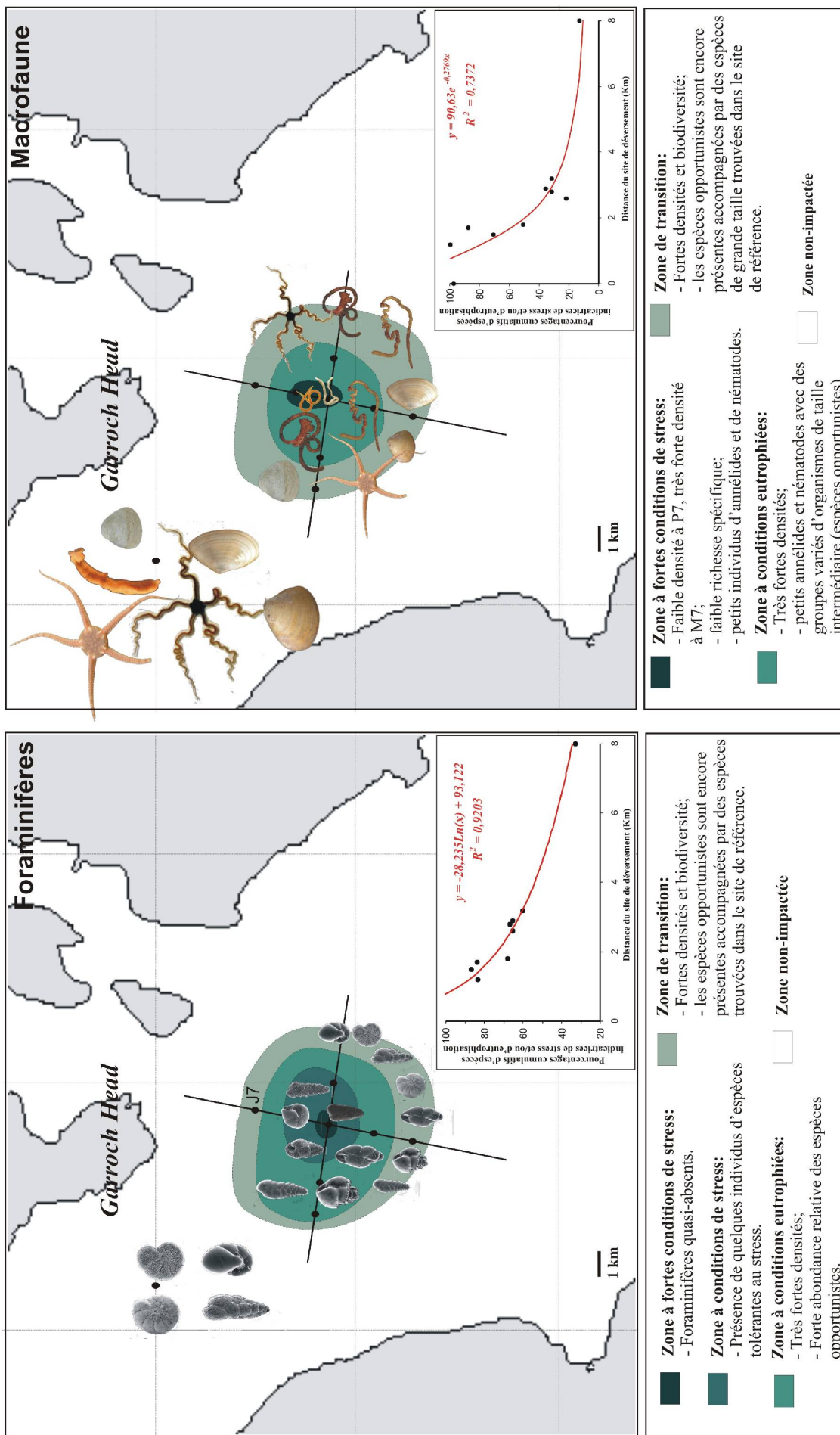


Figure s-3. Cartes représentatives des successions faunistiques des foraminifères benthiques et de la macrofaune vivants suivant un gradient décroissant d'enrichissement organique ainsi que les pourcentages cumulatifs des espèces bio-marqueurs de stress ou d'eutrophisation en fonction de la distance du site de décharge

Une comparaison plus détaillée entre les réponses des deux groupes de bio-indicateurs montre quelques différences importantes suggérant principalement que les foraminifères soient plus sensibles que la macrofaune à ce type spécifique de perturbation environnementale. En effet, l'impact environnemental demeure perceptible dans les faunes de foraminifères à des sites plus éloignés (3 km), avec un niveau d'enrichissement organique relativement bas. À cette distance, la macrofaune n'est apparemment plus (ou beaucoup moins) affectée. Également, au centre du site de déversement, la macrofaune est présente alors que les foraminifères sont quasi-absents. Ceci est d'autant plus étonnant que certaines espèces de foraminifères sont très tolérantes à l'anoxie (et/ou aux sulfures) (*Moodley et al., 1997; Ernst et al., 2005, Risgaard-Petersen et al., 2006*). D'où notre suggestion que cette zone azoïque est peut être due aux faibles teneurs de pH qui semblent particulièrement affecter des espèces dotées de tests calcaires. Ces espèces sont, dans d'autres zones, les plus résistantes aux conditions hypoxiques. Ces espèces à tests calcaires pourraient avoir des difficultés à calcifier dans les environnements sédimentaires acides présents autour du lieu de dépôt. Cette plus forte sensibilité fait des foraminifères un outil particulièrement efficace pour ce type de suivi environnemental.

#### **Exemple d'eutrophisation d'origine anthropique : le site pétrolier N'Kossa (Congo)**

Dans cette étude, nous proposons d'employer des faunes de foraminifères benthiques vivants comme bio-indicateurs de l'impact du dépôt des déblais de forages pétroliers imprégnés d'huile dans un environnement tropical du plateau continental externe du Congo (stations échantillonnées à 180 m de profondeur). Les analyses physico-chimiques montrent que, 4 ans après l'arrêt des activités de forage, le niveau de contamination du sédiment par des hydrocarbures et le Baryum est encore important dans un rayon de 250 m autour des points de décharge, et diminue progressivement vers les sites les plus éloignés. Les hydrocarbures ne sont plus perceptibles au-delà de 1000 m des sites de dépôt. Très logiquement, les faunes de foraminifères benthiques indiquent une forte diminution de l'impact environnemental avec l'augmentation de la distance des sites de décharge. En utilisant la densité et la composition des foraminifères benthiques, et en comparant les faunes avec celles du site de référence, nous avons pu distinguer trois zones où celles-ci sont affectées à différents degrés (Fig. s-4) :

1) une première zone, située à moins de 100 m du site de dépôt, est caractérisée par une faune pauvre composée principalement d'espèces résistantes à l'hypoxie (*Bulimina*

*marginata/aculeata/costata*, *Trifarina pauperata*, *Gyroidina* sp.1, *Eggerella* sp.1, *Nonionella turgida*).

2) une deuxième zone, située dans un rayon de 100 à 250 m des sites de dépôt des déblais de forage, contenant une faune typique des environnements eutrophiés, est caractérisée par une densité élevée et une forte dominance des mêmes espèces trouvées dans la zone 1 mais présentant un fort comportement opportuniste au niveau de cette zone.

3) une troisième zone, située à plus de 250 m et jusqu'à 750 m des sites de déversement, semble révéler une situation transitoire, où l'impact environnemental est minimal, mais encore perceptible. Les densités des faunes sont faibles, mais la composition faunistique montre toujours une légère augmentation des taxons opportunistes.

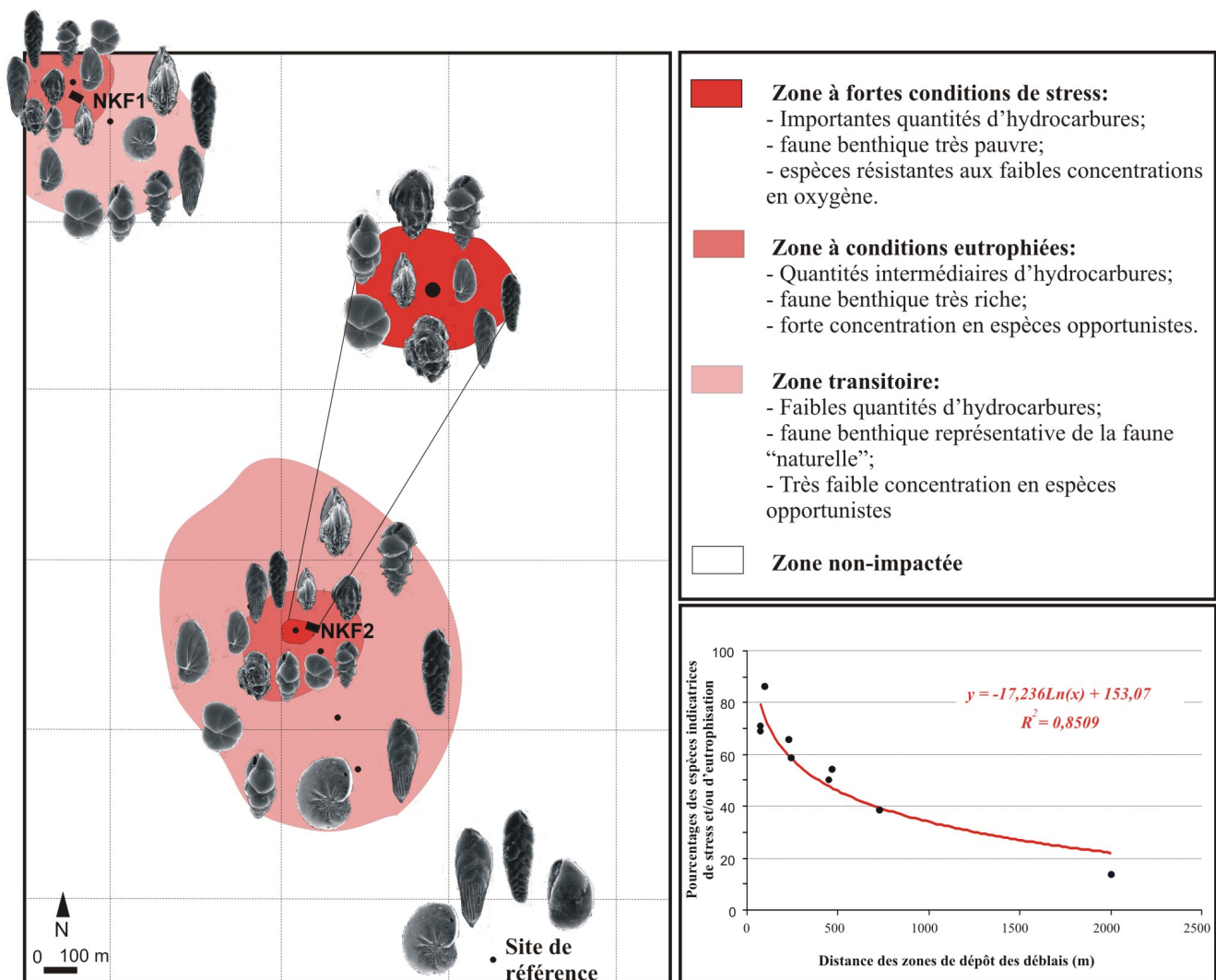


Figure s-4. Carte représentative des successions faunistiques des foraminifères benthiques vivants avec un gradient décroissant de l'impact des déblais de forages pétroliers au large du Congo ainsi que les pourcentages cumulatifs des espèces indicatrices de stress et/ou d'eutrophisation en fonction des sites de déversement NKF1 et NKF2.



Un indice quantitatif basé sur les proportions de tous les taxons indicatifs d'eutrophisation et/ou de stress d'origine naturelle ou anthropique (*Amphycorina scalaris*, *Bolivina dilatata*, *Bolivina seminuda*, *Bolivina spathulata*, *Bolivina* sp. 1, *Bulimina* spp., *Eggerella* sp. 1, *Gyroidina* sp. 1, *Nonionella turgida*, *R globularis*, *Textularia sagittula*, *Trifarina bradyi*, *Trifarina pauperata*, *Uvigerina peregrina* et *Valvulineria bradyana*) montre une très forte corrélation avec une distance croissante des sites de dépôt (Fig. s-4). Ces résultats prouvent que les foraminifères benthiques sont des bons outils pour un suivi environnemental de l'impact des dépôts des déblais de forages pétroliers dans un environnement marin ouvert. Quatre ans après l'arrêt des activités pétrolières, l'impact est en grande partie limité à une zone de 250 m autour des décharges mais reste perceptible jusqu'à un rayon de 750 m.

#### **Exemple d'eutrophisation d'origine anthropique : le site pétrolier AGM6 (Gabon)**

Dans cette étude, nous avons utilisé une méthodologie multiparamétrique (analyse des communautés benthiques ; macrobenthos et foraminifères, mesures de toxicité, contenu en hydrocarbures, potentiel redox, granulométrie) dans le but de se prononcer sur l'impact des boues de forages pétroliers 12 ans après l'arrêt de toute activité de rejet au large du Gabon (stations échantillonnées à environ 30 m de profondeur). Dans cette zone, la composition de la faune naturelle semble être affectée par les conditions naturellement eutrophiées du milieu, causées par les importants apports du fleuve Ogooué. En effet, la faune des foraminifères benthiques est fortement dominée par des espèces opportunistes typiques des zones sous influence deltaïque avec une forte introduction de matière organique. Ce site est comparable au delta du Rhône mais avec une charge de matière organique beaucoup plus importante.

Bien que nous ayons observé une présence persistante d'hydrocarbures, la toxicité est limitée (mesurée sur l'amphipode *Corophium arenarium* et sur des larves de mollusques) et la macrofaune et les foraminifères benthiques démontrent l'homogénéité de la zone en termes d'écologie benthique. Malgré le fait que ces hydrocarbures résiduels semblent avoir perdu la majeure partie de leur toxicité, nos données suggèrent que les hydrocarbures accentuent l'eutrophisation naturelle existante mais sans pour autant modifier sérieusement la composition taxonomique de la faune ou la structure de l'écosystème. Seule une influence sur les densités des foraminifères benthiques a été notée. La combinaison entre l'analyse des communautés benthiques (macrobenthos et foraminifères), les résultats de toxicité et le

contenu en hydrocarbures nous permet de distinguer trois zones, assez semblables d'un point de vue écologique (Fig. s-5):

1) Entre 0 et 70 m du site de dépôt, la pauvreté des faunes suggère qu'il y ait encore un faible impact sur l'environnement. Malgré la présence d'hydrocarbures, la toxicité est limitée et la faune est indicative d'une légère accentuation des conditions naturellement eutrophiées de la zone d'étude. En effet, une baisse de densité chez les foraminifères benthiques est observée dans cette zone ainsi qu'une baisse de biodiversité et une dominance des groupes typiques des zones très enrichies en matière organique sont observées dans la macrofaune.

2) Entre 70 m et 250 m, une zone de transition qui est caractérisée par une augmentation de la densité des foraminifères benthiques alors que dans la macrofaune, aucun changement significatif n'est observé.

3) Au delà de 250 m, aucun impact n'est perceptible. La faune est semblable à la faune de référence et il n'y a aucune toxicité.

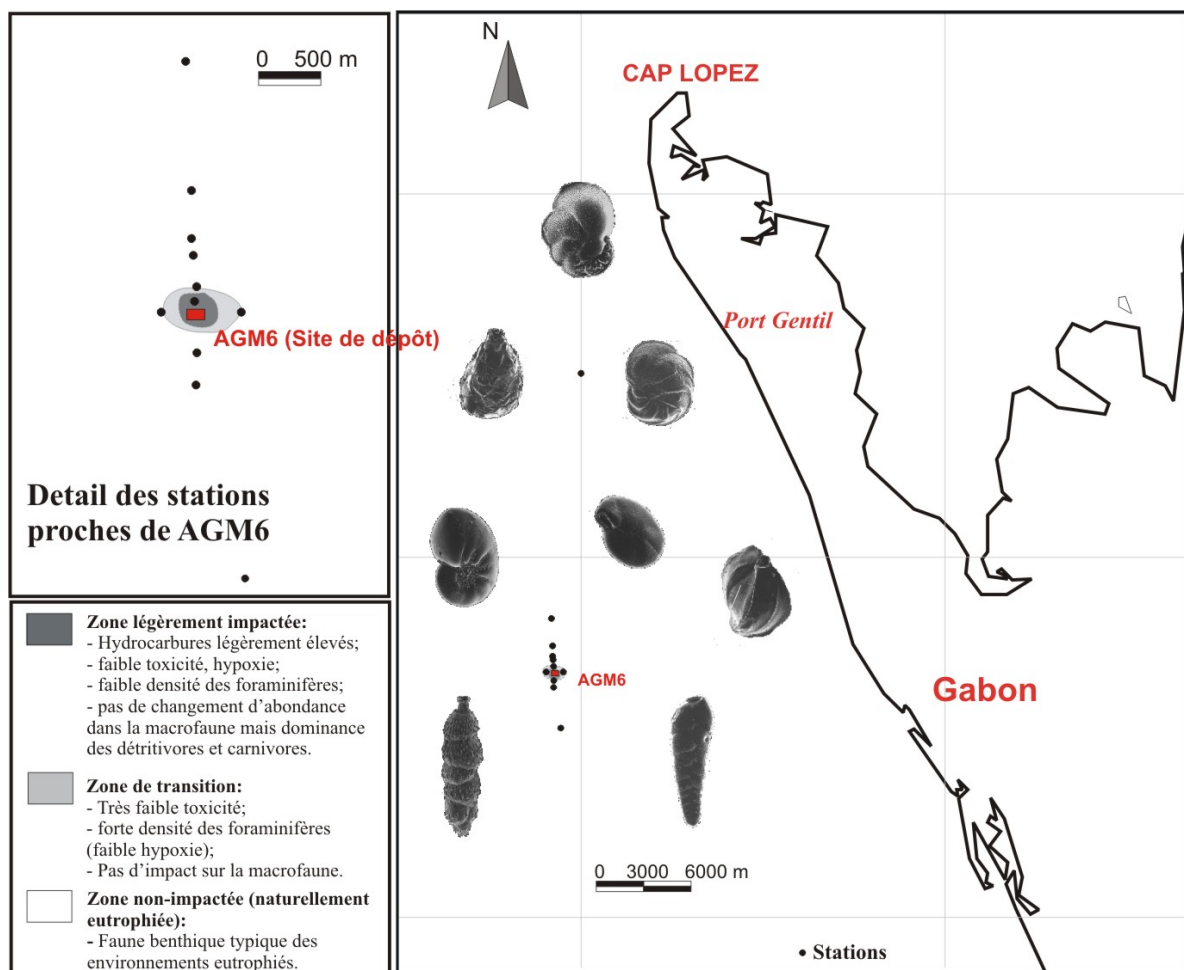


Figure s-5. Carte schématisant l'impact des déblais de forages pétroliers au large du Gabon

Nous concluons donc que l'impact sur l'environnement est minimal dans cette zone caractérisée par une eutrophication naturelle due à l'apport significatif des nutriments et de la matière organique par le fleuve Ogooué. Puisque nous ne disposons pas de données représentatives de la période de décharge, nous ne pouvons pas dire si cet état satisfaisant est le résultat de l'eutrophisation naturelle (qui tend à tempérer l'impact des déblais de forage), ou d'un bon rétablissement de l'écosystème 12 ans après l'arrêt des activités.

En termes de méthodologie, l'approche multiparamétrique est prometteuse. Les résultats des différentes méthodes ont donné des interprétations semblables. Cette étude est l'une des premières applications des foraminifères dans un suivi environnemental des décharges pétrolières.

### **Estimations qualitative et quantitative de l'état de santé des milieux étudiés**

La surveillance de la qualité de l'environnement marin passe impérativement par l'évaluation des effets des polluants sur les organismes vivants. Ces effets biologiques qui constituent des systèmes d'alarme précoces sont plus ou moins pertinents. Si les conséquences écologiques des polluants sont tardivement observables et sont parfois irréversibles, celles-ci ont l'avantage en retour de permettre d'établir un véritable diagnostic de l'état écologique du milieu. Cette surveillance environnementale a pour usage d'utiliser les communautés de macro-invertébrés marins afin d'évaluer l'impact de la pollution. Dans cette thèse, nous avons vu que les foraminifères benthiques constituent également d'excellents bio-indicateurs de la qualité de l'environnement. Nous essayerons dans ce contexte et comparativement aux études effectuées sur le macrobenthos d'explorer brièvement la faisabilité d'un indice environnemental basé sur les foraminifères benthiques. Il est évidemment nécessaire que cet indice soit élaboré et parachevé dans des études futures.

### **Approche qualitative de classification des différentes zones d'étude**

#### **Modèle théorique de succession faunistique dans le cas d'une eutrophisation, basé sur les foraminifères benthiques**

À la suite des résultats obtenus dans cette étude, nous pouvons établir un schéma théorique de succession des différents groupes écologiques. De la même manière que pour le

macrobenthos (chapitre 1, Fig. 1-7) et à travers la répartition et la composition des foraminifères benthiques, ce modèle représente le schéma classique des sites soumis à un gradient croissant d'enrichissement organique (Fig. s-6). En effet, la composition faunistique change progressivement avec l'augmentation de la perturbation environnementale. Ainsi, les espèces caractérisant les environnements en équilibre écologique diminuent progressivement laissant la place à des espèces opportunistes qui sont fortement compétitives en milieu enrichi. Si la perturbation s'intensifie, seules des espèces très résistantes au stress sont présentes. Quand la pollution est maximale, une zone azoïque pourrait prendre place.

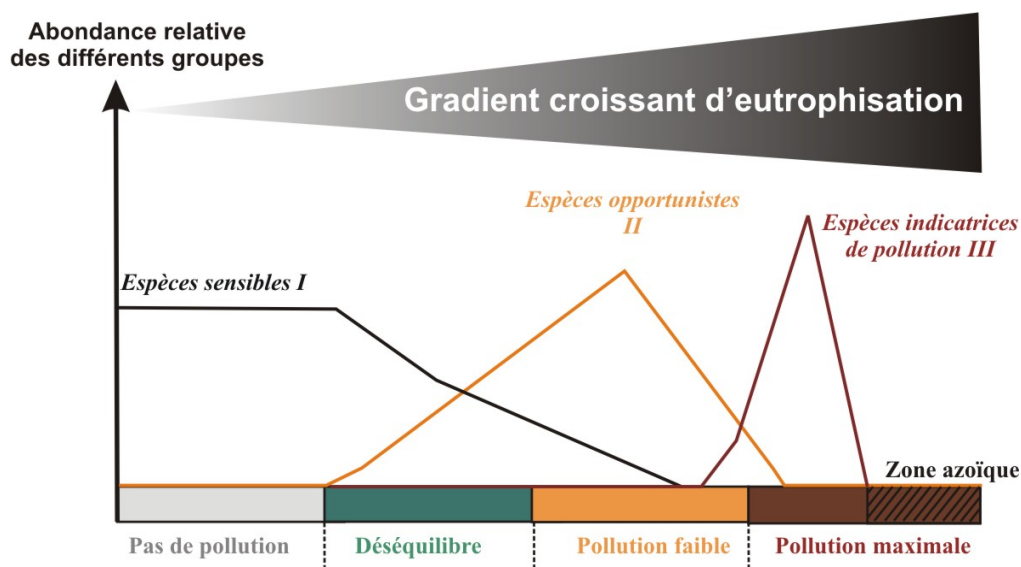


Figure s-6. Modèle théorique de succession faunistique des foraminifères benthiques

#### Classification des zones d'étude : Approche qualitative

En utilisant le modèle théorique de succession des différents groupes écologiques, nous pouvons classer les différents sites pollués que nous avons étudiés du plus impacté vers le moins impacté (Fig. s-7). Nous pouvons constater que dans le Firth of Clyde (Écosse), la pollution est perceptible dans un rayon de 3 Km du site de déversement. Au niveau du Congo, la pollution est perceptible dans un rayon de 750 m du site de rejet alors que, au large du Gabon, le site ne semble plus impacté par les déblais de forage. Néanmoins, la faune constituant cette zone est une faune adaptée à la forte eutrophisation naturelle du milieu comme celle que l'on retrouve à proximité de l'embouchure du Rhône.

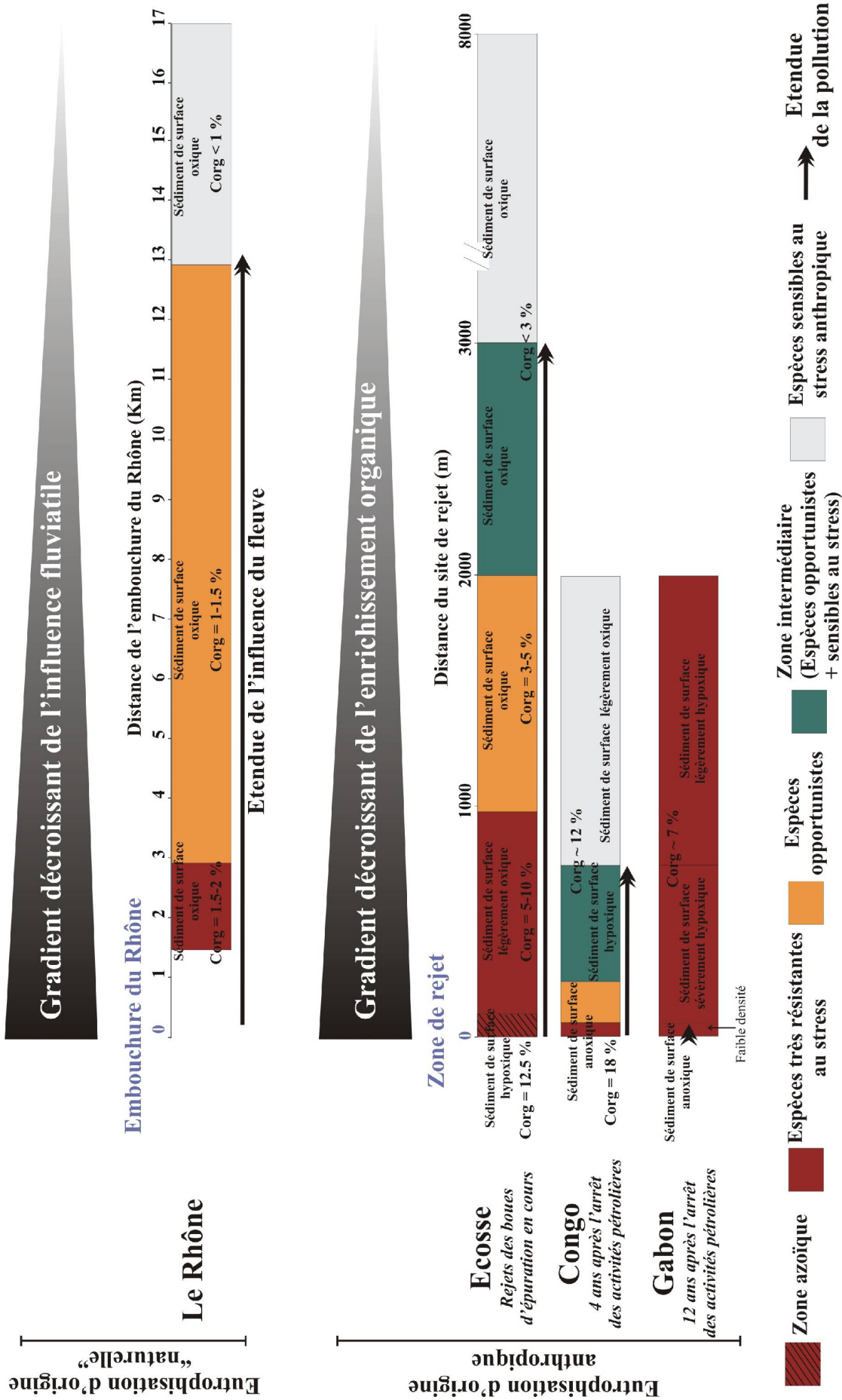


Figure s-7. Schéma récapitulatif de l'étendue de l'enrichissement organique dans l'espace indiquée par les groupes écologiques des foraminifères benthiques et comparaison entre les effets de l'eutrophisation d'origine naturelle et anthropique.

La figure s-7 montre aussi qu'un enrichissement organique d'origine « naturelle » (apports du fleuve du Rhône) présente des conséquences comparables à un enrichissement organique d'origine anthropique sur l'écosystème benthique mais sur une plus longue distance. En effet, la faune des foraminifères benthiques réagit fortement à cet enrichissement organique en changeant la composition faunistique et en s'adaptant aux conditions de stress environnemental. Ainsi, en utilisant les groupes écologiques, nous pouvons conclure l'étendue de l'influence fluviale qui, au moment de l'échantillonnage est perceptible à environ 13 Km de l'embouchure.

**Approche quantitative : Possibilité de développement d'un indice environnemental basé sur les foraminifères benthiques**

*FIEQ (Foraminiferal Index of Environmental Quality)*

Comme toutes les espèces vivantes, les foraminifères répondent aux stress anthropiques et naturels. Suite à une variation des variables environnementales, les assemblages de foraminifères vont montrer des changements de composition spécifique, de densité et de biodiversité. Ils révèlent ainsi un changement de leur habitat et indiquent la localisation et l'étendue du phénomène perturbateur. Dans les chapitres 5 et 6, nous avons utilisé un indice prenant en compte les pourcentages cumulatifs des espèces indicatrices de stress et/ou d'eutrophisation en fonction de la distance du site de pollution. Cet indice présente une corrélation fortement négative avec la distance de la source de perturbation. Nous avons appelé cet indice FIEQ (Foraminiferal Index of Environmental Quality). Dans la figure s-8, nous avons calculé cet indice pour tous les sites étudiés. Les espèces indicatrices de stress et/ou d'eutrophisation qui ont été sélectionnées pour calculer cet indice sont présentées dans le tableau s-1. Il faut noter que ces espèces ne sont pas les mêmes pour les différentes zones d'étude. Ce problème sera traité plus en détail dans le paragraphe suivant.

Nous pouvons constater d'après la figure s-8, que les foraminifères benthiques réagissent de la même manière à un gradient décroissant d'enrichissement organique qu'il soit de source naturelle ou anthropique. En effet dans le cas du fleuve du Rhône, plus on s'éloigne de l'embouchure et plus l'abondance relative des espèces indicatrices de stress et/ou d'eutrophisation diminue, laissant la place à des taxons d'équilibre écologique. Dans cette zone d'étude, la partie Est du prodelta est moins influencée par les apports du fleuve que la partie ouest. Pour cette raison, l'indice FIEQ y décroît plus rapidement avec la distance en

comparaison avec les sites à l'ouest de l'embouchure. Dans le Firth of Clyde (Écosse) et au large du Congo, tous deux affectés par une eutrophisation d'origine anthropique, l'indice décroît également fortement avec la distance du site de déversement. Au large du Gabon, un site naturellement hypereutrophe et échantillonné 12 ans après l'arrêt des activités pétrolières, la composition spécifique des foraminifères n'a pas été affectée par les hydrocarbures persistant sur ce site ; seulement un impact au niveau de la densité des faunes a été observé à proximité du site de déversement. Pour cette raison, l'indice FIEQ ne montre pas de tendance puisque environ 100 % de la faune est composée d'espèces opportunistes et/ou très tolérantes à l'hypertrophisation.

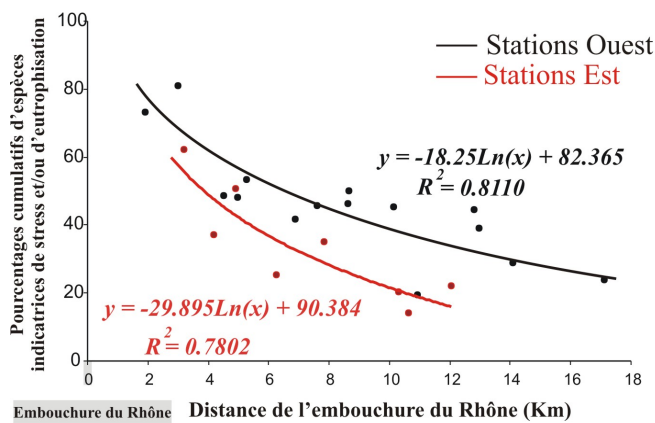
Groupe	Type d'espèces de foraminifères	Caractéristiques	Le Rhône	Firth of Clyde	Congo	Gabon
I	Sensibles à une hypertrophisation	- largement dominantes en conditions normales (faune du site de référence). - disparaissent en premier lors de l'enrichissement du milieu. - dernières à se mettre en place dans le cas d'une repopulation	<i>C. carinata</i> <i>E. vitrea</i> <i>V. bradyana</i> <i>N. iridea</i> <i>N. bradyi</i>	<i>E. albumbilicatum</i> <i>E. advenum</i> <i>E. advena</i> <i>N. turgida</i>	<i>B. striatula</i> <i>B. seminuda</i> <i>N. scaphum</i> <i>C. bradyi</i>	
II	Opportunistes	- cycle de vie court et prolifèrent en réponse à l'enrichissement organique et/ou à la disparition des prédateurs. Ces espèces sont plus tolérantes à de faibles oxygénations mais pas à des hypoxies sévères et durables	<i>N. scaphum</i> <i>R. phlegeri</i> <i>N. turgida</i>	<i>S. concava</i> <i>B. marginata</i> <i>B. seminuda</i>	<i>B. marginata</i> <i>B. aculeata</i> , <i>B. costata</i> <i>Eggerella</i> sp. <i>T. pauperata</i> <i>Gyroidina</i> sp. <i>N. turgida</i>	<i>C. congolensis</i> <i>Q. lamarckiana</i> <i>B. seminuda</i> <i>R. phlegeri</i> <i>H. boueana</i> , <i>E. vitrea</i> <i>N. scaphum</i>
III	Résistantes à une forte pollution	- espèces très résistantes au stress. Ces espèces peuvent être également très résistantes aux hypoxies sévères.	<i>B. aculeata</i> f. <i>elongata</i> , <i>A. longirostra</i> <i>F. fusiformis</i> <i>R. scottii</i>	<i>E. scabra</i> , <i>T. porrecta</i> <i>T. sagittula</i> <i>E. vitrea</i>	<i>B. marginata</i> <i>B. aculeata</i> , <i>B. costata</i> <i>Eggerella</i> sp. <i>T. pauperata</i> <i>Gyroidina</i> sp. <i>N. turgida</i>	<i>C. congolensis</i> <i>Q. lamarckiana</i> <i>B. seminuda</i> <i>R. phlegeri</i> <i>H. boueana</i> <i>E. vitrea</i> <i>N. scaphum</i>

Tableau s- 1. Groupes écologiques de foraminifères benthiques vivants avec différentes sensibilités à la pollution (le cadre rouge montre que se sont les mêmes espèces qui peuvent être de groupe II ou III).

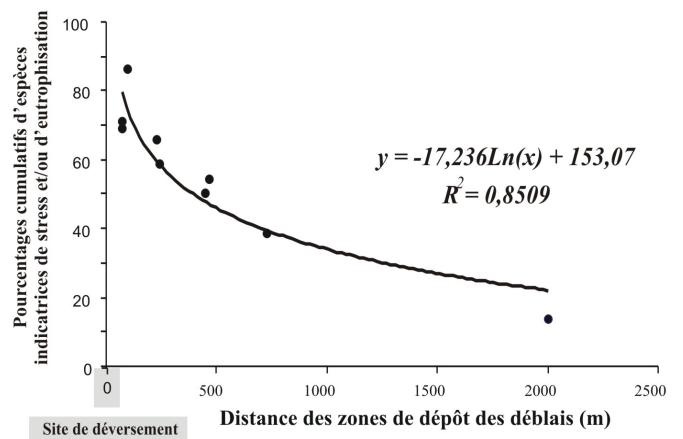
Nous pouvons également observer à travers la figure s-8 qu'au large du Gabon, où l'eutrophisation est naturelle et où l'enrichissement organique d'origine anthropique n'a que

peu d'impact sur la faune, que l'échantillonnage ne s'est effectué que sur 2 Km de distance. Or, dans le prodelta du Rhône, un site comparable, mais qui reçoit une décharge organique beaucoup moins importante que le site au large du Gabon, l'échelle d'échantillonnage est plus large, atteignant la vingtaine de kilomètres. Nous pouvons soupçonner qu'une succession faunistique sur une échelle plus importante, semblable à celle observée dans le prodelta du Rhône, pourrait également être présente au large du Gabon. En effet, en se dirigeant vers le NNW de la zone d'étude, les apports du fleuve Ogooué vont diminuer progressivement, et une faune plus stable se mettra probablement en place.

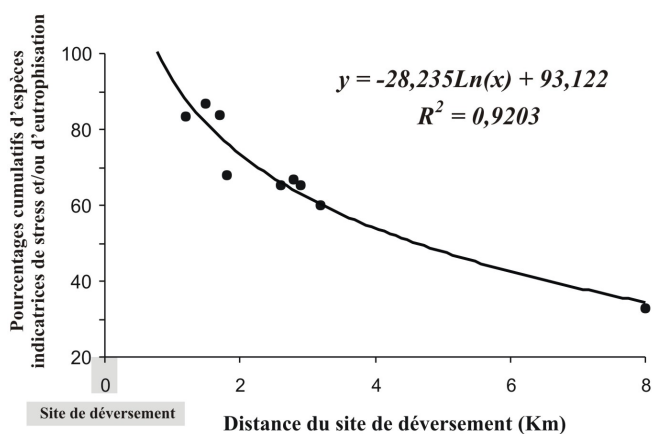
**Eutrophisation naturelle: Prodelta du Rhône**



**Eutrophisation anthropique: Congo**



**Eutrophisation anthropique: Firth of Clyde**



**Eutrophisation naturelle dominante (Impact anthropique légèrement perceptible) Gabon**

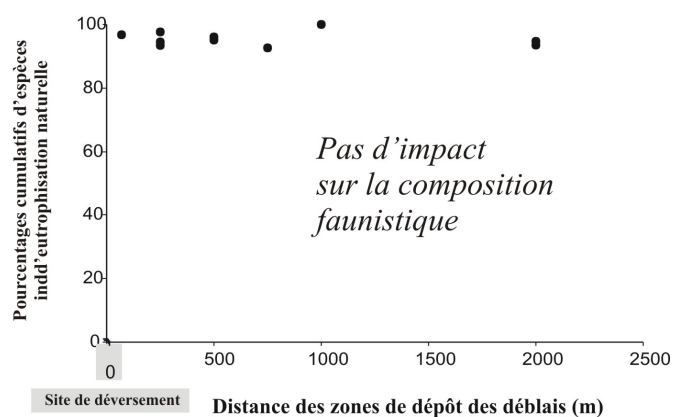


Figure s-8. L'indice FIEQ en fonction de la distance de la source d'enrichissement dans les 4 sites d'étude



Afin d'établir la qualité écologique de l'écosystème benthique, les études d'impact environnemental utilisent généralement une échelle biotique composée d'environ 4 à 7 classes basées sur la proportion des espèces indicatrices. La proportion d'abondance des individus dans les 3 groupes écologiques précédemment déterminés, peut être mise en relation avec la sensibilité/tolérance envers un gradient de stress environnemental. Nous proposons que la qualité écologique des sites étudiés pourrait être déterminée sur une échelle allant de 1 à 4 (1 : bonne à très bonne, 2 : moyenne, 3 : mauvaise et 4 : très mauvaise) en fonction de la valeur du FIEQ comme indiqué sur le tableau s-2.

<b>FIEQ</b>	< 20 %	20-40 %	40-70 %	> 70 %
<b>Qualité écologique du milieu</b>	Bonne à très bonne	Moyenne	Mauvaise	Très mauvaise
<b>Echelle biotique</b>	1	2	3	4

Tableau s-2. Estimation de la qualité écologique du milieu sur une échelle biotique de 1 à 4

#### Sélection des espèces marqueurs

Dans cette étude, et afin de calculer le FIEQ, nous avons classé nos différentes espèces dans des groupes écologiques (Tableau s-1). Dans ce contexte, nous nous sommes basés sur la méthode des groupes écologiques précédemment mise au point par *Hily (1984)* pour le macrobenthos. Ainsi, les foraminifères benthiques ont été classés en 3 groupes écologiques suivant la sensibilité ou la tolérance des espèces au gradient d'enrichissement dans chaque zone d'étude : Le premier groupe écologique est représenté par les espèces sensibles à l'hypertrophisation qui sont largement dominantes en conditions normales (faune du site de référence). Au fur et à mesure que l'eutrophisation s'intensifie, le deuxième groupe écologique, représenté par les espèces opportunistes, se met progressivement en place et prolifère en réponse à l'enrichissement organique. De plus, ces espèces profitent pleinement de la disparition progressive des prédateurs. Dans des conditions de pollution maximale, les espèces les plus résistantes au stress sont présentes.

Nous pouvons remarquer qu'entre nos quatre zones d'études, la sélection des espèces marqueurs varie fortement et dépend entièrement des conditions locales. Ainsi, il n'est pas possible de déterminer des marqueurs universels. En effet, l'indice de *Hily (1984)* a été appliqué avec succès le long des côtes bretonnes et de la Manche (*Grall et Glémarec, 2003* ;

Grall *et al.*, 2003) mais son extension à une échelle géographique plus large n'a pas été vérifiée. De tels indices sont généralement définis pour des zones ou des régions précises et leur calibration concernant l'appartenance des espèces aux différents groupes écologiques est nécessaire pour une extension géographique plus large. En effet, les espèces de foraminifères benthiques dans un milieu marin ouvert se répartissent principalement selon le flux organique (Murray, 2006). Ainsi, dans un site naturellement hypereutrophe, il y aura d'autres marqueurs que dans un site oligotrophe et dans un site profond, il y en aura d'autres que dans un site peu profond. Par conséquent, une même espèce peut être une espèce sensible (groupe I) dans une zone très riche naturellement en carbone organique, et avoir une forte tolérance (groupe III) voire une réponse opportuniste (groupe II) dans une autre zone moins riche. Prenons l'exemple de répartition d'une espèce théorique qui trouverait des conditions de vie optimales dans un environnement recevant entre 5 et 10 g/m<sup>2</sup>/an de carbone organique. Si la charge organique dépasse la limite supérieure de cette gamme, sa densité devrait baisser. Par contre, des populations relativement pauvres de cette espèce vivant dans un milieu avec une charge organique de moins de 5 g/m<sup>2</sup>/an peuvent montrer une réponse opportuniste en cas d'une eutrophisation de ce milieu, ramenant ainsi la charge organique dans la fourchette optimale pour cette espèce (Fig. s-9). C'est pour cette raison qu'il est toujours nécessaire de comparer la réponse des faunes dans les sites impactés aux faunes d'une zone de référence.

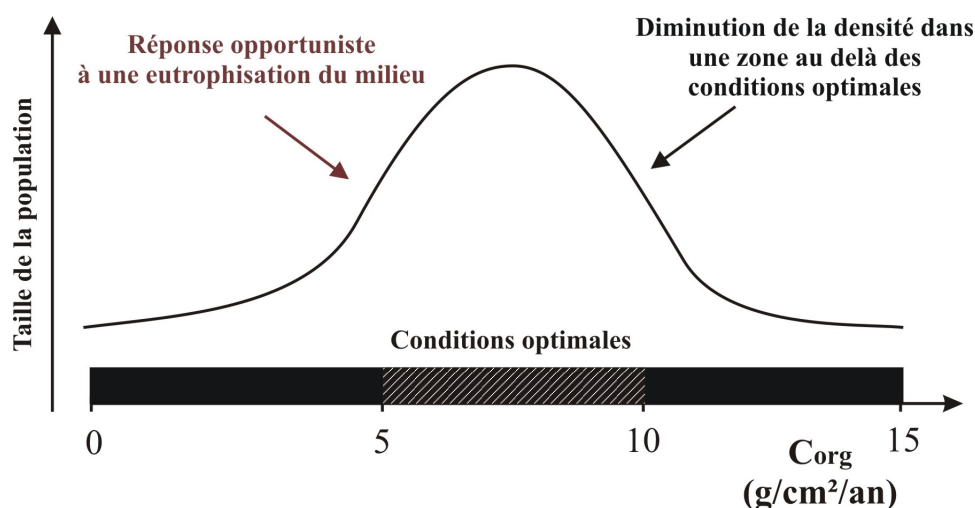


Figure s-9. Modèle théorique de répartition d'une espèce théorique selon le flux organique

Certes, le flux organique est le paramètre prépondérant dans la distribution des espèces de foraminifères benthiques mais celui-ci n'explique pas entièrement la répartition des faunes. D'autres paramètres rentrent en jeu, particulièrement dans ces environnements côtiers soumis

à l'influence anthropique. L'oxygène, le pH, la turbidité et la salinité varient beaucoup selon les zones. Ces paramètres ont certainement beaucoup d'influence sur la stratégie écologique des espèces, et de ce fait, compliquent davantage la sélection des espèces marqueurs.

*Classification des zones d'étude : Approche quantitative*

De la même manière que pour l'approche qualitative basée sur les groupes écologiques, nous proposons un schéma récapitulatif de classification des différentes zones d'études de manière quantitative. En effet, sur la figure s-10 sont représentées, la qualité écologique du milieu et l'échelle biotique déterminée sur la base du FIEQ pour chaque zone étudiée. Cette représentation graphique permet d'obtenir une comparaison plus efficace et plus rapide entre les différentes zones d'étude et de se prononcer avec plus d'objectivité sur la qualité écologique du milieu. Ce modèle de schématisation pourrait être employé avec efficacité dans des études de suivi environnemental basées sur les foraminifères benthiques et ceci dans le but d'avoir une méthode homogène pour se prononcer sur l'état de santé d'un milieu marin donné.

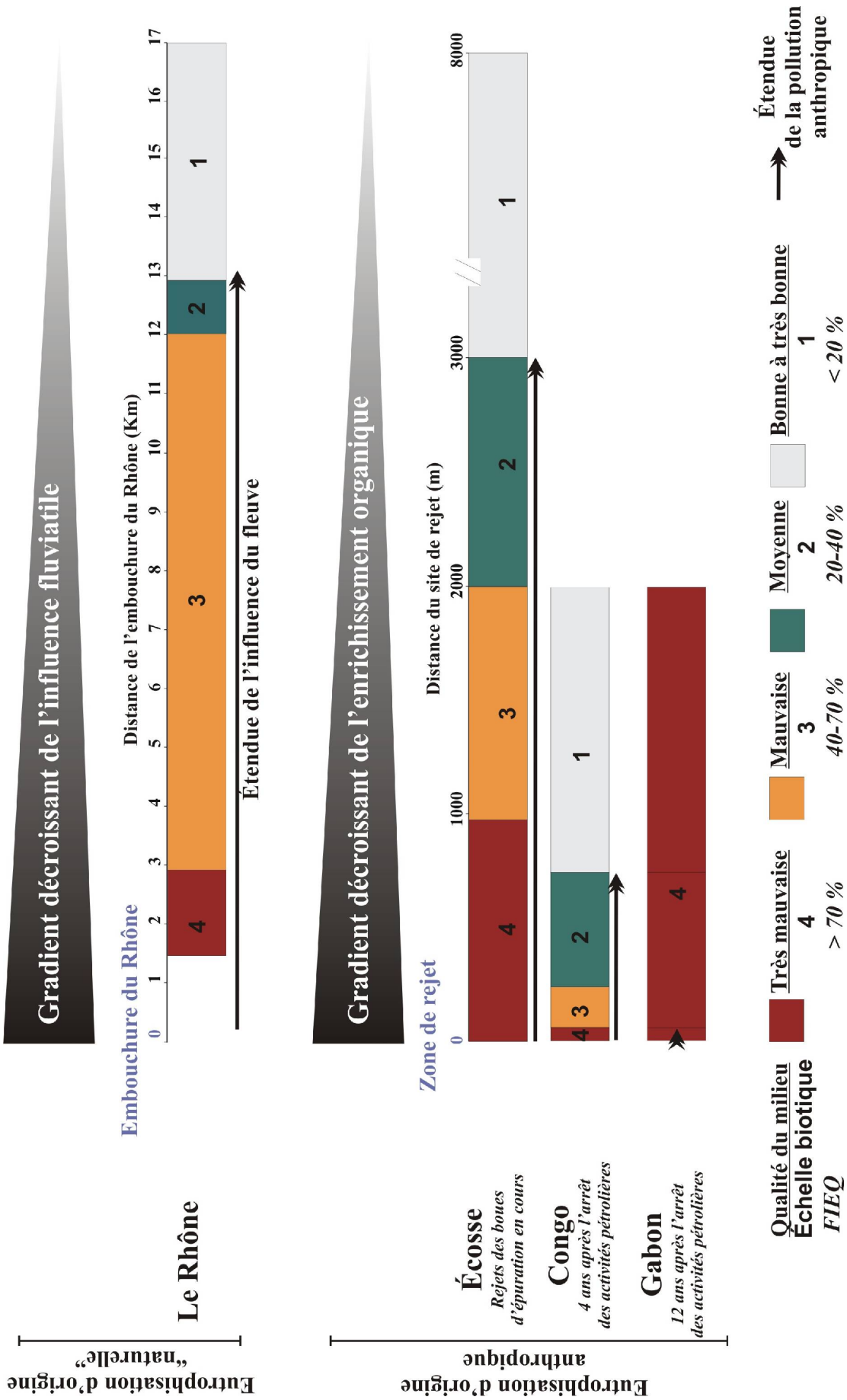


Figure s--10. Schéma récapitulatif de l'étendue de l'enrichissement organique dans l'espace indiquée par l'indice biotique et la comparaison entre les effets de l'eutrophisation d'origine « naturelle » et anthropique.

## **Conclusion générale**

Ce travail a permis de mettre en évidence l'applicabilité des foraminifères benthiques autant que bio-indicateurs d'écosystèmes marins ouverts de zones côtières soumis à un enrichissement organique d'origine naturelle ou anthropique. Dans un contexte plus général lié aux problématiques propres aux zones côtières, l'étude des foraminifères benthiques ainsi que les facteurs contrôlant leur habitat (oxygène, matière organique, pH...) a appuyé l'importance grandissante de l'influence humaine sur l'écosystème benthique. Cette pression anthropique s'est illustrée par l'intensité du recyclage de la matière organique et de la consommation en oxygène nettement plus forte dans les stations les plus proches des sites de déversement. Les changements de ces paramètres environnementaux dus à la forte introduction organique suite à des activités anthropiques suscitent la réaction des faunes de foraminifères benthiques qui changent ainsi de structure et de dynamique. En effet, cette réponse faunistique se traduit en général par le passage de groupes écologiques sensibles à la pollution dans les parties les plus éloignées de la source d'enrichissement organique, à des espèces opportunistes, suivi d'espèces fortement résistantes au stress à proximité du site de déversement et dans certains cas à une zone complètement azoïque dans la partie la plus dégradée. Cette succession faunistique nous informe sur l'étendue et le degré de la perturbation environnementale. L'étude de l'effet des introductions anthropiques a été également comparée à une introduction naturelle de matière organique dans un système côtier par les apports fluviaux. Bien évidemment, l'homme a également sa part de responsabilité dans cette dynamique notamment par le biais des engrais agricoles ainsi que des polluants organiques qui sont drainés par le fleuve et rejetés dans l'océan, accentuant ainsi l'enrichissement organique du milieu. Néanmoins, nous avons pu constater que les faunes de foraminifères benthiques réagissent de la même manière à cette introduction organique avec une succession faunistique comparable à celle causée par une activité anthropique directe, permettant ainsi de se prononcer sur l'étendue de l'influence des apports de la rivière. Cette étude a permis également, dans un contexte plus écologique, de mettre en liaison l'importance de la qualité de la matière organique qui s'est avérée être un paramètre très important dans la distribution spatiale et verticale (microhabitat) des foraminifères benthiques. Dans des conditions idéales, les études écologiques de base devraient être effectuées avant le début d'un impact environnemental particulier. Ceci n'est malheureusement pas souvent le cas, car en général, les suivis environnementaux se décident après la constatation d'une dégradation

environnementale. Dans ce contexte, et grâce à la préservation des tests dans le sédiment, les foraminifères benthiques constituent un outil précieux pour la reconstitution de l'écosystème avant qu'il soit affecté par la pollution. En effet, l'étude de la faune morte a permis d'avoir des informations écologiques supplémentaires et de déterminer dans certains cas le comportement opportuniste de certaines espèces qui montrent une plus forte abondance dans la faune vivante. Un autre aspect intéressant de cette thèse a été d'introduire, dans certains cas d'étude, la comparaison avec la macrofaune benthique qui est souvent utilisée dans ce contexte. Nous avons pu mettre en évidence une réponse assez comparable des deux groupes faunistiques avec un avantage pour les foraminifères benthiques qui présentent une plus grande sensibilité.

Cette thèse dresse donc la vision actuelle des relations existant entre les faunes de foraminifères benthiques côtiers et certains paramètres abiotiques majeurs ayant été modifiés par l'introduction dans le milieu d'une source d'eutrophisation. Ainsi, la conclusion majeure de ce travail est que les foraminifères benthiques constituent d'excellents bio-indicateurs environnementaux d'enrichissement organique.

### **Perspectives**

A l'issue de ce travail de thèse, de nombreuses interrogations demeurent concernant la réponse des faunes de foraminifères benthiques aux changements des facteurs abiotiques suite à un enrichissement organique de l'écosystème benthique. Parmi ces questions, certaines nécessiteront des investigations complémentaires ou des travaux précurseurs. Aussi, de nombreux travaux de recherche pourraient être entrepris en prolongement de ce travail :

- Les différentes réponses des faunes de foraminifères benthiques aux flux croissant de matière organique observées dans l'environnement demandent à être vérifiées en culture. En effet, les études en culture permettent d'étudier l'impact d'un seul paramètre, et non pas d'un complexe de paramètres, comme c'est toujours le cas sur le terrain.
- La comparaison entre la réponse de la macrofaune et des foraminifères est l'un des aspects intéressants et nouveaux de notre étude. Cependant, ces deux groupes faunistiques sont liés par différentes relations trophiques (bioturbation, prédation,.....).

Il serait intéressant d'approfondir l'étude de ces relations et de la façon dont elles sont modifiées par des phénomènes d'eutrophisation.

- L'une des limites de cette thèse est l'absence de répliquas d'échantillons et l'absence d'une étude de microdistribution spatiale « patchiness » ; il serait donc souhaitable que, dans l'avenir que de telles études soient réalisées afin de définir le biais qu'entraîne ce phénomène.
- Une autre limite de cette thèse réside dans l'absence d'un suivi temporel de la pollution nous permettant de nous prononcer sur la capacité de régénération de l'écosystème. Nous n'avons utilisé qu'un échantillonnage dans le temps. Pour plus de précision et d'exactitude, faire un suivi sur une plus longue période d'une seule zone d'étude serait une bonne démarche à suivre afin de se prononcer avec exactitude sur le temps et la capacité de rétablissement de l'écosystème benthique après une perturbation environnementale.
- L'indice (FIEQ) basé sur les pourcentages cumulatifs des espèces indicatrices de stress et/ou d'eutrophisation que nous avons mis au point pour quantifier un déséquilibre écologique devrait être testé dans d'autres environnements soumis à un enrichissement organique.
- Le fait que nous ne puissions pas distinguer des espèces marqueurs communes à nos 4 sites d'étude est l'une des limites de notre méthode de bio-indication basée sur les foraminifères benthiques. Le développement d'un indice basé sur des marqueurs universels se révèle être impossible. En effet, les communautés de foraminifères benthiques se répartissent suivant l'importance du flux organique et en fonction de différents paramètres abiotiques. Pour des études prochaines, il serait préférable d'essayer d'identifier certains marqueurs pour un site donné pour lequel les paramètres physico-chimiques qui le caractérisent sont bien définis. Ensuite, il faudrait faire un suivi sur une plus longue durée du même site afin de calibrer l'appartenance des bio-indicateurs aux groupes écologiques au niveau de cette zone et essayer d'extrapoler à d'autres régions ayant les mêmes contraintes physico-chimiques.

## **Références**

Ernst, S., Bours R., Duijnste I., and Van Der Zwaan, B., 2005. Experimental effects of an organic matter pulse and oxygen depletion on a benthic foraminiferal shelf community. *Journal of Foraminiferal Research*, 35, 177-197.

Hily, C., 1984. Variabilité de la macrofaune benthique dans les milieux hypertrophiques de la Rade de Brest. Thèse de Doctorat d'Etat, Université de Bretagne Occidentale. Vol. 1: 359 pp., Vol. 2: 337 pp.

Grall, J., Glémarec, M., 2003. Chapitre III., L'indice d'évaluation de l'endofaune côtière. In : Alzieu, C. (Editeur), Bioévaluation de la qualité environnementale des sédiments portuaires et des zones d'immersion. Ed. Ifremer, pp. 51-84.

Grall J., Quiniou F., Glémarec M., 2003. Bioévaluation de la qualité environnementale des milieux portuaires. In : Bioévaluation de la qualité environnementale des sédiments portuaires et des zones d'immersion. Alzieu C. (coord.), Éd. Ifremer, 87-133.

Moodley, L., Van Der Zwaan, G.J., Herman, P.M.J., Kempers, L., Van Breugel, P., 1997. Differential response of benthic meiofauna to anoxia with special reference to Foraminifera (Protista, Sarcodina). *Marine Ecology Progress Series*, 158, 151-163.

Murray, J.W., 2006. *Ecology and applications of benthic foraminifera*. Cambridge: Cambridge University Press, 426 pp.

Risgaard-Petersen N., Langezaal, A.M., Ingvarsen, S., Schmid, M.C., Jetten, M.S.M., Op den Camp, H.J. M., Derksen, J.W.M., Piña-Ochoa, E., Eriksson, S.P., Nielsen, L.P., Peter Revsbech, N., Cedhagen, T. and van der Zwaan, G. J., 2006. Evidence for complete denitrification in a benthic foraminifer. *Nature*, 443, 93-96.

Sen Gupta, B.K. and Machain-Castillo, M.L., 1993. Benthic foraminifera in oxygen-poor habitats. *Marine Micropaleontology*, 20,183-201.

Van der Zwaan, G.J and Jorissen, F., 1991. Biofacial patterns in river-induced shelf anoxia. In: R. Tyson and T.H. Pearson, Editors, *Modern and Ancient Continental Shelf Anoxia*, Special Publication Geological Society of London (1991).





## PUBLICATIONS ET COMMUNICATIONS

### Publications:

**Mojtahid, M.** and Jorissen, F. Microhabitat selection of benthic foraminifera in the Rhône prodelta. Article à soumettre à *Marine micropaleontology*.

**Mojtahid, M.** and Jorissen, F. Comparison between dead and living benthic foraminiferal faunas in the Rhône prodelta. Article à soumettre à *Journal of Foraminiferal research*.

**Mojtahid, M.**, Jorissen, F., Lansard, B., Fontanier, C., Bombled, B. and Rabouille, C. Spatial distribution of benthic foraminifera in the Rhône prodelta: faunal response to organic matter focussing. Article à soumettre à *Estuarine, Coastal and Shelf Science*.

**Mojtahid M.**, Jorissen F., Pearson T.H. Benthic Foraminifera as bio-indicators of organic pollution in the Firth of Clyde (Scotland). Article accepté dans *Marine Pollution Bulletin*.

Eynaud, F., Zaragosi, S., Scourse, J.D., **Mojtahid, M.**, Bourillet, J.F., Hall, I.R., Penaud, A., Locascio, M., Reijonen, A., 2007. Deglacial laminated facies on the NW European continental margin: the hydrographic significance of British Ice Sheet meltwater pulses. *Geochemistry, Geophysics, Geosystems*, 8, 1525-2027.

**Mojtahid M.**, Jorissen F., Durrieu J., Galgani F., Howa H., Redois F. and Camps R., 2006. Benthic foraminifera as bio-indicators of drill cutting disposal in tropical east Atlantic outer shelf environments. *Marine Micropaleontology*, 61, 58-75.

Durrieu J., **Mojtahid M.**, Cazes L., Galgani F., Jorissen F. and Camps, R., 2006. Aged drilled cuttings offshore Gabon: New methodology for assessing their impact. *Society of Petroleum Engineers paper 98414*, Abu Dhabi, UAE, April 2006.

**Mojtahid M.**, Eynaud F., Zaragosi S., Bourillet J.F., Scourse J., Garlan T., 2005. Palaeoclimatology and Palaeohydrography of the glacial stages on Celtic and Armorican margins over the last 360 000 years. *Marine Geology*, 224, 57-82.

Lo Cascio M., **Mojtahid M.**, Eynaud F., Scourses J., Zaragosi S., Ther O. et Saint-Paul J. "La déglaciation Saaliennne en Europe de l'Ouest : investigation très haute résolution et multiproxies d'une carotte de la marge irlandaise." Article en préparation.

### Posters scientifiques

**Mojtahid, M.**, F. Jorissen, T. Pearson, J. Durrieu; F. Galgani. Towards an operational use of benthic foraminifera for organic pollution monitoring in open and enclosed marine environments: case histories from the outer shelf off Congo and the Firth of Clyde in Scotland. Micropalaeontological Society's Foraminifera and Nannofossil Groups. Joint Spring Meeting, Angers, June 2007.

Mojtahid M., Eynaud F., Zaragosi S., Bourillet J-F. & Scourse J. "Paloclimatology and paleohydrology of the celtic and armorican margins over the last 350 000 years ». ICP8-Septembre 2004.

### **Communications orales**

**Mojtahid, M.**, F. Jorissen, B. Lansard, C. Fontanier, B. Bombled and C. Rabouille. Spatial distribution of benthic foraminifera in the Rhône prodelta: faunal response to organic matter focussing. IMBER/LOICZ Continental Margins Open Science Conference, September 2007, Shanghai, China.

**Mojtahid, M.**, F. Jorissen, B. Lansard, C. Fontanier, B. Bombled and C. Rabouille. Spatial distribution of benthic foraminifera in the Rhône prodelta: faunal response to organic matter focussing. Micropalaeontological Society's Foraminifera and Nannofossil Groups. Joint Spring Meeting, June 2007.

**Mojtahid M.**, Jorissen F., F.Galgani, J. Durrieu and Pearson T.H., 2006. Benthic foraminifera as bio-indicators of eutrophicated environments. International Symposium of foraminifera, Natal, brasil, September 2006.

**Mojtahid M.**, E. Gelsin, T.H. Pearson and F. Jorissen, 2006. Benthic foraminifera as bio-indicators of eutrophicated environments. International Symposium on Research and Management of Eutrophication in Coastal Ecosystems, June 2006 in Nyborg, Denmark.

**Mojtahid M.**, Jorissen F., J. Durrieu, F.Galgani and Pearson T.H., 2006. Benthic foraminifera as bio-indicators of eutrophicated environments. EGU assembly, April 2006, Austria.

**Mojtahid M.**, Eynaud F., Zaragosi S., Bourillet J-F. & Scourse J. « paloclimatology and paleohydrology of the celtic and armorican margins over the last 350 000 years » Conférence URM17, Brest, Mai 2004.

**Eynaud F.**, Zaragosi S., LoCascio M., Mojtahid M. & J. Scourse. "Laminated deposits in Quaternary sediments of the Bay of Biscay as a recurrent phenomenon of glacial cycle terminations: the global perspective of a local seasonal deglacial pattern." AGU SPRING MEETING, Mai 2004.

Zaragosi, S., Eynaud, F., Denhart, B., **Mojtahid, M.**, Bourillet, J.F. Impact De La Déglaçiation Européenne Sur Les Transferts Sédimentaires Au Sein Du Golfe De Gascogne. Joint Earth Sciences Meeting, September 2004.