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# Variabilité climatique holocène et impacts anthropiques historiques en zone subarctique. Étude multiparamètre de la séquence sédimentaire du lac d'Igaliku (Groenland)

Charly Massa

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## Thèse de Doctorat

spécialité Archéologie, Environnement, Territoires

Charly Massa

# Variabilité climatique holocène et impacts anthropiques historiques en zone subarctique

Étude multiparamètre de  
la séquence sédimentaire  
du lac d'Igaliku (Groenland)

6 juillet 2012 - Besançon

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Sur le littoral, les moutons broutent de la morue  
en regardant passer les icebergs.

*Jean Malaurie, Les derniers rois de Thulé*

Curiously, they didn't look so unhappy with their  
condition, their stares were philosophical. Their  
eyes said: I'm just a sheep, I don't expect you  
to like me, care for me, preserve me, except for  
your stomach's sake. There were no angry baas,  
no stamping of a frustrated hoof.

Just three grey sheep, waiting to die.

*Clive Barker, Scape-Goats*

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## Introduction

### 1 | La paléolimnologie : entre sociétés, climat et environnement

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De nos jours, les questions d'environnement sont l'objet de préoccupations majeures pour l'avenir de nos sociétés modernes. Face à ces inquiétudes, à la nécessité d'une gestion durable des écosystèmes et à la demande pressante de références et de scénarii prédictifs, les programmes de recherche se multiplient. Pour cela, les données paléoenvironnementales procurent les moyens de comprendre le fonctionnement des écosystèmes passés et de tester des modèles pour l'avenir. L'expression : «comprendre le passé pour prévoir le futur» (e.g. Anderson *et al.*, 2006) prend ici tout son sens.

Dans ce contexte, le principal intérêt suscité par l'étude des sédiments lacustres, objet de la paléolimnologie, réside dans le fait qu'ils contiennent des marqueurs des conditions environnementales des bassins versants, les dotant d'un excellent potentiel d'archives naturelles, tout particulièrement sur les climats passés et leur évolution au cours du temps. Les taux de sédimentation relativement élevés de la plupart des lacs permettent d'appréhender des variations climatiques à différentes échelles temporelles de fonctionnement : d'amplitude millénaire et séculaire (Andresen *et al.*, 2004 ; Wagner *et al.*, 2008), jusqu'à une précision de l'ordre de la saison dans le cas de sédiments varvés (Lamoureux, 2000 ; Giguët-Covex *et al.*, 2010 ; Larsen *et al.*, 2012). Pour alimenter les modèles et améliorer la fiabilité des prévisions, les chercheurs se focalisent notamment sur la période récente de l'histoire sédimentaire : l'Holocène, soit les dix derniers millénaires. Mais la plupart s'accordent à dire qu'au cours de la seconde moitié de l'Holocène, les sociétés humaines, qui se sédentarisent en développant l'élevage et l'agriculture, ont un impact grandissant sur la dynamique sédimentaire (Edwards and Whittington, 2001 ; Kalis *et al.*, 2003 ; Zolitschka *et al.*, 2003). En réponse aux multiples paramètres forçant, les systèmes lacustres génèrent alors des signaux complexes, où les rôles respectifs de l'Homme et du climat s'entremêlent (Itkonen and Salonen, 1994 ; Arnaud *et al.*, 2005 ; Leroux *et al.*, 2008 ; Giguët-Covex *et al.*, 2011).

Ainsi, l'étude et la compréhension de ces mécanismes d'interactions passées entre les activités humaines et la dynamique naturelle de la géosphère sont un enjeu majeur pour assurer la fiabilité de l'interprétation environnementale du signal sédimentaire, la

reconstruction des paléoclimats et pour prédire la réponse des écosystèmes continentaux aux changements climatiques (Ruddiman, 2003 ; Dearing, 2006 ; Hurtt *et al.*, 2006). Pour ce faire, les études à haute résolution temporelle des archives sédimentaires lacustres, associées à des données archéologiques et historiques abondantes et détaillées, se montrent tout à fait pertinentes pour lier les activités des sociétés humaines passées avec les changements environnementaux ; et ceci est valable dans les deux sens, que l'on s'intéresse à restituer les grandes étapes de l'histoire de l'humanité dans leur contexte bioclimatique (Dugmore *et al.*, 2007 ; Magny *et al.*, 2008) et/ou à l'Homme en tant qu'agent de l'évolution des milieux (Arnaud *et al.*, 2005 ; Enters *et al.*, 2008).

### 2 | Le Groenland, un système simplifié ?

Malgré des avancées certaines, la compréhension du forçage anthropique doit encore surmonter quelques obstacles. D'abord, la position des chercheurs oscille schématiquement entre deux pôles, accordant la prédominance soit aux contraintes naturelles, soit aux contraintes anthropiques. Or, cette complexité nécessite une véritable approche intégrée prenant en compte objectivement l'effet combiné des deux facteurs. D'autre part, la volonté de considérer l'effet potentiel de l'homme se heurte souvent à des données archéologiques lacunaires et imprécises, dans le temps et dans l'espace. L'incertitude des modalités de l'anthropisation, comme l'absence d'enregistrement continu des activités agropastorales (Jacob *et al.*, 2008), compliquent le décodage de l'enregistrement sédimentaire. Il apparaît donc nécessaire d'élaborer des référentiels constitués à partir d'exemples de colonisation agraire pour lesquels les paramètres géographiques, démographiques, techniques et temporels sont parfaitement maîtrisés. Parmi les fronts pionniers agricoles historiques, répondant à tous ces critères, le développement de l'agriculture médiévale dans les îles de l'Atlantique Nord apparaît comme un modèle d'étude exceptionnel.

La migration vers l'Ouest des colons scandinaves dans l'Atlantique Nord, entre le VIII<sup>e</sup> et le XX<sup>e</sup> siècle, semble être le cas d'étude idéal pour la recherche sur les interactions entre les sociétés humaines et leur environnement. L'absence de population pratiquant l'agriculture avant la colonisation médiévale offre l'occasion unique d'étudier l'impact environnemental d'une emprise agricole rapide sur un environnement quasi-vierge (pour une revue complète voir Dugmore

et al., 2005 et les références citées). Au Groenland, l'abandon post-médiéval fournit en outre l'opportunité d'évaluer les conséquences de la déprise et la résilience éventuelle des milieux.

Le caractère exceptionnel des colonisations scandinaves a suscité beaucoup d'intérêt et de nombreuses études ont été menées pour évaluer l'impact des pratiques agricoles sur l'environnement des îles Féroé (Hannon et al., 2001 ; Lawson et al., 2005 ; Gathorne-Hardy et al., 2007 ; Lawson et al., 2007a ; Lawson et al., 2008), de l'Islande (Lawson et al., 2007b ; Gathorne-Hardy et al., 2009) et du Groenland (Fredskild, 1973 ; Fredskild, 1978 ; Sandgren and Fredskild, 1991 ; Fredskild, 1992 ; Edwards et al., 2008 ; Schofield et al., 2008 ; Buckland et al., 2009 ; Schofield et al., 2010 ; Schofield and Edwards, 2011).

L'implantation des populations scandinaves au Groenland à la fin du X<sup>e</sup> siècle se révèle particulièrement bien documentée par la communauté archéologique, tant sur les pratiques agropastorales (Dugmore et al., 2005 ; Adderley and Simpson, 2006 ; Commisso and Nelson, 2008), la pression démographique (Lynnerup, 1998), que sur la localisation des sites (Guldager et al., 2002 ; Algreen-Møller and Madsen, 2006). Pour autant, les lacs sud groenlandais, très nombreux et diversifiés dans leur fonctionnement (Anderson and Bennike, 1997 ; Anderson et al., 1999) ont surtout fait l'objet de recherches visant à des reconstructions paléoclimatiques (Kaplan et al., 2002 ; Andresen et al., 2004) ou glacio-eustatiques (Bennike et al., 2002 ; Bennike and Sparrenbom, 2007), hors des zones d'emprise de la colonisation médiévale soumises au forçage potentiel de l'Homme. Quelques rares études, relativement anciennes, cherchant à caractériser l'impact de l'Homme à partir des sédiments lacustres (Sandgren and Fredskild, 1991) s'avèrent chronologiquement imprécises et ne tiennent pas vraiment compte des effets du forçage paléoclimatique.

### 3 | L'Homme au Groenland

#### 3.1 Les Inuits

L'Homme occupe le Groenland depuis des millénaires (fig. 1). De nombreux sites archéologiques témoignent effectivement de la succession de cultures paléo-Inuits et néo-Inuits au Groenland depuis environ 4500 ans (Meldgaard, 2004). Les traces les plus anciennes correspondent aux Saqqaq (4500 – 800 BC), peuple de chasseurs d'origine sibérienne qui cheminèrent vers le sud de l'île (Gilbert et al., 2008 ; Rasmussen

et al., 2010) et au peuple de l'Indépendance I, au Groenland le plus septentrional. Suivirent les Dorsets (800 BC – 1300 AD) et enfin la culture de Thulé (depuis 1300 AD), dont descend la majorité de la population Groenlandaise actuelle (Gulløv, 1997). *A priori*, ces populations paléo-Inuits, peu nombreuses, nomades et vivant strictement de la chasse, n'ont pas eu d'impacts significatifs sur les systèmes lacustres. Néanmoins, des données paléolimnologiques du Nunavut (haut arctique canadien) ont permis de montrer que les Thulés, par le dépôt de carcasses de baleines dans les bassins versants, ont pu causer l'eutrophisation de certains lacs (Douglas et al., 2004 ; Hadley et al., 2010). Ce genre de contexte archéologique reste tout de même exceptionnel, et on peut considérer l'environnement groenlandais comme quasiment vierge de tout impact anthropique avant l'arrivée des premiers européens au X<sup>e</sup> siècle.

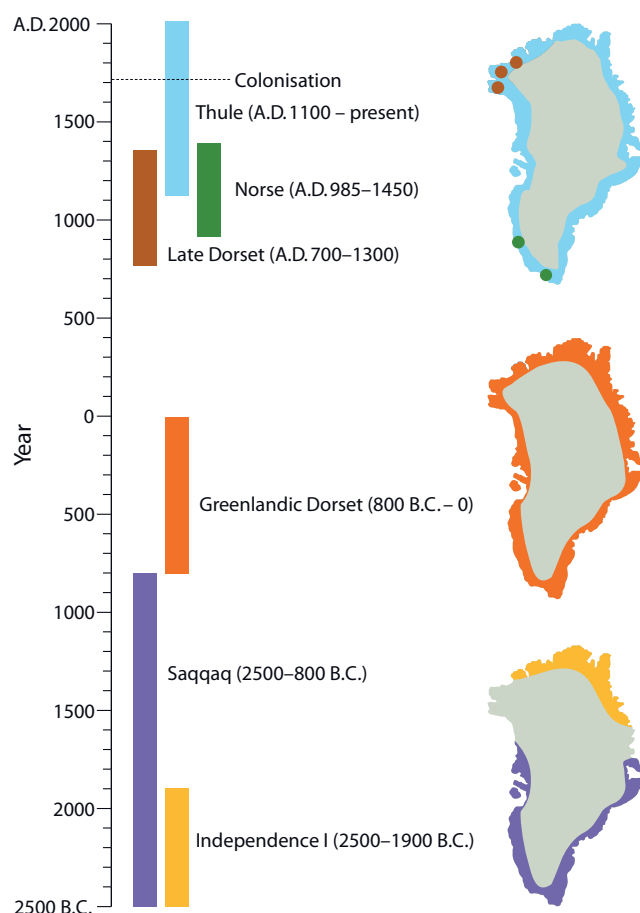
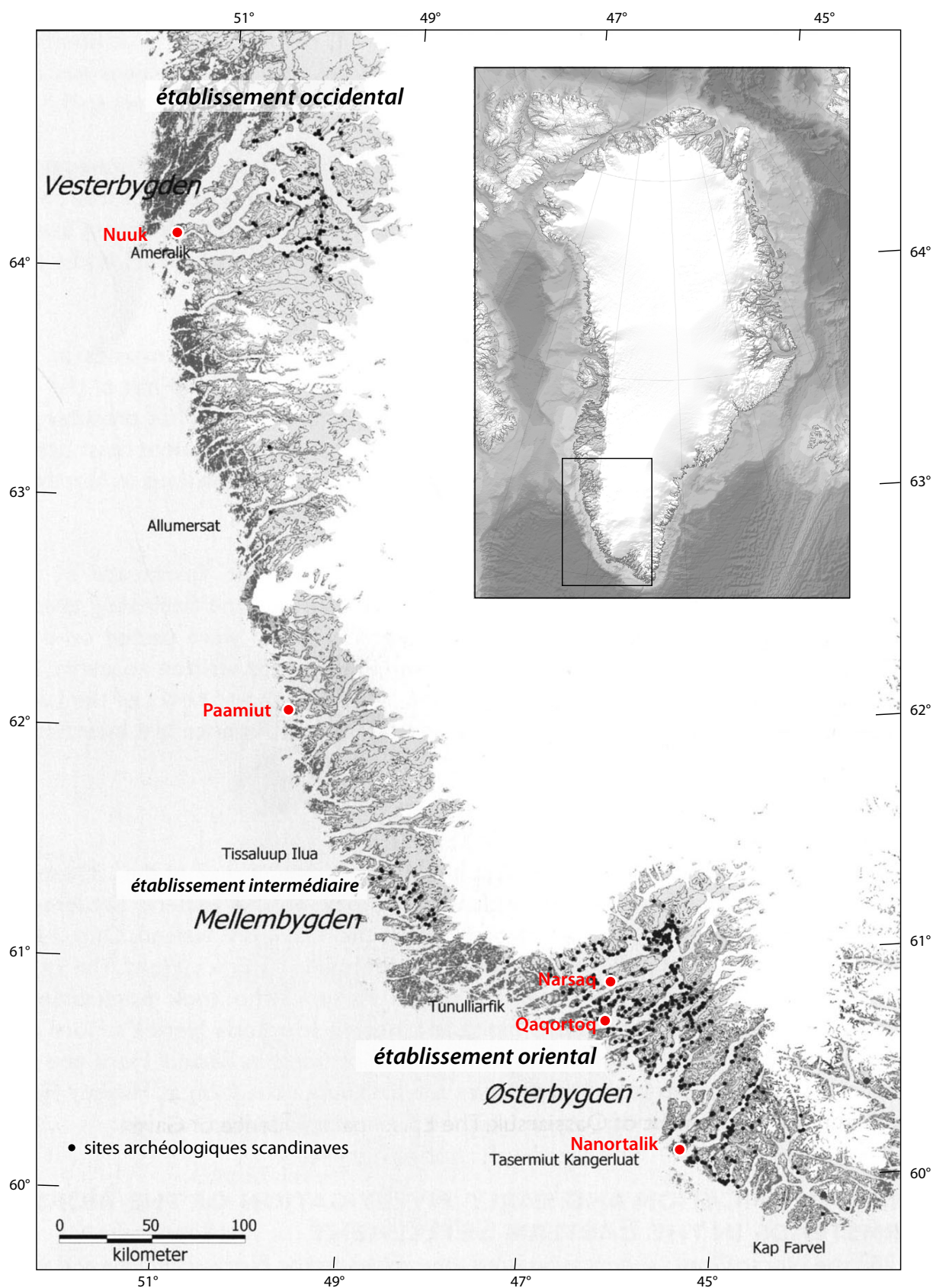


Fig. 1 Chronologie et répartition des différentes populations du Groenland (Weidick and Bennike, 2007)



**Fig. 2** Carte des implantations médiévales scandinaves sur la côte sud-ouest du Groenland (Arneborg et al. 2007). Les villes principales actuelles sont mentionnées en rouge.

### 3.2 Les scandinaves

Selon les historiens, la colonisation scandinave du Groenland est initiée par Eirik Thorvaldsen (surnommé Éric le Rouge) en l'an 986. Pendant environ cinq siècles, elle se développe sur la base d'une économie agropastorale jusqu'à atteindre 3000 à 6000 habitants (Lynnerup, 1998), répartis sur trois secteurs du Sud-Ouest du Groenland, les deux plus importantes implantations (fig. 2) étant situées à 61°N (Østerbygden, district de Narsaq – implantation dite « orientale ») et 64°N (Vesterbygden, district de Nuuk – implantation dite « occidentale »). Les *Landnamsmen*<sup>1</sup> élèvent bovins, moutons, chèvres, chevaux, chiens et porcs mais pratiquent aussi la chasse aux phoques, aux caribous et la pêche (McGovern, 1980 ; McGovern and Bigelow, 1984). Pour se chauffer, s'abriter et étendre les pâturages, ils défrichent la maigre « forêt<sup>2</sup> » subarctique (Fredskild, 1992), pratiquent la fertilisation par fumure (Commisso and Nelson, 2007 ; 2008 ; Buckland *et al.*, 2009) et l'irrigation (Arneborg, 2005 ; Adderley and Simpson, 2006 ; Golding *et al.*, 2009).

La chronologie de l'abandon de ces colonies est moins précise et sa causalité encore sujette à débats. Le seul point de consensus est le rôle de la péjoration climatique du Petit Âge de glaciaire (Dansgaard *et al.*, 1975 ; Barlow *et al.*, 1997 ; Dugmore *et al.*, 2012) qui isole la communauté de l'Europe et provoque la dégradation des rendements agricoles. Face aux dégradations des conditions climatiques, le peuple scandinave réorganise son économie vers la chasse et la pêche (Arneborg *et al.*, 1999 ; Dugmore *et al.*, 2012), mais les conditions climatiques deviennent telles qu'en 1448, le pape Nicholas V s'inquiète des conditions de survie des fidèles de *Garðar* (l'actuel Igaliku, 61°N) et ordonne aux évêques islandais de se porter à l'aide de leurs frères du Groenland (Rey, 1984). Malgré les efforts d'adaptation, la société scandinave du Groenland s'effondre au cours du XV<sup>e</sup> siècle.

Il faut attendre le XVIII<sup>e</sup> siècle pour que le Sud du Groenland soit réoccupé partiellement par des migrants européens et les années 1920 pour que de nouveau l'agro-pastoralisme se développe, au cœur même des bassins agricoles médiévaux (Hansen, 1991 ; Guldager *et al.*, 2002). Le développement progressif de la production ovine depuis les années 1920 et l'intensification des pratiques agro-pastorales dans les années 1960, conduisent à divers constats

d'impacts sur la végétation et l'érosion des sols liés au pâturage des troupeaux (Krogh, 1982 ; Hansen, 1991 ; Fredskild, 1992), soulignant la fragilité de l'espace agricole groenlandais. Au cours de la même période, la diminution des ressources marines suite aux effets combinés de la surexploitation et des changements climatiques, oblige également les autorités tutélaires danoises à réorganiser à plusieurs reprises l'économie de la pêche et de la chasse (Hamilton *et al.*, 2000). Ces situations viennent rappeler qu'au Groenland, les relations entre la société et son environnement sont au premier plan.

## 4 | L'Arctique, au cœur des préoccupations climatiques et environnementales

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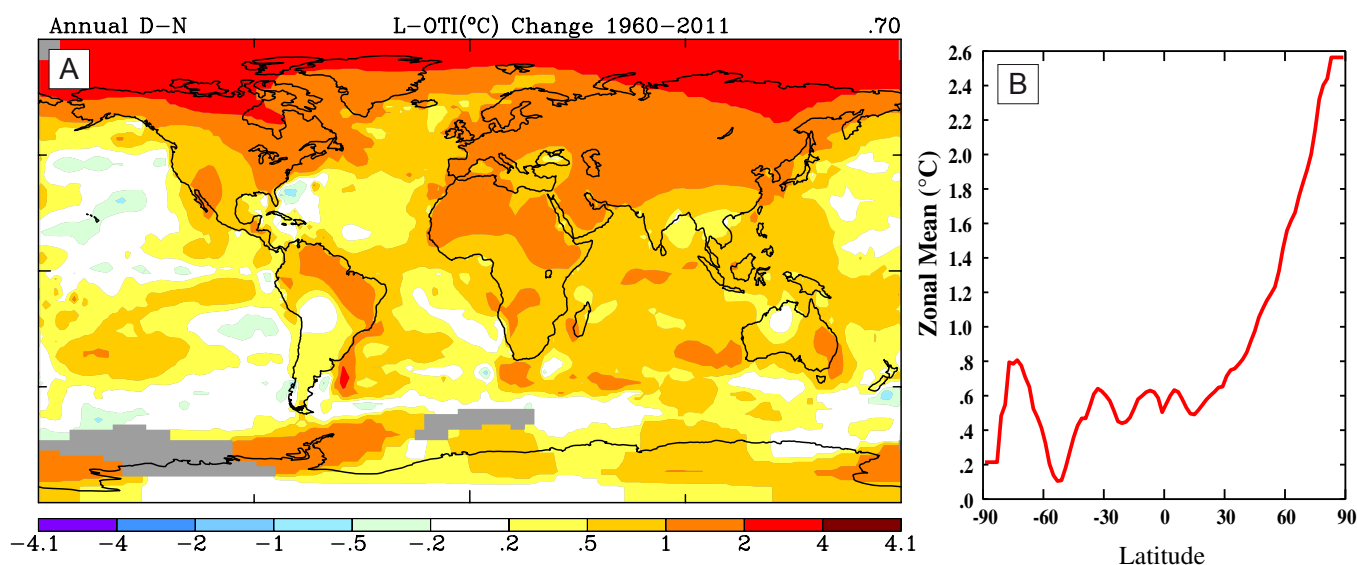
Longtemps considérée comme une région vierge de toute influence anthropique, car faiblement peuplée, la zone arctique n'échappe pas pour autant aux conséquences environnementales du développement de notre société moderne. Le milieu naturel est affecté par l'exploitation des ressources minérales, l'expansion de l'agriculture autour de 60°N (Sandgren and Fredskild, 1991 ; Schofield *et al.*, 2010), mais aussi par les apports atmosphériques lointains, d'azote industriel (Holtgrieve *et al.*, 2011), de polluants organiques persistants (Malmquist *et al.*, 2003 ; Braune *et al.*, 2005), et d'éléments traces métalliques (Murozumi *et al.*, 1969 ; Candelone *et al.*, 1995 ; Rosman *et al.*, 1997 ; Bindler *et al.*, 2001a ; Bindler *et al.*, 2001b ; Shotyk *et al.*, 2005 ; Zheng *et al.*, 2007 ; Michelutti *et al.*, 2009 ; Liu *et al.*, 2012).

L'Arctique subit aussi, et plus que toute autre région du monde, les effets du réchauffement climatique en cours (Arctic Climate Impact Assessment, 2005 ; Screen and Simmonds, 2010) associés aux émissions de gaz à effet de serre (Gillett *et al.*, 2008). Les mécanismes de l'amplification arctique font que la région se réchauffe plus vite que le reste de la planète (fig. 3), et ce phénomène devrait s'accélérer dans les décennies à venir (Serreze and Barry, 2011).

Dans ce contexte, la combinaison de ces processus de changements globaux anthropogéniques (changements climatiques, pollution, occupation des sols) devrait avoir des conséquences profondes, tant d'un point de vue écologique que socio-économique et culturel (Arctic Climate Impact Assessment, 2005 ; Post *et al.*, 2009 ; Callaghan *et al.*, 2010). Par conséquent, les études rétrospectives à long terme des variabilités climatiques et des impacts anthropiques, par le

1 Colons

2 Dans la plupart des cas, les espèces arborescentes ne dépassent pas quelques dizaines de centimètres.



**Fig.3** (a) Tendence linéaire de la moyenne annuelle des températures atmosphériques de surface pour la période 1960-2011. (b) La même tendence linéaire moyennée en fonction de la latitude (NASA GISS, <http://data.giss.nasa.gov/gistemp/>).

biais des enregistrements paléoenvironnementaux, sont plus que jamais nécessaires à la prévision des changements à venir dans cette région clé.

## 5 | Cadre et objectifs de la thèse

Dans le contexte géographique de la colonisation agro-pastorale médiévale groenlandaise, de très nombreux lacs offrent la possibilité de disposer d'archives sédimentaires optimales pour l'étude des évolutions environnementales des secteurs colonisés, mémoire des mutations écologiques engendrées par l'anthropisation et les variations climatiques naturelles. Le projet de recherche « *ULTIMAGRI<sup>3</sup> Impact environnemental de l'agro-pastoralisme médiéval au Groenland* » (UMR 6249, Chrono-environnement), où le présent travail de thèse trouve son origine, se situe dans une approche résolument Homme/Climat. Ses objectifs principaux et les résultats attendus portent sur trois axes :

- (i) la compréhension des mécanismes d'interaction entre le forçage climatique et le forçage anthropique sur la dynamique sédimentaire de systèmes lacustres dont les bassins versants ont été colonisés par les agriculteurs scandinaves ;
- (ii) l'évaluation des mutations environnementales liées à l'emprise de l'agro-pastoralisme ainsi que la résilience du milieu après l'abandon des colonies ;

<sup>3</sup> En référence à l'« Ultima Thule » de Jean Malaurie, explorateur et anthropologue français.

- (iii) la précision des connaissances de l'histoire du peuplement médiéval scandinave au Groenland.

Dans la lignée des travaux du pionnier Bent Fredskild (1973), le projet s'appuie sur l'étude multiparamètres à haute résolution temporelle de séquences lacustres prélevées au cœur des deux colonies vikings principales. Quatre missions de reconnaissance et de carottages (financements BQR Université de Franche-Comté, Région de Bourgogne, Institut Polaire Paul-Emile Victor et ANR Projet "Green Greenland") ont été entreprises en 2006, 2007, 2009 et 2011 dans l'implantation « orientale » (district de Narsaq / 61°N), hors zone archéologique (région de Paamiut / 62°N) et dans l'implantation « occidentale » (district de Nuuk / 64°N) (cf. chapitre 1).

Évidemment, les objectifs sont ambitieux et dépassent la capacité d'une thèse de doctorat à y répondre totalement. Aussi, ce travail constitue une étape en direction des réponses attendues. Il s'attache, dans un premier temps, à caractériser le cadre paléoclimatique et paléoenvironnemental de la région au cours de l'Holocène en intégrant la compréhension des mécanismes de forçages naturels avant l'arrivée des premiers agriculteurs. Dans un second temps, l'étude accroît sa résolution temporelle et se focalise sur l'implication des forçages anthropiques du dernier millénaire.

Parmi l'ensemble des séquences sédimentaires récoltées au cours des missions de terrain, la séquence du lac d'Igaliku (61°N) s'est rapidement imposée comme la pièce maîtresse du programme et le support

de ce travail de thèse. Centre politique et religieux de l'Établissement Oriental et première zone recolonisée après l'abandon des colonies médiévales, Igaliku est le site emblématique de l'agriculture au Groenland. La séquence sédimentaire du lac possède en outre le potentiel de documenter la variabilité du contexte climatique de la région au cours des 10 derniers millénaires.

## 6 | Organisation du manuscrit

Afin de valoriser le travail d'une équipe de recherche pluridisciplinaire, la présente thèse est rédigée sous la forme de cinq articles, formant chacun un chapitre du manuscrit. Parmi ces articles, quatre ont été publiés dans des revues à comité de lecture. La publication scientifique impose de nombreuses contraintes, notamment en termes de délais, de concision et d'exigences du comité de lecture. Les délais sont parfois très longs entre la soumission et la publication. Par conséquent, l'ordre de parution des articles ne correspond pas forcément à une logique scientifique mais dépend plutôt des opportunités et de la nécessité de publier en priorité les résultats les plus marquants et les plus novateurs. Pour pallier ces contraintes, le manuscrit est organisé selon une logique d'échelle temporelle décroissante, de l'Holocène (**chapitre 3**) jusqu'aux impacts les plus récents (**chapitres 5 et 6**), et aussi selon une logique méthodologique (le **chapitre 6** reprend des résultats des **chapitres 4 et 5**).

Après un court chapitre concernant le matériel étudié et les méthodes employées (**chapitre 1**), le **chapitre 2** pose le cadre historique de cette étude. Il correspond à un article publié dans la revue *Sciences Humaines Combinées*, revue électronique des écoles doctorales de Lettres et Sciences Humaines des universités de Bourgogne et de Franche-Comté (<http://revuesshs.u-bourgogne.fr/lisit491/document.php?id=627>). Ayant pour titre : « *L'implantation médiévale scandinave de la côte sud-ouest du Groenland comme la limite du modèle agro-pastoral importé d'Europe du nord : Implications paléoenvironnementales* », c'est une partie introductive relatant la colonisation agraire du Groenland au cours de la période médiévale. L'article fait aussi état de l'avancement de la recherche paléoenvironnementale au sud du Groenland lors du commencement de ce travail de thèse, pointant ses lacunes et évaluant le potentiel des enregistrements lacustres. Une version abrégée de cet article a également été publiée dans un volume faisant suite à un symposium international consacré à la préhistoire en Amérique tenu dans le

cadre du Congrès annuel des sociétés historiques et scientifiques, organisé à Québec en juin 2008 (Massa *et al.*, 2011).

Le **chapitre 3**, intitulé "*A multiproxy evaluation of Holocene environmental change from Lake Igaliku, South Greenland*", répond au premier objectif de cette thèse. Par le biais d'une approche multi-paramètres, incluant diatomées, pollen et marqueurs sédimentologiques, cette étude reconstitue les évolutions environnementales majeures ayant affecté le lac d'Igaliku et son bassin versant au cours de son histoire postglaciaire. Cette article est une contribution au numéro spécial de *Journal of Paleolimnology* : «*Holocene paleoenvironmental records from Arctic lake sediment*», à paraître en juin 2012 et édité dans le cadre du programme international ARCSS 8K supervisé par Darrel Kauffman (<http://www.arcus.org/synthesis8k/index.php>).

Le **chapitre 4** est consacré à l'étude des grains de pollen et des microfossiles non-polliniques (MNP) de la séquence lacustre d'Igaliku sur les 1500 dernières années. Intitulé : "*Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland*", cette étude est la première à utiliser, en plus de l'approche palynologique classique, l'abondance des MNP pour mettre en évidence la pression pastorale sur l'environnement groenlandais et suivre son évolution. Cet article est une contribution au numéro spécial de *Vegetation History and Archaeobotany* : "*Fresh insights into the palaeoecological and palaeoclimatological value of Quaternary non-pollen palynomorphs*", édité par Jean Nicolas Haas (Volume 19, novembre 2010). Les analyses polliniques et la détermination des MNP présentées dans cet article ont été réalisées par Emilie Gauthier (UMR CNRS 6249 Chrono-environnement).

Le **chapitre 5** combine l'utilisation des frustules de diatomées et des isotopes stables du carbone et de l'azote afin de caractériser l'impact des activités agricoles médiévales et récentes sur l'écologie du lac. Intitulé "*A Paleoeological Perspective on 1450 years of Human Impacts from a Lake in Southern Greenland*", c'est la première étude du genre au Groenland. Cet article a été publié dans la revue *The Holocene* (accessible en ligne depuis le 1<sup>er</sup> mars 2012, doi: 10.1177/0959683612437865). La détermination des flores de diatomées a été réalisée par Bianca Perren, dans le cadre de son contrat post-doctoral au laboratoire Chrono-environnement (UMR CNRS 6249).

Le **chapitre 6** reprend les résultats majeurs des deux chapitres précédents pour les associer à la première quantification de l'érosion passée des sols à partir

d'une séquence sédimentaire lacustre du Groenland. Dans cette partie, intitulée "*A 2500 year record of natural and anthropogenic soil erosion in South Greenland*", la comparaison quantitative et qualitative des flux détritiques, pendant et en dehors des périodes d'anthropisation, a permis d'estimer l'intensité de l'érosion provoquée par l'agriculture médiévale et contemporaine. Cet article a été publié dans la revue *Quaternary Science Reviews* (Volume 32, janvier 2012).

Enfin, une **conclusion générale** résume la contribution de cette thèse aux connaissances paléoenvironnementales du sud du Groenland, tant du point de vue des impacts anthropiques et du paléoclimat que de la méthodologie. Certains points de discussion et autres détails méthodologiques qui n'ont pas pu être détaillés dans les articles y sont approfondis. Sont aussi abordés les futurs développements nécessaires à l'étude des interactions Homme/Climat/Environnement au Groenland à partir de la paléolimnologie.



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# Chapitre 1

## Matériel et méthodes

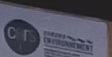


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## Chapitre 1

### Matériel et méthodes

#### 1.1 | Missions de terrain

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##### 1.1.1 Techniques de carottage

Les travaux antérieurs réalisés sur des lacs du sud du Groenland (Sandgren et Fredskild, 1991 ; Kaplan *et al.*, 2002), indiquent un taux de sédimentation annuel infra millimétrique. Au regard des objectifs chronologiques du projet de recherche, qui couvre la période historique, la longueur des carottages à réaliser n'excède guère 1 mètre. Cette situation offre l'avantage de permettre l'emploi d'un carottier gravitaire manipulable depuis une embarcation légère de type Zodiac. La plupart des carottages ont été réalisés au moyen d'un carottier UWITEC (Hammercorer) et d'un tubage PVC Ø 63 mm ou 90 mm.

Pour autant, lors de la mission 2007, dans la perspective de disposer de séquences couvrant l'intégralité de la sédimentation depuis le dernier retrait glaciaire, des carottages plus profonds ont été réalisés au moyen d'un carottier à percussion de trois mètres (Ø 63 mm) depuis une plate-forme de forage UWITEC). La plupart du temps les carottages ont été doublés sur un même site afin de disposer de quantités de sédiments suffisantes pour les besoins d'une étude sédimentologique multiparamètres.

Pour des raisons techniques, aucun remplissage lacustre n'a fait l'objet d'une reconnaissance par imagerie sismique préalable aux opérations de carottage. Aussi, l'une des stratégies de terrain a consisté à multiplier les lacs carottés afin de disposer, au final, de quelques séquences optimales pour répondre aux objectifs du projet.

##### 1.1.2. Région de Narsaq

(missions *ULTIMAGRI 2007 et 2009*)

Les carottages dans le secteur archéologique sud (61°N / région de Narsaq) ont été réalisés au cours de l'été 2007 (fig. 1.1, tab. 1.1). Les lacs carottés se trouvent parmi les ruines de nombreuses fermes et édifices religieux, au niveau des bassins agricoles médiévaux de *Brattahlid* (Qassiarsuk), *Garðar* (Igaliku) et du *Vatnahverfi* (Sondre-Igaliku).

Les sites d'investigation choisis ont été sélectionnés selon deux critères :

(i) un critère régional correspondant à une localisation au cœur des bassins agricoles médiévaux, comprenant une forte densité de vestiges archéologiques ;

(ii) un critère local avec la présence des ruines d'une ou plusieurs fermes vikings dans le bassin versant du lac étudié, principalement localisées à partir des prospections archéologiques d'Algreen-Møller et Madsen (2006) et de Guldager *et al.* (2002).

Au cours de l'année 2009, une nouvelle campagne menée sur les mêmes sites afin de compléter l'étude des sites carottés en 2007 par un échantillonnage des sols des bassins versant et par la mesure des caractéristiques physico-chimiques de la masse d'eau des lacs. Ces mesures sont en effet nécessaires à une bonne interprétation des conditions de sédimentation (stratification, état trophique, caractérisation des sources de sédiment).

##### 1.1.3. Région de Nuuk et Paamiut

(mission *ULTIMAGRI 2009*)

Cette mission avait pour objectif d'étendre le projet à l'étude de systèmes lacustres situés dans l'implantation « occidentale » (district de Nuuk / 64°N). Deux séquences lacustres ont ainsi été prélevées au printemps 2009 à proximité du village de Kapisillit (fig. 1.1, tab. 1.1), dans un contexte archéologique d'installations agricoles médiévales. Aux séquences prélevées en contexte archéologique s'ajoute le prélèvement de deux séquences situées hors de toute influence agropastorale, médiévale ou contemporaine, afin de disposer d'une référence sédimentaire en contexte non-anthropisé, mise en place uniquement sous forçage climatique. Deux séquences ont ainsi été prélevées à 62°N, à quelques dizaines de kilomètres de la ville de Paamiut (fig. 1.1).

##### 1.1.4. Région de Qaqortoq

(mission *ANR Green-Greenland 2011*)

Au cours de l'été 2011, une nouvelle série de carottages a été réalisée sur quelques lacs de la région de Qaqortoq (61°N – fig. 1.1, tab.1.1), à proximité du secteur d'étude de la mission *ULTIMAGRI 2007*. Ces carottages s'inscrivent dans une perspective d'étude



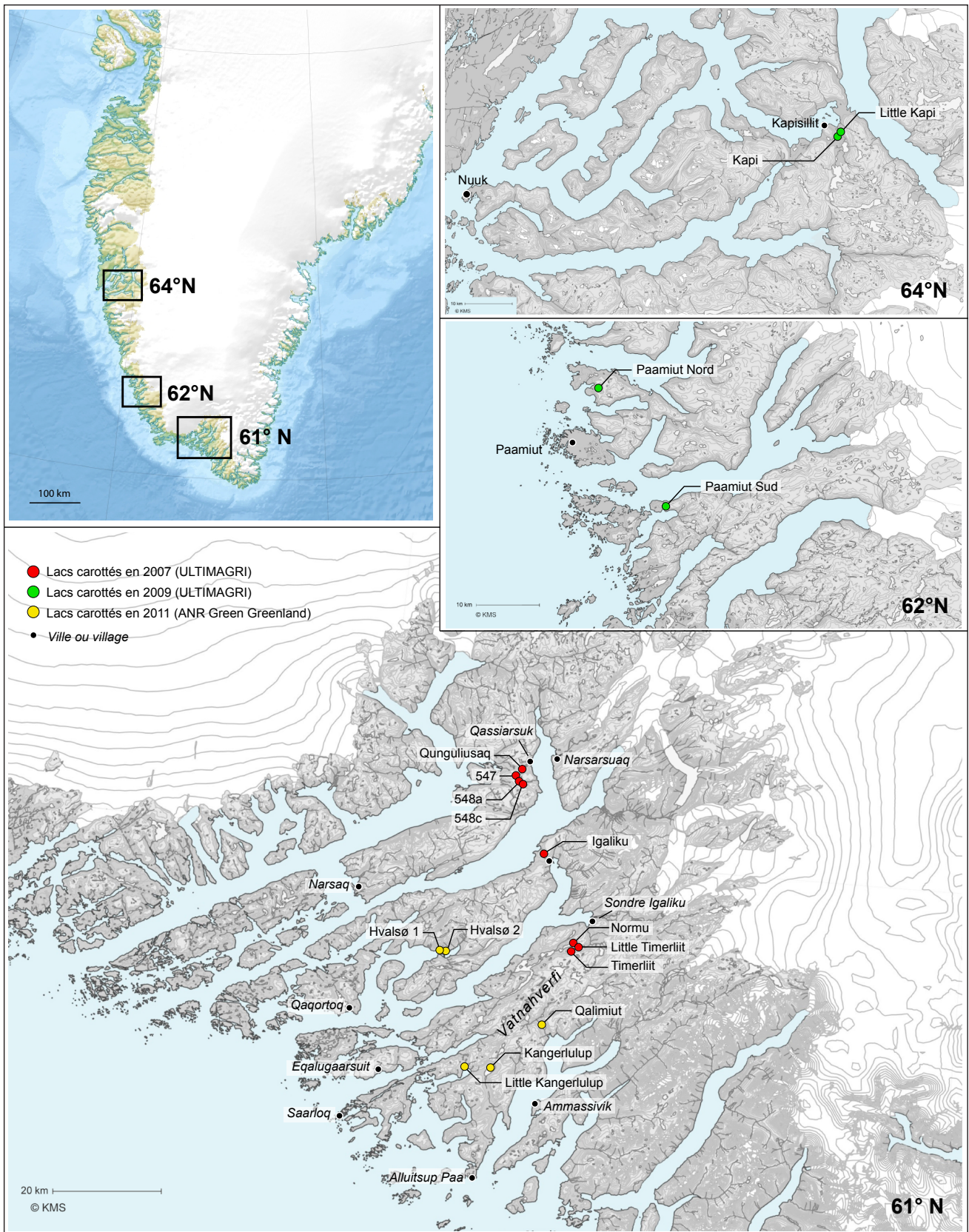


Fig. 1.1 Localisation des lacs carottés dans le cadre des programmes ULTIMAGRI et ANR Green-Greenland

Année	Mission	Zone	Secteur	Lac	GPS	Altitude	Longueur séquence	Profondeur interface	Site archéologique	Analyses réalisées
					Lat. / Long.					
2007	Ultimagri	Sud 61°N	Qassiarsuk Brattahlid	Qungulusaq	N61°08'11" O45°32'17"	120 m	4,5 m	-11,0 m	Ø548	MSCL (5 mm), XRF (2 mm), SCOPIX GS (91), LOI (143), <sup>14</sup> C (8)
				548-07a	N61°07'18" O45°31'48"	135 m	1.3 m	-2,0 m		MSCL (5 mm), XRF (5 mm), SCOPIX
				548-07c	N61°07'14" O45°31'49"	135 m	1.1 m	-9,8 m		
				547-07	N61°07'37" O45°33'19"	160 m	1.9 m	-2,5 m		
			Igaliku Gardar	Igaliku	N61°00'24" O45°26'30"	15 m	4 m	-20,1 m	Gardar	MSCL (5 mm), XRF (2 mm), SCOPIX GS (178), LOI (n), CNS (469) δ <sup>13</sup> C & δ <sup>15</sup> N (104), ICP-MS, DRX, Pb <sup>14</sup> C (34), <sup>137</sup> Cs (20), <sup>210</sup> Pb (14) POL (83), DIAT (155), CHIRO (104)
			Sondre Igaliku Vatnahverfi	Normu Saqqaata	N60°51'37" O45°19'09"	20 m	3.2 m	-4,6 m	Ø068	MSCL (5 mm), XRF (5 mm), GS (110), <sup>14</sup> C (5), <sup>137</sup> Cs (10)
				Timerliit	N60°51'08" O45°18'42"	30 m	2.6 m	-1,2 m	Ø069	MSCL (5 mm), XRF (5 mm), SCOPIX
				Little Timerliit	N60°51'05" O45°18'22"	30 m	0.9 m	-4,5 m		MSCL (5 mm), XRF (5 mm), SCOPIX
2009	Ultimagri	62°N	Paamiut	Paamiut Sud	N61°56'13" O45°18'09"	158 m	1.0 m	-25 m	aucun	MSCL (5 mm)
				Paamiut Nord	N62°04'51" O49°36'39"	97 m	0.9 m	-35 m	aucun	MSCL (1 mm), XRF (1 mm), SCOPIX <sup>14</sup> C (1)
2009	Ultimagri	Nord 64°N	Kapisillit	Kapi	N64°25'08" O50°11'45"	70 m	1.3 m		non ref.	MSCL (1 mm), XRF (1 mm), SCOPIX
				Little Kapi	N64°25'33" O50°11'39"	90 m	1.1 m		non ref.	MSCL (1 mm), XRF (1 mm), SCOPIX CNS (108), DIAT (36), <sup>14</sup> C (4)
2011	ANR Green-Gr.	Sud 61°N	Qallimiut	Qallimiut	N60°43'27" O45°23'12"	40 m	1.2 m	-26 m	77	MSCL (1 mm), XRF (1 mm), SCOPIX
				Kangerlulup	Kangerlulup	N60°38'23" O45°33'13"	180 m	0.75 m	-35 m	
			Little Kanger		N60°38'32" O45°38'11"	10 m	1.1 m	-6,4 m	E178	
			Hvalsø		Hvalsø I	N60°49'40" O45°23'12"	15 m	1.2 m	-2,0 m	
				Hvalsø II	N60°49'43" O45°44'39"	25 m	1.3 m	-2,5 m		

**Tab 1.1** Inventaire des lacs carottés lors des programmes ULTIMAGRI et ANR Green-Greenland

différente du projet ULTIMAGRI et visent à évaluer la réponse des écosystèmes lacustres au développement de l'agriculture contemporaine, dans le contexte du réchauffement climatique en cours.

L'étude de ces carottages sort du cadre initial de cette thèse et leur localisation n'est présentée ici qu'à titre informatif.

## 1.2. | Choix des séquences

Au total, dix-sept séquences lacustres inédites ont été échantillonnées le long de la côte Sud-Ouest du Groenland (fig. 1.1), au cours de 3 missions de terrain. En première approche, les carottes ont systématiquement fait l'objet de diagraphies non destructives (cf. § 1.4.1) et d'une description visuelle. Ce premier examen a permis d'écarter, *a priori*, les séquences offrant peu de variabilité sédimentaire ou, *a contrario*, des discontinuités susceptibles d'affecter la continuité de l'enregistrement (bioturbations, hiatus évidents, limites érosives, dépôts instantanés, etc.). Sur l'ensemble des séquences disponibles, six sont en cours d'étude. Dans le cadre de la présente thèse, seuls

les développements analytiques approfondis menés sur la séquence du lac d'Igaliku sont présentés.

La priorité d'étude donnée à la séquence du lac d'Igaliku a été guidée par les observations suivantes :

(i) la séquence d'Igaliku présente une variabilité remarquable par rapport aux autres séquences, avec notamment la présence de laminations visibles sur la radiographie X, garantes d'une sédimentation continue et non perturbée ;

(ii) le lac d'Igaliku a fait l'objet d'un carottage profond, de 4 mètres depuis l'interface eau-sédiment, permettant l'évaluation de la réponse sédimentaire et paléocéologique aux changements environnementaux historiques mais aussi holocènes ;

(iii) contrairement aux autres séquences, celle du lac d'Igaliku est relativement riche en macrorestes végétaux d'origine terrestre, permettant l'établissement d'une chronologie radiocarbone précise et non biaisée (cf. **chapitre 3**). Les autres séquences se sont avérées, soit très minérales pour les grands lacs (Normu, Paamiut, Timerliit, Kapisillit), soit très peu compactées, avec 80-90% d'eau pour les sédiments des petits lacs



Fig. 1.2 Vue du village d'Igaliku (photo V. Bichet)

(Qungulusaq, 548, 547, Little Timerliit, Little Kapissilit). Parmi ces derniers, une seule carotte de 63 mm a été prélevée dans lacs 547, 548 et Little Timerliit, limitant ainsi grandement la disponibilité en sédiments et donc l'éventualité d'une chronologie robuste et *a fortiori* d'une étude multi-paramètres ;

(iv) enfin, l'argument majeur est que le lac d'Igaliku est situé à proximité des ruines de *Garðar*, site archéologique emblématique de la colonisation médiévale scandinave (cf. **chapitre 2**). Il est aussi au cœur de la zone agricole moderne et le lieu du renouveau de l'agriculture au Groenland depuis les années 1920 (cf. **chapitres 5 et 6**).

Pour l'ensemble de ces raisons, le lac d'Igaliku s'avère être le lieu idéal pour étudier les impacts de l'agriculture médiévale et moderne sur les écosystèmes lacustres groenlandais.

### 1.3. | Le site d'Igaliku

#### 1.3.1. Le lac

Diverses appellations locales désignant le lac d'Igaliku, nous avons retenu, par simplification et avantage de localisation géographique, la dénomination éponyme du village d'une cinquantaine d'habitants situé au bord du fjord à moins de 2 kilomètres des rives du lac (fig. 1.2).

Le lac (fig. 1.3) est situé à 15 m d'altitude au dessus du niveau marin moyen. Il couvre une surface oblongue globalement Nord-Sud, de 35 hectares. Il ne reçoit pas de tributaire majeur mais un ensemble de petits tributaires à faible débit, qui drainent les versants du lac (cf. § 1.3.2). La bathymétrie réalisée par échosondeur lors de la campagne de carottage (fig. 1.4) indique une topographie en cuvette et un maximum de profondeur de 26 m, dans la partie septentrionale du lac. L'exutoire

du lac, est drainé au Nord, vers le fjord de Tunulliarfik (Erik's Fjord).

La variabilité saisonnière de son niveau semble faible, limitée à quelques décimètres entre les hautes et les basses eaux. Aucun indice de terrain ne laisse supposer que le lac ait connu des variations anciennes particulières.

#### 1.3.1. Le bassin versant

Le lac d'Igaliku est associé à un bassin versant de 4 kilomètres carrés, limité à l'Est et à l'Ouest par les fjords d'Igaliku et de Tunulliarfik (Erik's Fjord), et par des reliefs avoisinant 400 mètres d'altitude au nord, et plus de 800 mètres au sud (fig. 1.3). Autour du lac, la végétation arbustive actuelle est dominée par le bouleau (*Betula glandulosa*), le saule (*Salix glauca*), et le genévrier (*Juniperus communis*). Une ferme associée à un parcellaire de prairies de fauche d'environ 30 hectares occupe aujourd'hui la rive sud du lac. Une très large part du bassin versant est pâturée par les moutons en période estivale, favorisant le développement d'une flore typique des milieux agropastoraux groenlandais. Les espèces les plus emblématiques de cette flore sont les renoncules (*Ranunculus acris*), l'oseille (*Rumex acetosa*) et le pissenlit (*Taraxacum officinale*). Au-delà de 500 m la végétation se raréfie et les sols sont peu développés.

Le cadre géologique régional est caractérisé par une large diversité lithologique incluant divers corps plutoniques, volcaniques et sédimentaires (fig. 1.5). Le substratum géologique du bassin versant d'Igaliku est principalement composé de granites. Ceux-ci font partie du batholite de Julianehåb (appellation danoise de la ville de Qaqortoq) mis en place entre 1855 et 1800 Ma lors de l'orogénèse Ketilidienne (début du Protérozoïque) (Upton *et al.*, 2003). Ces granites



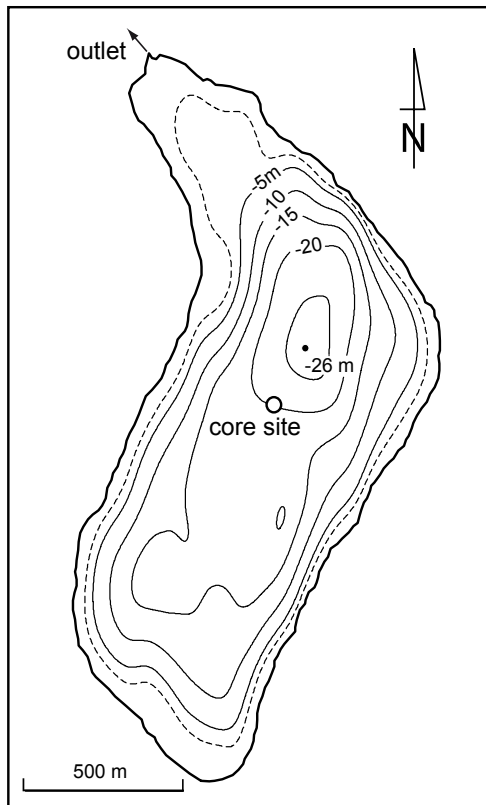
**Fig. 1.3** Le lac d'Igaliku dans son contexte agricole - vue vers le Nord (photo V. Bichet)

calco-alcalins sont recouverts en discordance par la formation d'Eriksfjord, constituée de grès arkosiques fluvio-éolien riches en fer, intercalés de sills basaltiques (Poulsen, 1964 ; Clemmensen, 1988 ; Tirsgaard et Øxnevad, 1998).

Bien qu'il n'affleure pas dans le bassin versant du lac, on peut signaler un peu plus à l'Est, la proximité du complexe igné d'Igaliku mis en place entre 1300 et 1120 Ma (Protérozoïque Moyen). Ce complexe sous-

saturé, le plus important de la province, comprend cinq centres parmi lesquels celui nommé Igdlersfigsalik Ancien (1143 Ma) est le plus proche du lac. Il est particulièrement riche en néphéline et syénite, des feldspathoïdes caractéristiques des roches alcalines sous-saturées. Pearce and Leng (1996) y soulignent aussi la présence de dykes de carbonatites.

Toutes les formations citées précédemment sont parcourues par un faisceau de failles orientées ENE-OSO, affectant préférentiellement la Formation d'Eriksfjord, et recoupées par de nombreux dykes de syénites et dolérites parallèles au réseau de failles. Enfin, des dépôts glaciaires non-consolidés, éoliens, fluvio-glaciaires ou glacio-marins (dépôts quaternaires indifférenciés) témoignent du dernier retrait glaciaire il y a environ 12000 ans dans le secteur d'Igaliku (Larsen *et al.*, 2011). Ces dépôts superficiels qui tapissent le bassin versant sont susceptibles de comporter un spectre pétrographique et minéralogique silicaté, nourri par l'ensemble des formations géologiques régionales. Les sols, sont généralement sableux, les silts et les sables constituant plus de 90% de la fraction > 2 mm, et très acides avec un pH compris entre 3,6 et 4,5 (Rutherford, 1995). Malgré le pH faible et la teneur réduite en argiles, la capacité d'échange cationique est élevée grâce à une forte teneur en matière organique. La courte durée de la saison estivale limite en effet la décomposition de la matière organique. Dans le bassin versant d'Igaliku, la teneur en matière organique des 5 premiers centimètres de sol varie entre 6% et 75%, avec une moyenne de 22,3% (n = 25) (cf. **chapitre 6**).



**Fig. 1.4** Bathymétrie du lac d'Igaliku et localisation du site carotté

### 1.3.2. Le climat actuel

Le lac d'Igaliku se trouve dans la zone climatique subcontinentale à subarctique du sud du Groenland (Feilberg, 1984), influencé à la fois par des masses

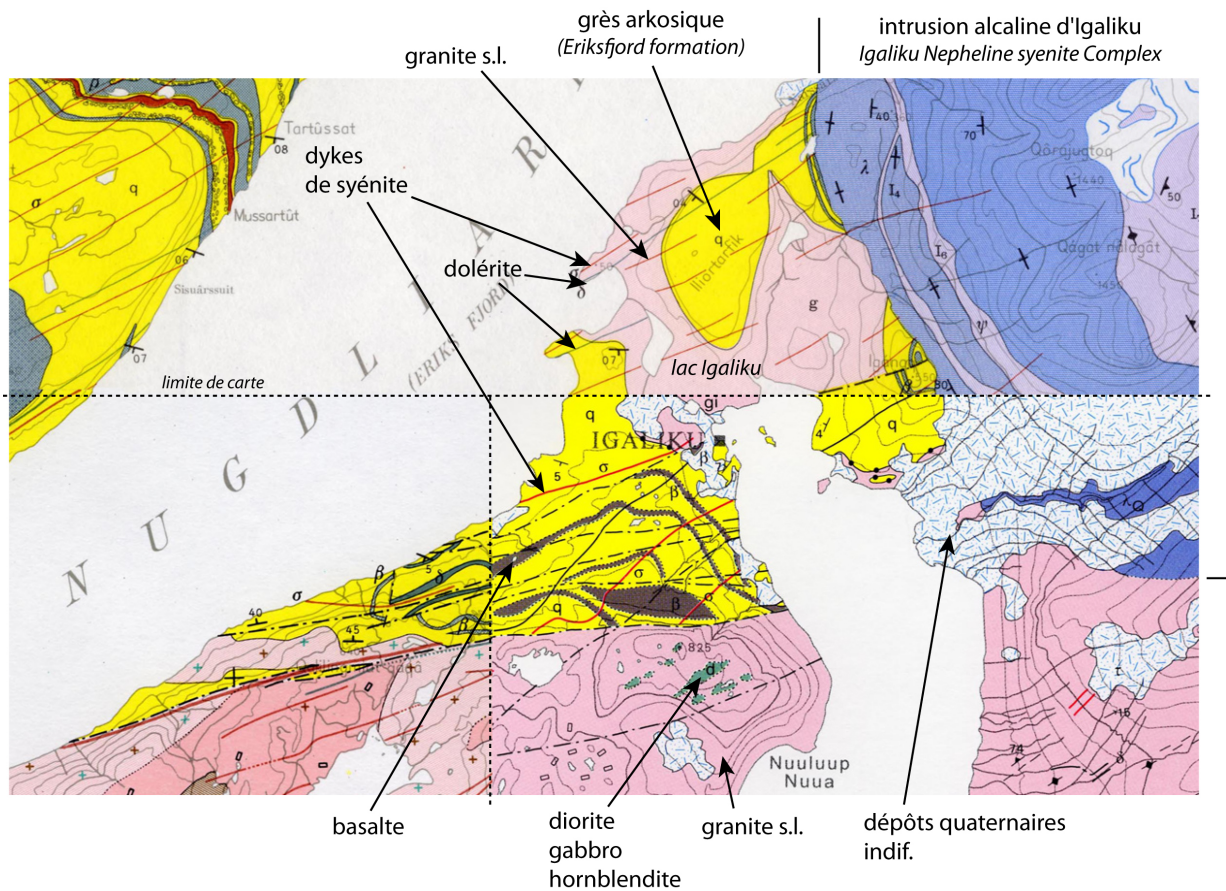


Fig. 1.5 Carte géologique du secteur d'Igaliku (cartes 1/100 000<sup>e</sup> GEUS-Copenhague)

d'air froid, associées à la proximité de la calotte polaire, et par un air maritime plus chaud lié aux courants océaniques de surfaces (cf. **chapitres 2 et 3**). La région est notamment sous l'influence des eaux polaires froides ( $< 0^{\circ}\text{C}$ ) et de faible salinité du Courant Est Groenlandais et des eaux relativement chaudes et salées ( $+ 4^{\circ}\text{C}$ ) dérivant du courant d'Irminger. Il existe un large gradient climatique entre la zone côtière et l'intérieur des terres (fig. 1.6). L'hiver, la côte sous l'influence de l'océan, est plus chaude que l'intérieur des fjords d'environ  $2^{\circ}\text{C}$ . L'été on peut observer le gradient inverse avec des plus hautes températures dans les fjords (Cappelen *et al.*, 2001). En contrepartie, tout au long de l'année, les précipitations sont nettement moins abondantes dans les terres. Les données météorologiques relevées à la station de Narsarsuaq, à 5 km au nord d'Igaliku, indiquent que les températures moyennes mensuelles varient entre  $- 6,8^{\circ}\text{C}$  (janvier) et  $+ 10,3^{\circ}\text{C}$  (juillet) avec des précipitations moyennes annuelles de 615 mm. Avec une température positive seulement 6 à 8 mois de l'année et des gelées pouvant intervenir durant l'été, la région est proche des limites physiques et climatiques des systèmes agricoles de

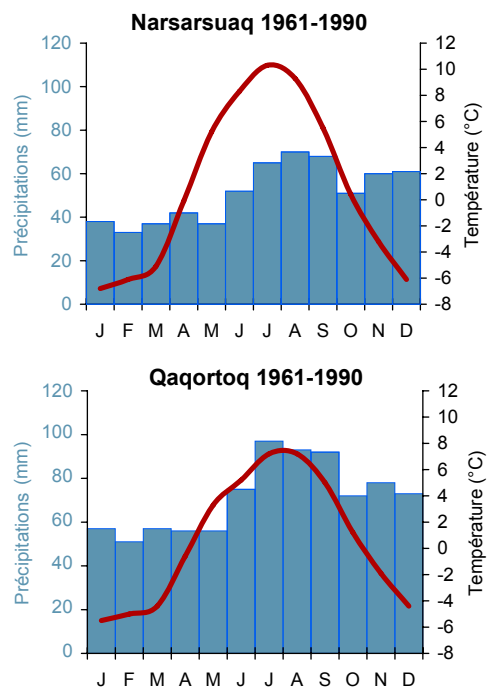


Fig. 1.6 Diagrammes ombrothermiques des stations de Narsarsuaq et de Qaqortoq (sud du Groenland) au cours de la période 1961-1990 (données de Cappelen *et al.*, 2001)

type européen (Dugmore *et al.*, 2005, cf. **chapitre 3**). Une caractéristique locale accroît encore la rudesse du climat : la récurrence de vents catabatiques violents issus de l'inlandsis, pouvant dépasser 40 m/s (Cappelen *et al.*, 2001).

#### **1.4. | Analyse des sédiments**

Les marqueurs physiques, chimiques et biologiques choisis pour cette étude sont pour la plupart utilisés en routine dans le cadre des recherches menées en paléolimnologie (Last et Smol, 2002). Ceux-ci sont connus pour varier sous l'influence de paramètres environnementaux forçant, naturels ou anthropiques. Avant l'échantillonnage des séquences et la réalisation d'analyses destructives, les carottes ont été soumises à une première série d'analyses diagraphiques avec un pas de mesure d'ordre millimétrique. Afin d'éviter les redondances, seules les méthodes de diagraphie continues sont plus particulièrement détaillées dans cette section. Les autres méthodes utilisées sont abordées dans les chapitres suivants (articles publiés).

##### **1.4.1. Diagraphie continue**

Les méthodes de diagraphie sont aujourd'hui largement utilisées pour obtenir un enregistrement haute résolution, voire continu, du message sédimentaire et permettre ainsi une caractérisation rapide et non destructive des sédiments (Zolitschka *et al.*, 2002). Elles permettent notamment l'évaluation rapide de la qualité de l'information et les corrélations stratigraphiques entre carottes. Aussi fournissent-elles l'information nécessaire à la mise en place de stratégies d'échantillonnage adaptées. Pour notre étude, différentes techniques de diagraphie physique, chimique et d'imagerie haute résolution ont été mises en œuvre :

##### *Diagraphie physique : Geotek "Multi-Sensor Core Logger"*

La mesure des paramètres pétrophysiques a été réalisée avec un banc Geotek "Multi Sensor Core Logger" (Laboratoire Chrono-environnement, Université de Franche-Comté), équipé de capteurs pour la mesure de la susceptibilité magnétique, de la  $\gamma$ -densité (densité apparente estimée par l'atténuation d'un rayonnement gamma<sup>1</sup> lors de son passage à travers la carotte), de

la vitesse de propagation des ondes acoustiques et d'une caméra numérique pour l'acquisition d'images haute résolution de la surface du sédiment (Gunn et Best, 1998). Les paramètres physiques dépendent habituellement d'une combinaison de facteurs tels que la variation de la taille des grains, la minéralogie, la teneur en matière organique ou la porosité. Ils sont des indicateurs sensibles des changements environnementaux qui contrôlent la productivité de la biomasse du lac et du bassin versant, l'altération, le transport et la sédimentation de la matière (Einsele, 2000).

Une attention particulière est portée à la susceptibilité magnétique qui permet de quantifier le contenu sédimentaire en minéraux magnétiques. En raison de l'érosion et du transport de la matière minérale, l'augmentation de la susceptibilité magnétique dans les zones d'accumulation sédimentaire peut être mise en relation avec la nature de la zone d'approvisionnement (Dearing *et al.*, 2001) et avec l'érosion des sols, qu'elle soit d'origine anthropique ou non (Vannière *et al.*, 2000 ; Arnaud *et al.*, 2005). Sur la base de l'étude des propriétés magnétiques de 4 séquences lacustres prélevées au cœur du bassin agricole de Qassarsuk, Sandgren et Fredskild (1991) étayaient l'hypothèse d'une érosion des sols accélérée par le défrichement et l'agropastoralisme pratiqués par les populations médiévales, puis par les pratiques actuelles. Nous discuterons de la pertinence de cette analyse dans le **chapitre 6**.

##### *Diagraphie chimique : Avaatech XRF Core Scanner*

L'analyse géochimique en continue a été réalisée au laboratoire EPOC (Université de Bordeaux 1) avec un scanner XRF Avaatech. Sous l'influence du rayonnement X incident, le cortège électronique de chacun des éléments constitutifs du sédiment est excité. Le surplus d'énergie est réémis sous la forme d'un rayonnement électromagnétique d'une longueur d'onde caractéristique pour chaque élément. Les amplitudes des pics du spectre XRF sont proportionnelles à la concentration des éléments correspondants. Du fait de la non homogénéité de l'échantillon (teneur en eau, texture) et des irrégularités de sa surface, les mesures obtenues sont seulement semi-quantitatives (Richter *et al.*, 2006). Pour limiter ces effets, chaque demi-section a été soigneusement lissée, perpendiculairement au plan de sédimentation pour supprimer les irrégularités, et recouverte d'un film plastique fin (Ultralene 4 $\mu$ m) qui diminue la rugosité de la surface et empêche la carotte de sécher. Malgré cela, les résultats obtenus doivent être interprétés avec précaution et il est préférable

1 Source : <sup>137</sup>Cs

d'utiliser des rapports entre éléments ou entre sommes d'éléments pour réduire les erreurs (cf. **chapitre 6**). Selon les séquences analysées, le pas de mesure varie de 1 à 5 mm et l'intensité du rayonnement de 10 à 30 kV. Les éléments détectés à 10kV sont : Al, Si, S, Cl, K, Ca, Ti, Mn, Fe ; et à 30kV : Fe, Rb, Sr, Ru, In, Pb.

#### *Imagerie aux rayons X : SCOPIX*

L'acquisition d'images haute résolution en 256 niveaux de gris a été réalisée avec le système d'imagerie SCOPIX, développé au laboratoire EPOC (Université de Bordeaux 1) (Migeon *et al.*, 1999 ; Lofi et Weber, 2001). Les rayons X passent à travers la demi-section et sont capturés par une caméra numérique, puis transmis à un ordinateur qui convertit le signal en une image en niveau de gris. Les rayons X sont atténués par des phénomènes variés tels que l'absorption et la dispersion. La densité du sédiment est le principal facteur de l'atténuation, mais par rapport à la  $\gamma$ -densité, qui est une mesure discrète, l'image en niveau de gris à l'avantage de permettre la distinction de variations locales dans la composition de l'échantillon (porosité, taille des grains). Les images obtenues sont ainsi des sources fiables en termes de propriétés physiques et d'interprétations lithostratigraphiques.

#### **1.4.2 Méthodes destructives**

Un vaste panel d'analyses sédimentologiques a été engagé sur la séquence d'Igaliku, dans la perspective d'avoir une lecture optimale des changements environnementaux survenus au cours des 10 millénaires que recouvre la séquence sédimentaire. La démarche analytique porte sur les paramètres biotiques (pollens, spores et microfossiles non polliniques, diatomées, chironomes, géochimie organique) et abiotiques ( $\mu$ -granulométrie, minéralogie, géochimie des éléments majeurs et ETM, isotopie du carbone et de l'azote). La méthodologie de ces analyses est développée dans les chapitres suivants.

#### **1.4.3. Chronologie**

La datation du sédiment est une étape indispensable dans toute étude sédimentologique. Elle permet d'établir une chronologie et de replacer le signal sédimentaire dans son contexte paléoclimatique et historique. La construction d'une chronologie fiable, et donc de flux non-biaisés, est un exercice difficile dans le cas des sédiments lacustres du Groenland. En général, les lacs de haute latitude ont un taux de sédimentation faible par rapport aux lacs des régions tempérées

(Wolfe *et al.*, 2004). Pour notre période d'intérêt, les 3 derniers millénaires, les taux de sédimentation des lacs sud-groenlandais varient entre 0,021 (Kaplan *et al.*, 2002) et 0,035-0,040 cm/an (Sandgren et Fredskild, 1991 ; Andresen *et al.*, 2004 ; Bennike et Sparrenbom, 2007) selon les critères géographiques et géomorphologiques. Compte tenu de ces différentes études, l'horizon du *landnám* se situe généralement dans les 50 premiers centimètres de sédiments de la plupart des lacs de l'« Etablissement oriental ». Ces faibles taux de sédimentation combinés à la grande incertitude des dates calibrées (communément  $\pm$  100 ans), compliquent l'identification de variations significatives des flux, et ceci d'autant plus pour des périodes relativement courtes : environ 450 ans pour la colonisation médiévale, et 100 ans pour les impacts anthropiques récents.

Pour surmonter ce problème, nous avons multiplié les datations et les méthodes pour les obtenir. Le contrôle chronologique de la séquence d'Igaliku est finalement basé sur 28 dates radiocarbone obtenues par spectrométrie de masse par accélérateur, dont 16 pour la période historique (Poznan Radiocarbon Laboratory et ARTEMIS-Lyon/Saclay). La plupart des datations ont été réalisées sur des matières organiques terrestres, principalement des feuilles et du bois de bouleau ou de saule. Aucune datation n'a été réalisée directement avec du sédiment brut.

La chronologie récente est établie par la mesure de l'activité en radio-isotopes du plomb-210 (spectrométrie alpha) et du césium-137 (spectrométrie gamma) par la société MyCore (Canada). La confiance que l'on peut placer dans un modèle plomb-210 est grandement renforcée lorsque celui est couplé à un profil d'activité du  $^{137}\text{Cs}$  (Smith, 2001 ; Giguët-Covex *et al.*, 2010). C'est particulièrement vrai dans la région arctique, où la diffusion du radon-222 dans l'atmosphère est réduite par l'influence du pergélisol et la faible surface continentale libre de glace, et son transfert dans les sédiments lacustres réduit par la couverture de glace prolongée (Wolfe *et al.*, 2004). Idéalement la mesure de l'activité du  $^{137}\text{Cs}$  fournit trois repères chronostratigraphiques complémentaires : 1954, l'année de la détection de niveaux significatifs de  $^{137}\text{Cs}$  provenant des essais nucléaires atmosphériques, le pic de retombées radioactives de 1963 (Pennington *et al.*, 1973) et l'accident de Tchernobyl en 1986.

## 1.5. | Confrontation des résultats avec les données paléoclimatiques régionales

Souvent, dans le cas d'un probable forçage anthropique de la dynamique sédimentaire, il s'avère difficile de démêler le rôle de l'Homme de celui du climat ; faute de référentiel climatique régional indépendant de l'action des sociétés humaines auquel le signal sédimentaire lacustre pourrait être comparé. Dans notre cas, le problème est partiellement levé par la toute proximité géographique d'archives climatiques de référence : celles de la calotte polaire groenlandaise, celles des sédiments des fjords et enfin ceux des sédiments des lacs situés hors contexte archéologique (fig. 1.7).

### 1.5.1 Les carottages glaciaires

Née de la transformation de la neige précipitée sur le continent, la calotte polaire groenlandaise (ou inlandsis) a stocké sur plusieurs kilomètres d'épaisseur des informations relatives aux variations des températures

atmosphériques et des précipitations depuis -123 000 ans (North Greenland Ice Core Project members, 2004). Willie Dansgaard (1964) a montré la forte relation existante entre les températures atmosphériques et la teneur en isotopes lourds de l'eau (fig. 1.8). Le  $\delta^{18}\text{O}$  des glaces constitue donc un «thermomètre isotopique» qui reflète les températures moyennes de l'atmosphère sur le site du forage (Jouzel *et al.*, 2000).

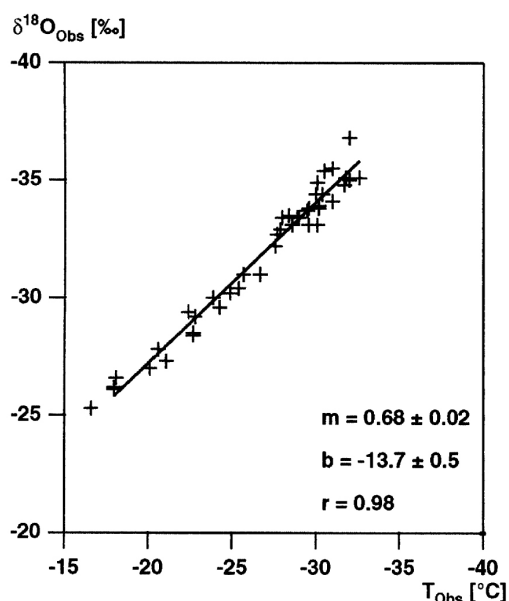
Le taux d'accumulation de neige est un autre paramètre classique tiré des carottages glaciaires. Il est issu du décompte et de la mesure de l'épaisseur des lits annuels de neige conservés dans la glace (stratification saisonnière des névés). Ce paramètre n'est pas une mesure directe des précipitations solides, mais la masse restée au sol après l'exportation par le vent et les pertes subies par évaporation et par sublimation. Néanmoins le taux d'accumulation de neige reflète d'assez près le total des précipitations régionales (Hanna *et al.*, 2006).

Pour confronter les marqueurs sédimentologiques aux données des glaces, notre choix s'est porté sur

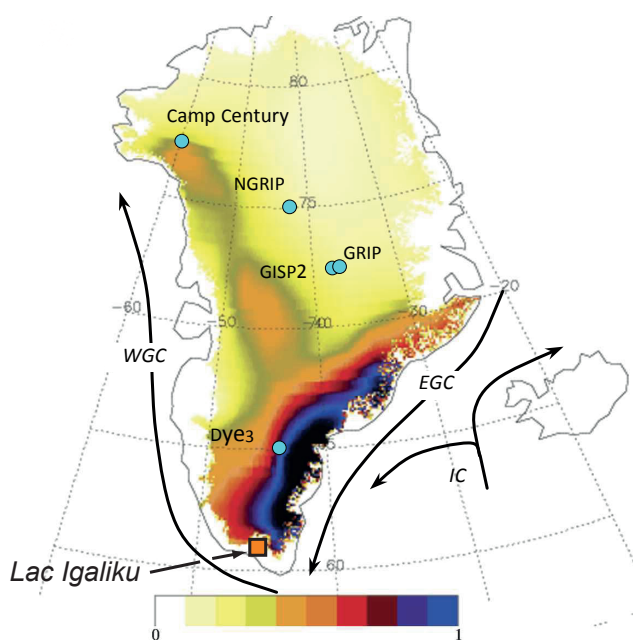


**Fig. 1.7** Cartes de localisation des référentiels paléoclimatiques holocènes disponibles au Sud du Groenland





**Fig. 1.8** Le «thermomètre isotopique» pour la calotte groenlandaise. Le  $\delta^{18}\text{O}$  observé dans les précipitations neigeuses actuelles est spatialement et linéairement corrélé aux températures mesurées dans l'atmosphère. (D'après Werner *et al.*, 1998, dans Jouzel *et al.*, 2000)



**Fig. 1.9** Taux annuel moyen d'accumulation de neige sur l'inlandsis groenlandais entre 1958 et 2003. L'échelle est graduée de 0 à 1m/an. On remarque que les précipitations neigeuses sont inégalement réparties, notamment au profit de la côte SE, sous l'influence du courant marin d'Irminger (IC), et d'une moindre mesure au profit de la côte ouest, sous l'influence du courant Ouest groenlandais (WGC). Elles présentent aussi un gradient général nord-sud. Sont figurées les positions des principaux carottages glaciaires et de la zone d'étude. (Modifié d'après Hanna *et al.* (2006))

la carotte Dye-3 (Dansgaard *et al.*, 1982) qui présente l'avantage d'être la plus proche de notre zone d'étude (fig. 1.7) et semble plus appropriée du fait de la signification régionale du  $\delta^{18}\text{O}$  (voir plus haut) et du taux d'accumulation de neige (fig. 1.9). Le site du forage se trouve en effet à 475 km du lac d'Igaliku, contre 1317 km pour GISP2 et 1328 km pour GRIP. Néanmoins, le taux d'accumulation de neige de Dye-3 est affecté par des déformations dues à l'écoulement gravitaire de la calotte groenlandaise (Reeh *et al.*, 1985). Ainsi, il est préférable d'utiliser le taux d'accumulation de neige à Dye-3 sur 1800 ans, corrigé des effets non climatiques (Andersen *et al.*, 2006).

### 1.5.2. Les carottages des fjords

Deux carottes de sédiments du fjord d'Igaliku, PO243-443 et PO245-251 (fig. 1.7) ont été l'objet d'études paléoclimatiques approfondies (Kuijpers *et al.*, 1999 ; Jensen *et al.*, 2004 ; Lassen *et al.*, 2004 ; Roncaglia et Kuijpers, 2004). Les auteurs se focalisent principalement sur la seconde moitié de l'Holocène et notamment sur les oscillations de l'Optimum Climatique Médiéval et du Petit Âge Glaciaire. Ces variations climatiques sont mises en relation avec les modifications de la circulation océanique de surface et de l'activité éolienne. Plus récemment, l'étude des débris rocheux transportés par les icebergs et retrouvés dans les sédiments de Narsaq Sound (carotte Ga 3-2 ; fig. 1.7), documente la dynamique de la terminaison glaciaire locale en réponse aux changements climatiques holocènes (Nørgaard-Pedersen et Mikkelsen, 2009).

### 1.5.3. Les sédiments lacustres

À proximité de l'Etablissement Oriental, deux séquences sédimentaires lacustres ont fait l'objet d'études à visées paléoclimatiques : lac Qipisarqo et le lac N14. Le lac Qipisarqo est situé à proximité d'une langue glaciaire s'écoulant du lobe de Qassimiut, un peu à l'Ouest de notre zone d'investigation (fig. 1.7). Une première étude basée essentiellement sur le dosage de la silice biogénique et de la matière organique documente la paléo-productivité du lac en relation avec les températures passées (Kaplan *et al.*, 2002). Une étude menée ultérieurement propose une reconstruction quantitative des paramètres climatiques (températures, luminosité, précipitations) à partir des assemblages polliniques (Fréchette et de Vernal, 2009). Le lac N14 est situé sur une île à proximité de la pointe sud du Groenland. L'interprétation paléoclimatique de la séquence du lac N14 est basé essentiellement sur le dosage à très

haute résolution de la silice biogénique (paramètre de températures / précipitations) et sur l'estimation des flux de sulfures (paramètre exprimant la fréquence et l'intensité des tempêtes) (Andresen *et al.*, 2004).

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## Chapitre 2

### **L'implantation médiévale scandinave de la côte sud-ouest du Groenland comme la limite du modèle agro-pastoral importé d'Europe du Nord : Implications paléoenvironnementales**





## Chapitre 2

Sciences  
Humaines  
Combinées

### L'implantation médiévale scandinave de la côte sud-ouest du Groenland comme la limite du modèle agro-pastoral importé d'Europe du Nord : Implications paléoenvironnementales

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#### Résumé

L'exploration des îles de l'Atlantique Nord au cours des IX<sup>e</sup> et XI<sup>e</sup> siècles par les populations scandinaves a conduit à la formation du front pionnier agricole le plus septentrional de l'époque médiévale. La colonisation de la côte sud-ouest du Groenland par des agriculteurs islandais puis norvégiens de 986 AD à environ 1450 AD, d'un milieu aux conditions climatiques extrêmes, va fournir l'exemple de la limite de l'agro-pastoralisme en contexte arctique. Face à la rigueur du climat, les colons scandinaves devront adapter leurs pratiques agricoles et se tourner de plus en plus vers la chasse et la pêche pour leur alimentation, conversion probablement accélérée par la dégradation des conditions climatiques au cours du Petit Age Glaciaire. Une bonne connaissance de ces pratiques par le biais des textes historiques et de l'archéologie est nécessaire à l'interprétation des archives sédimentaires témoins de l'activité agricole, de son impact sur l'environnement et de son évolution.

#### Abstract

During the Viking Age (ca. AD 800-1100) Scandinavian explorers settled the islands of the western North Atlantic, making the northernmost agricultural area of the medieval period. Expansion to south-west coast of Greenland at the end of the tenth century brought Norse settlers closer to the limits of their European-style agricultural systems. In response to the harsh low arctic climate, the Greenland Norse have adapted their farming strategies and changed their subsistence pattern, giving a more important place to hunting and fishing. This evolution had probably been accelerated by climatic changes of the Little Ice Age. A good knowledge of the Greenland Norse economy by means of historical and archaeological literature is necessary for the interpretation of sedimentary archives, witness of human land use, its impact upon the environment and its evolution from settlement to abandonment.

#### 2.1 | La découverte du Groenland

##### 2.1.1 L'expansion viking

A la fin du VIII<sup>e</sup> siècle, sous l'impulsion de différents facteurs dont l'essor du commerce scandinave et la forte pression démographique qui pèse alors sur l'étroit littoral norvégien, et par-dessus lesquels viennent se

greffer des raisons conflictuelles, un vaste mouvement d'émigration en direction des régions subarctiques et arctiques s'amorce pour culminer à la fin du X<sup>e</sup> siècle avec la découverte du Groenland et des côtes de l'actuel Canada. De nombreux auteurs s'accordent à dire que l'expansion vers les îles de l'Atlantique Nord a été grandement favorisée par l'embellie climatique du IX au XII<sup>e</sup> siècle appelé Optimum Climatique Médiéval

qui diminuait fortement la présence de glaces dérivantes comme le renseignent les chroniques de navigation des marchands islandais de l'époque (Koch, 1945). De même, la présence d'inscriptions runiques à très haute latitude (73°N au Groenland, 79°N en terre d'Ellesmere) ne peut se concevoir sans un faible englacement de la baie de Baffin et du détroit de Davis (fig. 1).

Les Scandinaves colonisent alors l'archipel des Orcades (800 AD), les Féroé (860 AD) puis l'Islande qui est investie par vagues d'immigration successives principalement entre 874 et 930 AD. À la fin du X<sup>e</sup> siècle, l'Islande compte plus de 50 000 habitants ; l'île connaît alors une sévère famine. Ce contexte tourmenté ouvre la voie à la colonisation du Groenland menée en l'an 986 par *Eiríkr Thorvaldson* (940-1010 ou 950-1003) plus connu sous le nom d'Erik le Rouge (*Eiríkr Rauði*).

### 2.1.2 La terre verte d'Erik le Rouge

D'après le *Landnámabók*<sup>1</sup>, Erik le Rouge fut contraint à un exil forcé à deux reprises. Son père, Thorvald Asvaldson fut d'abord banni de Jæren, ville située au sud de Stavanger en Norvège, à la suite d'un meurtre. Ainsi, le père et le fils s'exilèrent au nord-ouest de l'Islande à Drangát, dans la péninsule du Hornstrandir, vers l'an 970. Après son mariage avec Thjóðhild, fille de Jorund Atlason et Thorbjorg Knarrarbringa (Bruun, 1918), Erik déménagea à maintes reprises, toujours

à la recherche de meilleures terres afin d'améliorer leurs conditions de vie. Au cours de ce périple, en 981, une altercation violente entre Erik le Rouge et son voisin Thorgest Gamli provoqua la mort de plusieurs personnes. La responsabilité des protagonistes étant mal établie, un procès fut instruit et Erik condamné au bannissement pour une durée de trois ans.

En l'an 982, Erik le Rouge quitta l'Islande et partit à la recherche d'une nouvelle terre où il pourrait s'installer définitivement. Il navigua vers l'ouest en ayant probablement eu connaissance de l'aventure de Gunnbjörn Ulfsson. Cette histoire était bien connue dans le nord-ouest de l'Islande où Erik et la famille de Gunnbjörn avaient vécu (Gad, 1970 ; Jones, 1987 ; Nørlund, 1936). On racontait alors l'histoire de ce navigateur qui, entre 870 et 930, fut dérouteré par les vents au cours d'un voyage entre l'Irlande et l'Islande et échoua sur des îles situées à l'ouest de l'Islande jusqu'alors inconnues. Ces îles, qu'il nomma *Gunnbjarnar sker* (les écueils de Gunnbjörn), sont probablement situées à proximité de la localité actuelle de Angmagssalik sur la côte est du Groenland (Boyer, 1992). Erik rencontra les côtes du Groenland qu'il explora dans sa partie sud-ouest, du Cap Farewell (Nanortalik) à la localité actuelle de Julianehåb (Gad, 1970). Son voyage est évoqué dans la Saga d'Erik le Rouge<sup>2</sup> :

1 Le livre de la colonisation.

2 "La Saga d'Erik Le Rouge." M. Gravier, Paris. (1955).

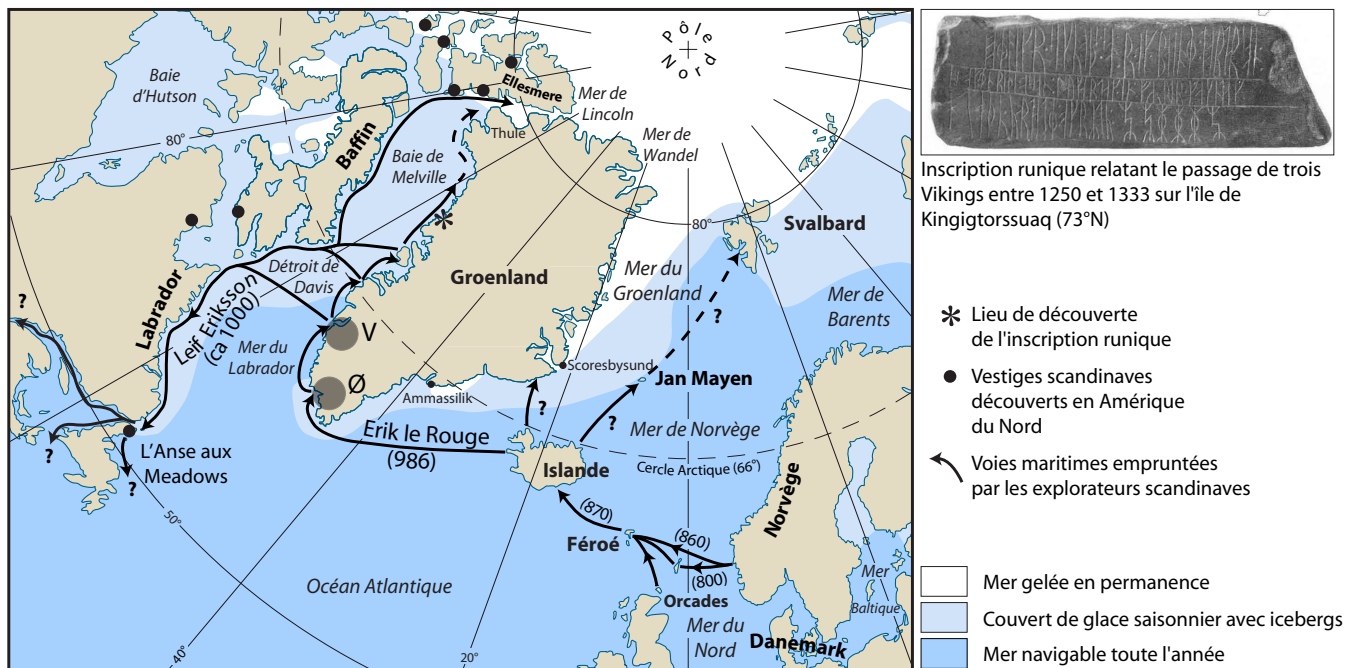


Fig. 2.1 Routes maritimes, colonies groenlandaises médiévales et conditions moyennes d'expansion des glaces

« Erik leur dit qu'il avait l'intention de partir à la recherche du pays qu'avait vu Gunnbjörn, fils d'Ulf le Corbeau, quand il naviguait à la dérive vers l'ouest et qu'il découvrit les écueils de Gunnbjörn. Il déclara qu'il reviendrait chercher ses amis, s'il découvrait ce pays [...] Erik prit la mer au large du glacier des monts des Neiges. Il arriva près du glacier que l'on nomme le Manteau Bleu. [...] Il passa le premier hiver à l'île d'Erik [...]. L'été venu, il partit pour le désert de l'ouest et il donna des noms à tous les lieux qu'il voyait. Le second hiver, il le passa dans les îlots d'Erik, près du pic de la Disparition, et le troisième il fit route vers le plein nord [...] L'été suivant, il partit pour l'Islande (où il passa l'hiver). L'été venu, Erik partit pour coloniser le pays qu'il avait découvert et qu'il appelait le Pays Vert (Groenland) parce que, selon lui, les gens auraient grande envie de venir dans un pays qui avait un si beau nom. »

Erik retourna en Islande avant la fin de sa condamnation, prévue pour l'hiver de l'an 985-986, avec le projet de convaincre des Islandais à le suivre dans la conquête d'une nouvelle terre. La population locale qui vivait dans des conditions difficiles fut rapidement séduite et au cours de l'été 986, 25 vaisseaux partirent pour le Groenland. Les familles islandaises qui l'accompagnèrent venaient des régions surpeuplées de Breidifjord et Borgarfjord. La plupart possédaient des terres de qualité médiocre, les secteurs les plus fertiles étant déjà accaparés par les familles les plus riches. Toutefois, comme le mentionne le *Landnámabók*, certains compagnons d'Erik étaient de riches propriétaires, à l'image de Herjolf Bardarson qui abandonna les vastes terres de son héritage pour partir à l'aventure (Gad, 1970 ; Jones, 1987).

Il est vrai que l'utilisation du qualificatif « vert » pour une île couverte à 80% par une calotte de glace peut surprendre de prime abord. Mais l'adjectif paraît choisi à juste titre car après l'hiver, la neige recouvrant les reliefs vallonnés des côtes cède la place à un étonnant tapis d'herbes et d'arbres nains au feuillage d'un vert éclatant. Comme le souligne Régis Boyer (1992): « À la belle saison, le Groenland peut, sur ses côtes, présenter de vastes étendues d'un vert effectivement peu banal ». Mais plus qu'un intérêt esthétique, la construction du mot n'est pas un choix anodin et plus concrètement peut-on sans doute voir derrière ce choix sémantique l'intérêt stratégique que pouvait avoir Erik d'entraîner avec lui une population cherchant à améliorer ses conditions de vie. La mise en opposition de l'*Ísland*, la « terre de glace », arrivant quelque part à la limite de son expansion démographique, avec la promesse de verts pâturages et de terres fertiles abondantes était le meilleur moyen pour mener à bien le projet d'une colonie groenlandaise.

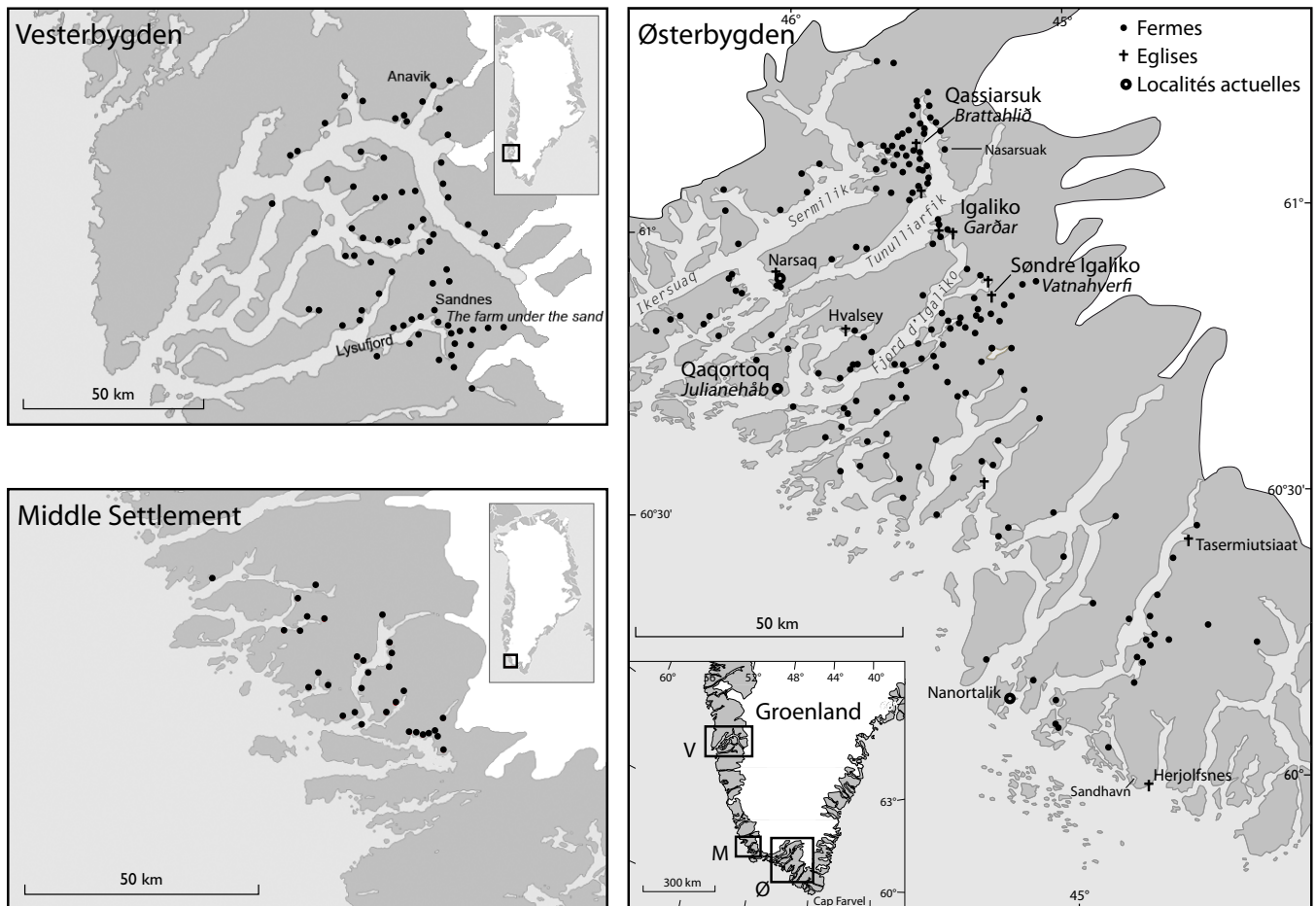
Les causes qui mènent à la colonisation du Groenland s'inscrivent ainsi pleinement dans l'ère mouvementée des conquêtes vikings, marquée par des conflits et une démographie galopante. Dans ce contexte, on ne peut qu'insister sur la volonté initiale des premiers groenlandais, poussés par une « faim de terre », d'établir sur ce nouveau territoire une économie basée sur l'agriculture comme elle se pratiquait alors en Islande.

## 2.2 | L'agro-pastoralisme au Groenland

### 2.2.1 La création des fronts pionniers agricoles

Au cours du voyage une forte tempête éprouva la flotte, certains bateaux firent demi-tour et d'autres se perdirent en mer (Gad, 1970 ; Jones, 1987). Seulement 14 bateaux arrivèrent à destination. La calotte polaire couvrant environ 80% du territoire, l'activité agricole ne peut être cantonnée qu'aux seules régions côtières. À leur arrivée, les premiers colons prirent possession des meilleurs fjords, ceux qui pénètrent profondément dans les terres, les abritant ainsi au mieux des aléas climatiques. D'après le *Landnámabók*, neuf chefs de clan se partagèrent les fjords du Sud-Ouest du Groenland (61°N, district de Qaqortoq), dont Erik le Rouge qui s'installe avec sa famille à *Brattahlíð* (la pente raide) dans le secteur de l'actuelle Qassiarsuk (fig. 2). Cette colonie, prendra le nom de *Østerbygden* (Établissement Oriental) et se développa jusqu'à comprendre une cathédrale, une douzaine d'églises et de 190 à 220 fermes de dimensions variées (Jones, 1986 ; Jones, 1987 ; Krogh, 1967 ; Vebæk, 1991), concentrées majoritairement autour des fjords d'Igaliko et de Tunulliarfik (nommé *Eiriksford* à l'époque médiévale). Un deuxième front pionnier agricole, le *Vesterbygden* (Établissement Occidental) se développa à 575 kilomètres au nord-ouest du premier (64°N, vers Nuuk). Il est probable que l'investissement des deux régions soit synchrone. D'une part le *Landnámabók* mentionne qu'après l'occupation effective des fjords de l'Est, des hommes partirent vers l'Ouest où ils s'installèrent à leur tour. Vers l'an 1005, des familles auraient vécu dans le fjord de Lysu (Gad, 1970), reconnu aujourd'hui comme étant le fjord d'Ameralik. D'autre part, certaines structures d'habitation présentent des caractéristiques architecturales similaires aux premières constructions de *Brattahlíð* (Gad, 1970). Avec près de 90 fermes et 4 églises, l'Établissement Occidental prospéra tout en gardant des proportions moins importantes. La rumeur de bonnes conditions de vie au Groenland





**Fig. 2.2** Carte des implantations médiévales scandinaves du Groenland : Østerbygden (Établissement Oriental), Vesterbygden (Établissement Occidental). Le « Middle Settlement » est considéré comme une extension de l'Østerbygden (d'après Kuijpers et al., 1999, modifié)

circula jusqu'en Islande et en Norvège aidant à attirer de nouvelles familles. Les colonies groenlandaises se développèrent ainsi jusqu'à atteindre selon les estimations entre 2250 (Lynnerup, 1996) et 6000 habitants (McGovern, 1991).

Il est fort probable que la colonisation des terres groenlandaises ait suivi une logique à la fois chronologique et sociale (Christensen-Bojsen, 1991). Une hiérarchisation de l'occupation des sols peut être mise en évidence par la comparaison de l'importance des fermes et de la qualité des pâtures exploitées (Keller, 1990). Il apparaît que les premiers colons, ou ceux jouissant d'un haut statut social, se soient accaparés les meilleures et les plus vastes terres et que les seconds arrivants, ou ceux d'un rang inférieur, aient été relégués vers des terres plus ingrates. La taille des exploitations est un aussi signe de pouvoir évident. L'exemple le plus spectaculaire est celui du site de *Gardar* (le village actuel d'Igaliko). D'après le *Groenlendinga Saga* (la saga des Groenlandais), l'exploitation fut fondée par la fille d'Erik le Rouge,

Freydis, et son mari Thorvard. La ferme de *Gardar* est de loin la plus imposante du Groenland médiéval, elle compte au moins 52 structures archéologiques, dont de nombreux enclos pour animaux. Le dénombrement des stalles montrent que le site pouvait accueillir plus de 100 têtes de bétail, sans compter les chèvres et les montons (Nørlund and Roussell, 1929). Le site occupe une position stratégique, au centre de l'Établissement Oriental, à l'amont du fjord d'Igaliko et seulement séparé du Tunulliarfik par un petit col aisément franchissable donnant ainsi un accès facile par bateau à l'ensemble de l'Østerbygden, de la *Brattahlíð* d'Erik le Rouge au Nord, au *Vatnahverfi* au Sud. Cette situation motiva probablement le clergé norvégien d'y établir le diocèse groenlandais. Après l'évangélisation de la colonie en 1124, le premier évêque fut installé en 1126 (Bruun, 1918). Le dernier évêque connu pour avoir résidé à *Gardar* fut Alfur qui décéda en 1378 (Arneborg, 2007). Bien qu'on ne sache pas si tous les évêques envoyés au Groenland s'établirent à *Gardar*, le fait que ce lieu ait

aussi accueilli le *Ping*, une sorte d'assemblée générale du Groenland, témoigne de son importance<sup>3</sup>.

### 2.2.2 Un système agraire sous contraintes

À plus basse latitude que les bassins agricoles islandais (66°N), la colonie sud groenlandaise ne bénéficie pas pour autant d'un climat plus clément. Au contraire, l'Islande bénéficie de l'apport thermique direct du courant marin nord atlantique alors que les températures du Groenland sont influencées par la descente des eaux polaires froides et chargées d'icebergs du Courant Est Groenlandais. Cependant, le Sud présente un climat plus favorable que le reste de l'île grâce à l'apport tempéré du Courant d'Irminger, dérivant du Courant Nord Atlantique (fig. 3). Avec un climat froid et relativement sec, une température positive seulement 6 à 8 mois de l'année et des gelées pouvant intervenir durant l'été, le Sud du Groenland n'en demeure pas moins une région difficile pour pratiquer l'agriculture. Quant à l'Établissement Occidental, situé à proximité du cercle arctique, les conditions climatiques y sont encore plus défavorables. La période hivernale est plus rude, avec 7 à 9 mois de l'année sous le couvert de la neige et de la glace. Par contre, les journées d'été sont plus longues qu'à basse latitude ce qui permet d'obtenir malgré tout des températures douces, notamment à l'intérieur des fjords où les températures estivales peuvent dépasser les 20°C.

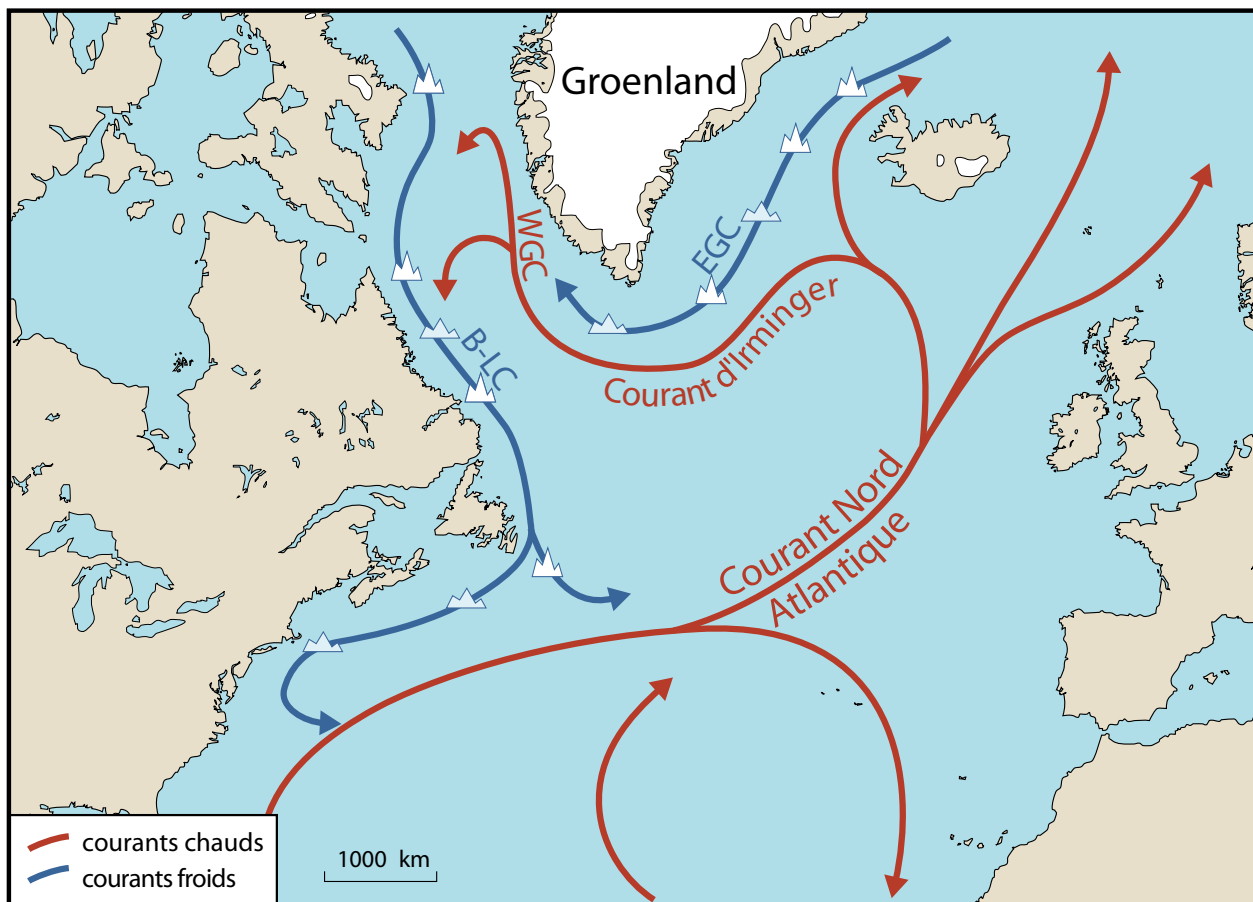
Ces conditions climatiques difficiles vont conditionner le type d'agriculture pratiqué mais aussi son évolution au cours des cinq siècles de colonisation. Les premiers colons vont développer sur le modèle islandais une économie essentiellement basée sur le pastoralisme. Ils importent avec eux les animaux domestiques habituellement élevés en Islande : bovins, moutons, chèvres, chevaux, chiens et porcs ; la basse-cour n'est pas représentée dans la faune archéo-zoologique. Mais sous le climat groenlandais, les prairies peuvent être pâturées seulement quatre à cinq mois par an ; le reste de l'année, les herbivores domestiques nécessitent l'apport de fourrage. Ceci est particulièrement vrai pour les bovins qui doivent être maintenus à l'étable pour au moins six mois pendant l'hiver et qui nécessitent près de 2,5 tonnes de fourrage par tête soit la production d'environ 1 hectare de prairie (Albrethsen and Keller, 1986). Du fait de la brièveté de la saison végétative, la production et la récolte d'une quantité suffisante de fourrage pour l'hivernage des herbivores au cours de la longue et froide nuit polaire s'avèrent ainsi au

centre des préoccupations des colons. Pour étendre les pâturages et les terres cultivées ils défrichent la maigre « forêt » groenlandaise (Fredskild, 1992) composée essentiellement de bouleaux nains et de saules arctiques dont la taille excède rarement quelques dizaines de centimètres. Les recherches archéologiques menées à proximité de certaines fermes ont montré que la fertilisation par fumure était utilisée pour augmenter les rendements (Buckland *et al.*, 2009). Les traces de cette pratique sont d'ailleurs encore détectables aujourd'hui dans le parcellaire de certaines fermes de la vallée de Qorlortoq par une anomalie de la composition isotopique de la végétation, les sols étant enrichis en azote 15 par l'épandage du fumier (Commisso and Nelson, 2008).

Grâce à un fort gradient climatique allant de l'inlandsis à la mer, les fonds de fjords présentent un climat relativement tempéré, à l'abri des tempêtes et du brouillard froid, typiques des côtes de l'Arctique. Mais les précipitations y sont moins abondantes que sur la façade océanique. La comparaison des données météorologiques des stations de Narsarsuaq et de Qaqortoq illustre bien ce fait. La première station, située à environ 5 km de *Brattahild*, a enregistré pour la période 1961-2006 une température moyenne annuelle de 0.9°C, une moyenne de 10.3°C au mois de juillet, un total de 115 jours sans gelées et 615 millimètres de précipitations ; ces mêmes paramètres atteignent respectivement 0.6°C, 7.2°C, 68 jours et 858 millimètres à la station littorale de Qaqortoq située à l'exutoire du fjord, à seulement 59 kilomètres au Sud-Ouest de Narsarsuaq. La région est aussi soumise à l'effet des foëhns. Ces vents chauds et secs d'origine gravitaire peuvent s'écouler de l'inlandsis pendant plusieurs jours et provoquer des sécheresses catastrophiques pour la production agricole. Ainsi, certains auteurs considèrent la sécheresse estivale, plus que la brièveté de la saison végétative, comme la contrainte majeure à laquelle les colonies scandinaves devaient faire face (Nørlund and Roussell, 1929). Le manque d'eau associé au caractère drainant des sols rendait indispensable la pratique de l'irrigation (Adderley and Simpson, 2006) comme en témoignent les vestiges de canaux découverts sur de nombreux sites tel celui de *Garðar* (Arneborg, 2005) et qui présentent des similarités avec les systèmes norvégien et islandais (Buckland *et al.*, 2009).

Toujours dans le souci d'optimiser le potentiel productif du milieu, les pionniers vikings vont aussi développer la pratique de la transhumance. Des ruines singulières ont été découvertes tardivement, entre 1974 et 1979, lors de prospections archéologiques (Albrethsen and Keller, 1986) dans la vallée de Qorlortoq. Situées

3 D'après Halldórsson (1978) dans Buckland *et al.* (2009).

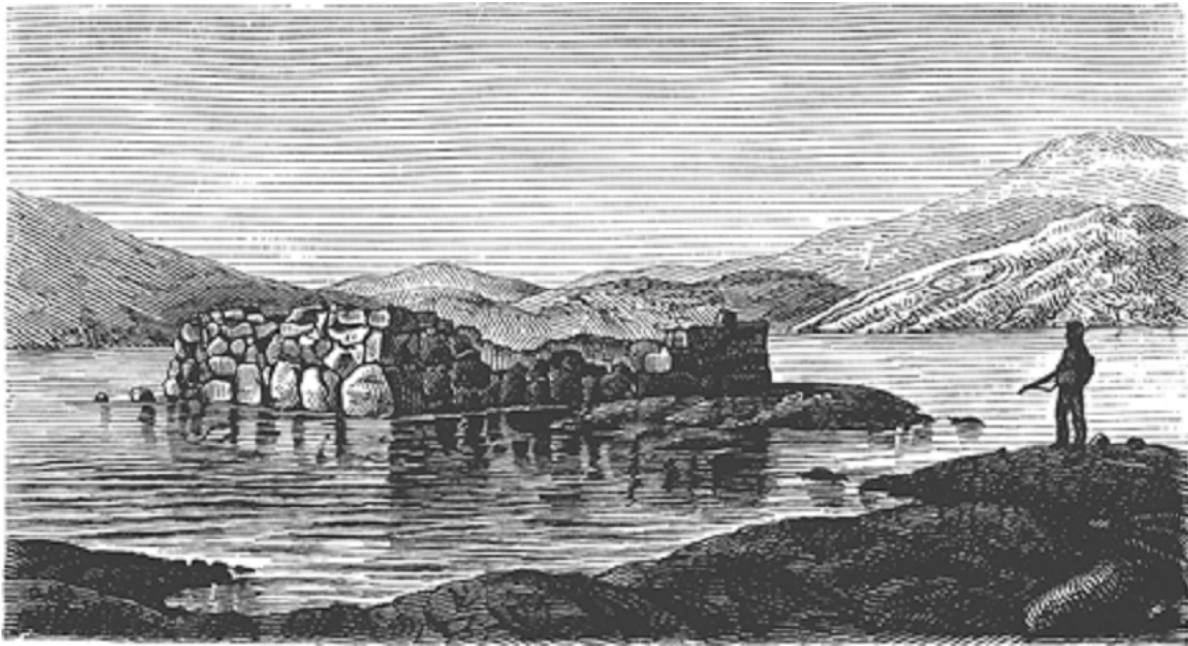


**Fig. 2.3** Principaux courants marins de l'Atlantique nord. WGC : Courant ouest-groenlandais ; EGC : courant est-groenlandais ; B-LC : Courant Baffin-Labrador

entre 200 et 400 mètres d'altitude et de construction simple, ces structures ne sont pas à proprement parlé des fermes mais sont apparentées aux *sæters* islandais et norvégiens. Le terme norvégien *sæters* réfère en effet à des groupes de maisons utilisées pendant la transhumance estivale (*Sæterbruk*). Les troupeaux étaient alors menés de pâtures en pâtures où chaque *sæter* servait de camp de base tandis que les terrains à proximité des fermes, fertilisés et irrigués, étaient préservés pour la production de fourrage. Le changement permanent de pâture permet aussi aux animaux de sélectionner les jeunes pousses plus riches en nutriments, ce qui donne des résultats positifs en termes de prise de poids et de quantité/qualité du lait produit. Ainsi, certains *sæters* devaient servir d'unité de production de lait et les enclos permettaient le ramassage du fumier, d'autres servaient uniquement à produire du fourrage. Les ruines des *sæters* de Qorlortoq sont les témoins d'une stratégie agro-

pastorale « décentralisée » permettant d'exploiter au mieux toutes les ressources du milieu.

Il est aussi établi que dès le début de l'occupation du Groenland, la chasse et la pêche constituaient une part importante des ressources. Il paraît naturel en effet que face aux conditions climatiques difficiles et à l'abondance de gibier, les colons aient étendu leurs activités agro-pastorales à la pratique de la chasse. Cette évolution était une adaptation nécessaire à l'environnement groenlandais et à la faiblesse des rendements agricoles. L'économie fonctionnait probablement selon un système d'échange : les fermes les mieux situées avec de larges troupeaux servaient de centre de redistribution pour d'autres fermes plus modestes qui étaient situées à l'intérieur des terres et spécialisées dans la chasse aux rennes, ou côtières et spécialisées dans la chasse aux mammifères marins et la pêche (Berglund, 1986 ; Keller, 1990). Cette organisation de la société dans la diversification des ressources est illustrée parfaitement par les études



**Fig. 2.4** Gravure de 1876 représentant une ruine du XIV<sup>e</sup> siècle à Igaliko (d'après Steenstrup and Kornerup, 1881). La base de la structure est en dessous du niveau de la mer. Ce cas illustre la montée relative du niveau de la mer à laquelle les vikings furent confrontés dans la région.

archéozoologiques. Par exemple dans les petites fermes littorales, les restes de phoques constituent de 65 à près de 80% des vestiges osseux pour seulement 2 à 5% de bovins (McGovern, 1980).

### 2.2.3 Evolution et fin du système : adaptation ou destruction ?

La chronologie de l'abandon des colonies est moins précise que celle de leur création, et la causalité multiple de la fin de l'occupation viking du Groenland est encore sujette à débats. Ivar Baardson, un émissaire épiscopal, signale l'abandon du *Vesterbygden* dès l'an 1350. Le dernier témoignage écrit de la présence des scandinaves au Groenland est une lettre de 1409 annonçant un mariage célébré à l'église de *Hvalsey* (*Østerbygden*) l'année précédente (Gad, 1970). Parmi les explications avancées pour la disparition de la population médiévale scandinave du Groenland, les chercheurs ont proposé un changement climatique, le déclin des liaisons commerciales avec l'Islande et l'Europe, des raids de pirates européens, des conflits avec les inuits, l'infertilité congénitale et des épidémies (Barlow *et al.*, 1997). Le seul point sur lequel les auteurs s'accordent est le rôle primordial de la péjoration climatique du Petit Âge de Glaciaire (Dansgaard *et al.*, 1975 ; Dugmore *et al.*, 2007 ; Lamb, 1977). Le froid et

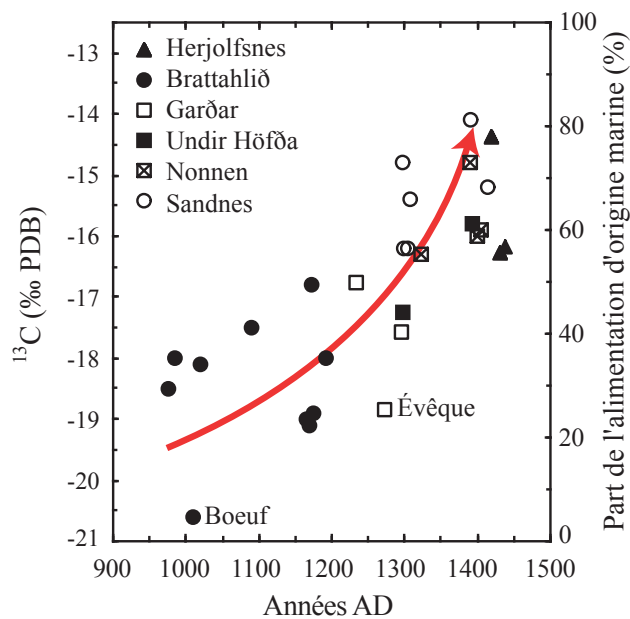
l'augmentation de l'occurrence des tempêtes provoqua une chute des rendements agricoles, isola les colonies de l'Europe et coupa la route maritime du bois du Labrador. L'abandon précoce du *Vesterbygden* dès 1350, probablement dû à son climat plus rigoureux, apporte un argument supplémentaire en faveur de la cause climatique. Les fermes y sont également situées plus près de la calotte polaire que dans l'*Østerbygden* et sont ainsi plus régulièrement affectées par les vents de fœhn (Hansen, 1991). Plus récemment fut invoqué le rôle de la montée du niveau de la mer provoqué par la progressive subsidence du continent sous le poids des glaciers en progression depuis la néoglaciation amorcée dès le premier millénaire avant Jésus-Christ (Mikkelsen *et al.*, 2008 ; Sparrenbom *et al.*, 2006). La montée des eaux réduisant les surfaces cultivables au bord des fjords se serait conjuguée aux dégradations du climat pour précipiter l'effondrement de la société viking à l'aube du XV<sup>e</sup> siècle (fig. 4).

Entre 986 et 1450 l'évolution des pratiques agropastorales face aux caprices du climat reste mal connue. A ce sujet, deux écoles aux théories apparemment paradoxales s'affrontent. La première, évoque la réorganisation de l'économie viking de l'agropastoralisme vers la chasse et la pêche. L'analyse des collections archéozoologiques accumulées au cours des fouilles sont ici riches d'enseignements et montrent

sur plusieurs sites une évolution de l'apport carné entre le début et la fin de la colonisation. Il apparaît que le porc, mal adapté aux conditions climatiques, disparaît rapidement du Groenland (Enghoff, 2003 ; McGovern *et al.*, 1996 ; McGovern *et al.*, 1983). Pour les mêmes raisons, les troupeaux de vaches sont progressivement diminués à la faveur des moutons et des chèvres, moins gourmands en fourrage. L'adaptation des pratiques d'élevage s'accompagne d'une utilisation accrue des ressources sauvages comme en témoigne l'augmentation des restes de phoques, de caribous ou d'oiseaux (Enghoff, 2003 ; McGovern *et al.*, 1996). Ces constatations sont corroborées par l'analyse isotopique d'ossements humains qui indique que nombre de groenlandais augmentent leur consommation de ressources alimentaires marines au cours des XIII<sup>e</sup> et XIV<sup>e</sup> (Lynnerup, 1995) siècles. Plus récemment l'archéologue Jette Arneborg (1999) est venue confirmer ces résultats, grâce à l'analyse d'ossements issus des différents cimetières des deux implantations. Ces travaux montrent, avec une tendance généralisée à toute la colonie, que la part de l'alimentation d'origine marine des populations passe de 20%, au début de l'occupation, à près de 80% vers 1450 AD, montrant ainsi l'importance croissante de la chasse au phoque et de la pêche dans l'économie (fig. 5).

D'autres chercheurs défendent la théorie de la destruction des ressources à cause du développement excessif des troupeaux de moutons qui auraient provoqué une érosion catastrophique des sols (Dugmore *et al.*, 2005 ; Jakobsen, 1991 ; Mainland, 2006). Face à la faiblesse des arguments sédimentologiques, aux preuves de l'adaptation des pratiques agro-pastorales aux conditions du milieu et à l'évolution des consommations alimentaires attestées par les analyses isotopiques, cette théorie, plus fondée sur des spéculations que sur des preuves matérielles, paraît improbable. Elle reste néanmoins soutenue actuellement par divers chercheurs (Edwards *et al.*, 2008) et trouve un écho retentissant dans le contexte de la médiatisation actuelle des problèmes environnementaux<sup>4</sup>.

Parmi les cause du déclin puis de l'abandon, il est aussi proposé des concepts « annexes » tels que l'« intransigeance culturelle » (Barlow *et al.*, 1997) ou encore la « rigidité idéologique » (Diamond, 2005). Ceux-ci expliqueraient pour partie la non-adaptation des populations scandinaves qui se seraient obstinées



**Fig. 2.5** δ<sup>13</sup>C mesuré sur des ossements vikings et exprimé en fonction du temps. Les différents symboles font référence aux cimetières dans lesquels furent inhumés les individus. Celui de Sandnes se trouve dans l'établissement occidental (*Vesterbygden*), les autres se trouvent dans l'établissement oriental (*Østerbygden*). L'axe de droite indique la proportion de produits d'origine marine dans l'alimentation, estimée à partir du δ<sup>13</sup>C. Remarquez la valeur terrestre de l'os de boeuf, un herbivore strict. Le haut statut social associé à un régime alimentaire privilégié ou son arrivée récente de Norvège pourrait expliquer la faible part de marin dans l'alimentation de l'évêque, enterré dans la cathédrale de *Garðar*. (Modifié, d'après Arneborg *et al.*, 1999).

à maintenir une économie agro-pastorale jusqu'à la fin du XV<sup>e</sup> siècle malgré la dégradation des conditions climatiques. La population viking a probablement été attachée à une tradition de vie pastorale et sédentaire, vecteur d'une forte signification identitaire (Lynnerup and Nørby, 2004). On comprend dès lors que l'ancrage dans cette tradition ait joué un rôle dans l'abandon des colonies, lorsque les conditions climatiques devinrent intenable et que seul le mode de vie inuit fut possible.

Malgré ces incertitudes, il est certain que l'évolution défavorable du climat, engendrant la fragilisation d'un système socio-environnemental proche de ses limites, ait été la cause majeure dans l'issue fatale des colonies médiévales du Groenland.

4 Illustré par le succès de l'ouvrage de Jared Diamond qui trace des parallèles volontairement inquiétants entre la disparition supposée catastrophique des sociétés passées ayant refusé de s'adapter (mayas, île de pâque, viking du Groenland) et l'évolution du monde industriel moderne.

## 2.3 | L'apport des archives paléoenvironnementales

### 2.3.1 Interactions société, territoire, environnement

Au-delà de l'aspect romanesque de l'aventure viking, et bien que son caractère épique ait pu motiver de nombreux chercheurs, la colonisation médiévale du Groenland constitue un modèle particulièrement adapté à l'étude des relations entre une communauté humaine et son environnement, que l'on s'intéresse aux conséquences des variations climatiques sur les populations, ou que l'on cherche à estimer l'impact de l'activité de l'Homme sur son environnement. Nombre de paléoclimatologues travaillant au Groenland traitent de façon plus ou moins complète des relations entre les populations médiévales et le climat (Kaplan *et al.*, 2002 ; Kuijpers and Mikkelsen, 2009 ; Lassen *et al.*, 2004 ; Stuiver *et al.*, 1995). Dans l'autre sens, celui de l'impact de la société viking sur son environnement, la recherche se heurte encore à de nombreux obstacles. Les apports de l'histoire et de l'archéologie dans ce domaine, bien que fondamentaux, se révèlent néanmoins limités sur plusieurs points. En premier lieu, les résultats des fouilles archéologiques donnent une vision intrasite, c'est-à-dire très stationnelle du mode de vie des agriculteurs groenlandais. Se pose alors le problème fondamental de la représentativité spatiale des renseignements apportés par chacun des sites étudiés et de l'extrapolation des acquis à l'échelle régionale ; difficulté *a fortiori* majeure dans le cas du Groenland où relativement peu de structures ont été fouillées<sup>5</sup>. D'autre part, certains auteurs comme Albrethsen et Keller (1986) remarquent que malgré les nombreux archéologues impliqués<sup>6</sup>, les prospections archéologiques ne sont probablement pas exhaustives. Les recherches se sont focalisées dans la périphérie des sites historiques tels ceux de *Brattahlíð* ou de *Garðar* et dans les zones facilement accessibles, délaissant les structures d'altitude et notamment les *sæters*. Cette remarque est toujours pertinente aujourd'hui, bien que des travaux de prospection plus complets aient été repris ces dernières années (Algreen-Møller and Madsen, 2006 ; Guldager *et al.*, 2002). Des précautions doivent aussi être prises dans l'interprétation des Sagas. Ces récits étaient transmis

5 Depuis le IX<sup>e</sup> siècle, une vingtaine de sites archéologiques a été fouillée sur près de 300.

6 Près de 22 publications entre 1816 et 2006.

oralement, de génération en génération, avant d'être retranscrits au XII<sup>e</sup> et XIII<sup>e</sup> siècles par des clercs islandais. On peut légitimement douter de la véracité de faits écrits et développés plusieurs siècles après Erik le Rouge. Enfin, Christan Keller (1990) étend cette précaution à l'ensemble de la littérature sur la conquête du Groenland, celle-ci ayant pu être biaisée par des intérêts politiques et idéologiques. C'est notamment le cas entre 1921 et 1933 à l'apogée du conflit entre la Norvège et le Danemark portant sur la possession du Groenland : c'est au cours de ces 12 années qu'une grande part des fouilles archéologiques a été conduite. Pour compléter les connaissances archéologiques, quelques études paléoenvironnementales<sup>7</sup> ont été conduites. Les travaux fondateurs de Fredskild (1973), effectués dans les années 1970 à partir de séquences lacustres, ont permis de caractériser l'impact des pratiques agro-pastorales sur la végétation, marqué par le défrichement des espèces arborescentes et l'importation d'espèces non autochtones. Plus récemment Edwards, Schofield et Buckland ont effectué quelques travaux du même ordre dans l'*Østerbygden* (2009 ; 2008 ; 2008). Les auteurs concluent sur une érosion des sols provoquée par le surpâturage, mais ils négligent complètement le rôle potentiel du climat dans la dynamique de sédimentation en privilégiant une interprétation toute « anthropique ». D'autres auteurs, dont des paléoclimatologues travaillant sur des sites en dehors de toute influence anthropique, viennent nuancer ces interprétations en démontrant que l'accélération du détritisme au cours de la période viking a pu être provoquée par une activité éolienne exacerbée entre le IX<sup>e</sup> et le XIV<sup>e</sup> siècle (Kuijpers and Mikkelsen, 2009 ; Lassen *et al.*, 2004). Mais les travaux de Fredskild ou encore du pédologue Jakobsen (1991) ne sont jamais remis en question par les théoriciens de la surexploitation des ressources et servent toujours de base à l'écriture d'une fin tragique et probablement romancée. Les études paléoenvironnementales récentes partagent également une lacune avec les travaux archéologiques : les auteurs préfèrent se focaliser sur des séquences de proximité immédiate avec les ruines de fermes telles des fosses pédologiques et des petits dépôts tourbeux. Ces enregistreurs sédimentaires locaux (ou stationnels) posent divers problèmes susceptibles d'affecter leur représentativité à l'échelle régionale. Ces milieux ne

7 Le paléoenvironnement est un domaine de la recherche qui a pour objectif la reconstitution des conditions environnementales passées à partir d'archives sédimentaires, déposées notamment au fond des lacs et dans les tourbières.

sont en effet pas idéaux pour la bonne conservation des marqueurs environnementaux (le pollen par exemple) et peuvent de ce fait fournir une image tronquée pour la reconstitution des environnements passés. De plus la stratigraphie n'y est pas continue et peut être perturbée par le piétinement du bétail, les labours ou encore le prélèvement de tourbe pour le chauffage et l'isolation des habitations. Mais encore, ce genre d'objet géologique, surtout les sols dont la formation résulte des processus combinés d'altération et d'accumulation, sont soumis à des régimes de sédimentation mal connus et difficilement interprétables, pouvant conduire à des conclusions hâtives et erronées.

### 2.3.2 Les enjeux actuels

Nous avons vu que le cas de la population scandinave médiévale du Groenland et de sa relation étroite avec son environnement pose de nombreux problèmes encore irrésolus. Afin de mieux comprendre les interactions Climat-Société-Territoire dans cette région, il apparaît nécessaire d'étudier des enregistrements sédimentaires continus et non perturbés, significatifs des signaux anthropiques et climatiques. En effet, la fiabilité de l'interprétation environnementale d'une archive sédimentaire repose essentiellement sur la discrimination des effets de l'activité humaine (le forçage anthropique) de ceux provoqués par les variations climatiques (le forçage climatique). Les fortes contraintes environnementales du Groenland ont été un facteur limitant pour le développement spatial et temporel des occupations offrant ainsi un modèle d'étude très contrasté favorable à cette démarche.

L'étude de séquences sédimentaires lacustres profondes, semble à même de répondre à ces questions. Les côtes du Groenland sont en effet riches de milliers de lacs multipliant la perspective d'un enregistrement continu des conditions environnementales passées. Les dépôts profonds des lacs ne sont pas perturbés par la proximité de l'activité humaine et sont intégrateurs des conditions environnementales locales comme régionales, selon les dimensions du lac et de son bassin versant. La nécessité de comparer des signaux locaux et régionaux est ici primordiale car, nous l'avons vu, en particulier dans le cas des *Sætters*, la toute proximité d'une ferme n'est pas une condition suffisante à l'évaluation globale de l'impact de son activité.

La continuité de la sédimentation lacustre permet également d'avoir une meilleure idée de la chronologie des événements en termes d'emprise et de déprise agro-pastorale. On pourra vérifier s'il existe, ou non, un phasage des activités agricoles modulées par les

variations climatiques. Ainsi pourra-t-on observer une déprise progressive liée à l'adaptation des pratiques face aux aléas climatiques ou une érosion importante, liée aux défrichements et à l'introduction d'animaux domestiques qui se refléteront dans la dynamique de la sédimentation.

Les spécificités de la colonisation agro-pastorale médiévale au Groenland et ses limites en font un modèle d'étude unique. Le projet de recherche « *ULTIMAGRI Impact environnemental de l'agro-pastoralisme médiéval au Groenland* » auquel le présent article est une contribution, a germé à l'issue de ce constat. Celui-ci se situe dans une approche résolument Homme-Climat dans laquelle la compréhension des mécanismes d'interaction entre le forçage climatique et le forçage anthropique sur la dynamique sédimentaire est à la base de toute interprétation. Une dizaine de lacs a été sélectionné à proximité de sites favorables au pastoralisme afin d'évaluer les mutations environnementales liées à cette activité et la résilience du milieu après l'abandon des colonies. Ce projet devrait permettre d'évaluer précisément l'impact des vikings sur leur environnement et d'évaluer la part du déterminisme climatique dans l'évolution de la colonisation, au-delà des spéculations et des mythes.

## 2.4 | Conclusion

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L'histoire du Groenland est celle de la survie et de l'adaptation des hommes aux conditions climatiques extrêmes de l'Arctique, dans les limites de leurs traditions culturelles. Les particularités climatiques de la région et le contexte de sa colonisation ont engendré un système agraire proche de ses limites, fragile et sensible aux variations du climat. La brièveté de la colonisation médiévale, son caractère contrasté et la richesse des informations apportés à ce sujet par la communauté des archéologues, fait du modèle agro-pastoral viking un cas d'étude exceptionnel dans le cadre de recherches paléoenvironnementales. Les travaux, actuellement en cours le long de la côte sud-ouest du Groenland, basés sur des enregistrements sédimentaires lacustres, devraient aboutir à une meilleure compréhension des relations Homme-Climat-Environnement et apporteront sans doute une contribution à l'écriture de l'histoire de la société médiévale scandinave du Groenland, à l'extrême limite des capacités d'adaptation du modèle agro-pastoral européen.

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## Chapitre 3

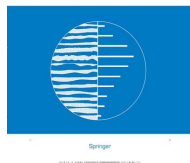
### **A multiproxy evaluation of Holocene environmental change from Lake Igaliku, South Greenland**





## Chapitre 3

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# A multiproxy evaluation of Holocene environmental change from Lake Igaliku, South Greenland

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*This is one of 18 papers published in a special issue edited by Darrell Kaufman, and dedicated to reconstructing Holocene climate and environmental change from Arctic lake sediments.*

## Abstract

This is the first integrated multiproxy study to investigate climate, catchment evolution and lake ecology in South Greenland. A 4-m-long sedimentary sequence from Lake Igaliku (61°00'N, 45°26'W, 15 m asl) documents major environmental and climatic changes in south Greenland during the last 10 ka. The chronology is based on a <sup>210</sup>Pb and <sup>137</sup>Cs profile and 28 radiocarbon dates. The paleoenvironmental history is interpreted on the basis of magnetic susceptibility, grain size, total organic carbon, total nitrogen and sulphur, sedimentation rates, pollen, and diatom assemblages. The basal radiocarbon date at ca. 10 cal ka BP provides a minimum age for the deglaciation of the basin, which is followed by ~500 years of high sedimentation rates in a glacio-marine environment. After the glacio-isostatic emergence of the basin ca. 9.5 cal ka BP, limnological and terrestrial proxies suggests early warmth, which may have been interrupted by a cold, dry and windy period between 8.6 and 8.1 cal ka BP. A dry and windy event ~5.3–4.8 cal ka BP preceded the Neoglacial transition at Lake Igaliku, which is characterized by a shift toward moister and perhaps cooler conditions ~4.8 cal ka BP, causing major changes in terrestrial and aquatic ecological conditions. Significant cooling is documented after ~3 cal ka BP. Since ~1 cal ka BP the climatic-driven changes were overprinted by the human influence of Norse and recent agriculture.

**Keywords:** *South Greenland, Lake sediments, 8.2 event, Holocene thermal maximum, Neoglacial, Norse*

## 3.1 | Introduction

The Arctic is an important area for understanding environmental responses to climate change, not only in the past but also as it relates to the future. Atmospheric and oceanic circulation patterns have modulated the spatio-temporal response to declining insolation during the Holocene (Kaufman *et al.* 2004), but our knowledge of regional differences remains patchy. The southern coast of Greenland is a strategic location for understanding the environmental response to forcing mechanisms not only in relation to the nearby Greenland Ice Sheet, but also to adjacent North Atlantic

oceanographic currents and dynamics (Nørgaard-Pedersen and Mikkelsen 2009). Understanding Holocene environmental dynamics in this region may shed light on processes and events that have broader implications both paleoclimatically and geographically. Despite this key geographical setting, only a few Holocene lake cores have been studied in southern Greenland. These include Lake Qipisarqo in the Narsaq region (Kaplan *et al.* 2002; Wooller *et al.* 2004; Fréchette and de Vernal 2009), Lake N14 near Kap Farvel (Andresen *et al.* 2004), and the pollen study sites of Fredskild (1973).

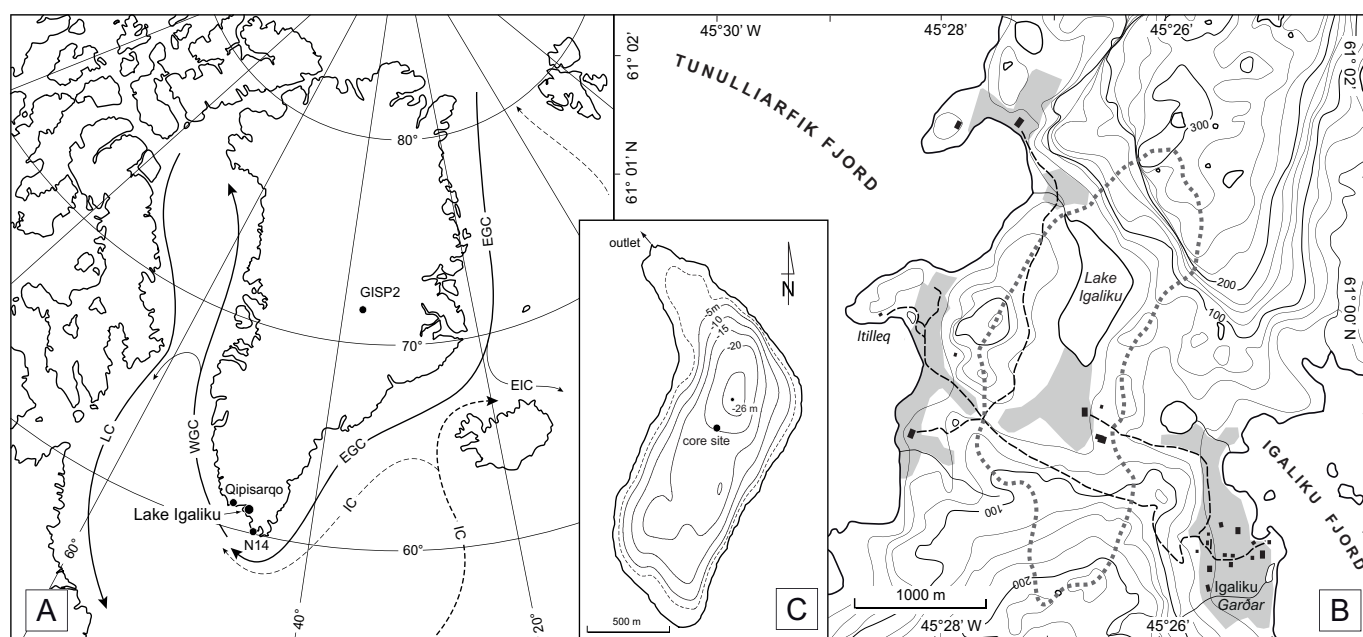
To date, no multiproxy paleolimnological analyses have been conducted in the inner fjords of south Greenland. Yet, Holocene climate records show distinct differences between the outer and the inner coastal region elsewhere in Greenland (see Perren *et al.* this volume) and the inner fjord regions represent an important ecoclimatic zone, which is unique in Greenland. Existing paleoenvironmental archives from this inner fjord region have mainly been studied for the evaluation of Norse impact during the last millennium (e.g. Fredskild 1992; Edwards *et al.* 2011) as has the Lake Igaliku site (Perren *et al.* in press; Gauthier *et al.* 2010; Massa *et al.* 2012). However, in addition to its archaeological significance, this lacustrine sequence situated in the Norse Eastern Settlement contains an archive of ~10,000 years of natural climatic and environmental evolution in a critical location for paleoclimatic studies in the North Atlantic. In this paper, we present the results of chronological, sedimentological, and biological investigations of a sediment record from Lake Igaliku, located in the interior of southern Greenland. This is the first study combining terrestrial, aquatic, and lake-sediment properties in southern Greenland, which allows for the exploration of climate/catchment/lake linkages (Presthus Heggen *et al.* 2010). The main objective of this study is to describe the major environmental changes that affected Lake Igaliku and its catchment since the last glacial retreat, with a special emphasis on the timing and nature of

the Holocene thermal maximum and the onset and signature of Neoglacial cooling.

### 3.2 | Regional setting

Lake Igaliku (61°00'N, 45°26'W, 15 m asl) is located close to the village of Igaliku from which it takes its unofficial name (Fig. 1). The area is bordered by the head of Igaliku Fjord to the east and Tunulliarfik Fjord to the west. Lake Igaliku is ca. 0.35 km<sup>2</sup> in size with a catchment area of about 3.55 km<sup>2</sup>. The lake has no major inflow, but is fed by numerous small streams. A small outflow on the northern shore drains into the Tunulliarfik fjord. The surroundings are of relatively low relief with flat-topped hills reaching 300 m asl to the east. The bedrock geology is characterized by Proterozoic granites of the Julianehåb batholith, partially overlain by arkosic sandstones and lavas of the Mesoproterozoic Eriksford Formation that outcrop on the hills.

The climate of southern Greenland is low-arctic with a notable influence of the cold (< 0°C) polar waters of the East Greenland Current and the relatively warm (+4°C) Irminger current that mix together west of Kap Farvel (Fig. 1). Conditions are more continental towards the innermost and sheltered fjords where copses of grey willow, dwarf birch and white birch grow on well-developed soils (Rutherford 1995). At Narsarsuaq, 17 km north of Igaliku, mean annual temperature is



**Fig. 3.1** (a) Location of Lake Igaliku on the south coast of Greenland and other lakes mentioned in the text. The major North Atlantic oceanic surface currents influencing the coastal climate are represented. (b) Enlargement of Lake Igaliku and the surrounding area including roads (dashed lines), buildings (black rectangles), current hay fields (shaded area), and the archaeological site of *Gardar*. The catchment delimitation is drawn in dotted line. (c) The bathymetry of Lake Igaliku and coring position

0.9°C, with a maximum in July of 11°C, 195 days yr<sup>-1</sup> with frost and a mean annual precipitation of 615 mm (climatological standard normals 1961-90, Cappelen *et al.* 2001). Although there is no continuous permafrost in the lake catchment, the deepest soil horizons may not thaw until July. The area is windy, with a mean wind speed of 3.8 m s<sup>-1</sup>, and strong desiccating katabatic winds blowing from the inland ice year round. Owing to favorable climatic conditions, Igaliku, which corresponds to the medieval site of *Garðar* (Nørlund and Roussel 1929), was settled at the beginning of the Norse *Landnám* (“land-take”, colonization). *Garðar* was the largest medieval farmstead of Greenland and may have hosted over 100 cattle in addition to sheep and goats, thus requiring the exploitation of the total surrounding vegetated landscape (Christensen-Bojsen 1991). Agriculture in the region resumed in the 1920s and current farming consists of two farms that breed 400-450 sheep (Miki Egede, pers. commun.). One of these is established in the catchment and manages 30 ha of hay meadows on the fields surrounding the lake (Fig. 1).

### 3.3 | Material and methods

#### 3.3.1 Coring

The bathymetry of the basin was investigated with an echo sounder and the center of the lake (23 m deep) was chosen for coring site. A 4-m-long sediment sequence was recovered from a floating platform by overlapping three piston core segments in the deeper sediments with a gravity core that kept the surface sediments undisturbed (both from UWITEC Co.). The correlation of the overlapping cores is based on the observation of high-resolution X-ray images obtained using the Scopix system at the University of Bordeaux 1 (Lofi and Weber 2001). The X-ray radiographs reveal a continuous sedimentation with distinct laminae and similar variations in the porosity to X-rays between each overlapping core, allowing the composite stratigraphy to be made by matching the laminations.

#### 3.3.2 Sedimentological analysis

The whole core was logged at 5 mm increments with a Geotek Multi Sensor Core Logger for wet bulk density (WBD, reported in g cm<sup>-3</sup>), split lengthwise and then logged for high-resolution magnetic susceptibility (Gunn and Best 1998). One core half was continuously subsampled in 0.5 cm (0-10 cm), 1 cm (10-332 cm), and 2 cm (332-400 cm) intervals with small adaptations to the varying lithology (n = 404). The slices were

then separated into different sets and dispatched for destructive analysis. A set of samples was dried at 60°C until constant weight and their water content (WC) was calculated from the mass differences between the wet and dry sediments.

The dried samples were ground to < 63 µm with an agate ball miller, homogenized and processed for total organic carbon (TOC), total nitrogen (TN) and total sulphur (TS) analysis with a vario MAX CNS analyzer (Elementar). Sample reproducibility, based on 63 duplicates, is ±0.022, ±0.003, and ±0.013 % for TOC, TN and TS, respectively. TOC/TN and TOC/TS values are expressed as atomic ratios, with a sample reproducibility of ±0.1 and ±0.3, respectively. The error bars are too small to be graphically represented.

Grain-size analysis was performed continuously on the upper 75 cm and then at 2 to 4 cm (75-300 cm), and 20 cm intervals (300-400 cm) using a laser diffraction particle analyzer (LS230 Beckman-Coulter). Wet samples of ~2 cm<sup>3</sup> were pre-treated with H<sub>2</sub>O<sub>2</sub> to digest organic matter and with sodium-hexametaphosphate followed by an ultrasonic bath to disperse the aggregates.

#### 3.3.3 Core chronology

Sediment chronology is based on <sup>210</sup>Pb and <sup>137</sup>Cs (for the uppermost sediments), and <sup>14</sup>C analyses. Alpha spectroscopy was used to determine <sup>210</sup>Pb activity, and ages were calculated by applying the constant rate of supply (CRS) model to the unsupported <sup>210</sup>Pb inventory (Appleby and Oldfield 1978). The bulk <sup>137</sup>Cs activity was measured by gamma spectrometry in a calibrated geometry using a high-purity Ge well-type detector. The 1963 AD nuclear test bomb spike (Pennington *et al.* 1973) was detected at 5.5-6.0 cm depth and is found to be in agreement with the <sup>210</sup>Pb CRS model. More details on the dating of the surface sediments are given in Massa *et al.* (2012).

Radiocarbon dating (Table 1) was conducted on terrestrial plant remains and aquatic moss by accelerator mass spectrometry (AMS) at the Poznań Radiocarbon Laboratory (Poland) and at the Lyon Radiocarbon Laboratory (France). The bryophyte date at 66.3-67.3 cm is 310 years older than the two terrestrial macrofossils that closely surround it. This is likely due to a reservoir effect, which sometimes can affect Arctic lakes due to the in-lake recycling of carbon (Abbott and Stafford 1996). Thus, a reservoir correction of 310 years was applied to <sup>14</sup>C ages of the three aquatic moss samples before calibration. Radiocarbon dates were calibrated to calendar years using the atmospheric calibration dataset IntCal09 (Reimer *et al.* 2009) by means of the

Depth (cm)	Material	Lab code	<sup>14</sup> C yr BP (±1σ)	Corrected <sup>14</sup> C age	Cal year BP (2σ range)	Cal year BP (weighted mean)
0	bulk	<sup>210</sup> Pb	-	-	-57.6 - -57.6	-57.6
1.0	bulk	<sup>210</sup> Pb	-	-	-53.0 - -52.0	-52.5
2.0	bulk	<sup>210</sup> Pb	-	-	-47.9 - -44.9	-46.4
3.0	bulk	<sup>210</sup> Pb	-	-	-43.6 - -39.6	-41.6
4.0	bulk	<sup>210</sup> Pb	-	-	-39 - -31	-35
3.5 - 4.5	Undetermined plant remains	Poz-24707	*107.11 ± 0.36	-	-6 minimum	-
5.0	bulk	<sup>210</sup> Pb	-	-	-30 - -24	-27
5.5 - 6.5	bulk	<sup>137</sup> Cs	-	-	-16 - -10	-13
6.0	bulk	<sup>210</sup> Pb	-	-	-16 - -8	-11
7.0	bulk	<sup>210</sup> Pb	-	-	-3 - 20	8
8.0	bulk	<sup>210</sup> Pb	-	-	1 - 51	26
9.0	bulk	<sup>210</sup> Pb	-	-	8 - 70	39
10.0	bulk	<sup>210</sup> Pb	-	-	12 - 102	57
11.6	bulk	<sup>210</sup> Pb	-	-	20 - 150	85
13.2	bulk	<sup>210</sup> Pb	-	-	27 - 203	115
17.4 - 17.7	Aquatic moss	Poz-31628	680 ± 100	370	555 - 0	391
27.5 - 28.5	<i>Betula</i> leaf	Poz-31632	620 ± 80	-	685 - 515	603
30.0 - 30.7	<i>Betula</i> bark fragment	Poz-31629	655 ± 35	-	670 - 555	613
32.6 - 33.6	<i>Salix</i> leaf	Poz-26852	775 ± 30	-	735 - 670	702
39.9 - 40.7	Undetermined twig	Poz-31630	945 ± 35	-	930 - 785	855
51.5 - 52.5	Undetermined wood	Poz-35136	1005 ± 30	-	970 - 800	915
60.7 - 61.7	1 <i>Salix</i> and 2 <i>Betula</i> leaves	Poz-38952	1260 ± 40	-	1280 - 1080	1197
66.3 - 67.3	Aquatic moss	Poz-30535	1570 ± 35	1260	1280 - 1085	1201
67.1 - 67.3	Undetermined wood	Lyon-7300	1265 ± 30	-	1285 - 1090	1211
67.9 - 68.1	Undetermined wood	Lyon-7301	1410 ± 30	-	1355 - 1285	1319
68.8 - 69.8	Undetermined twig	Poz-35135	1305 ± 30	-	1290 - 1180	1238
71.0 - 71.7	<i>Betula</i> leaf	Lyon-7302	1450 ± 30	-	1385 - 1300	1341
78.6 - 79.8	Undetermined leaf	Poz-31633	1580 ± 60	-	1605 - 1345	1470
89.0 - 90.0	<i>Betula</i> wood	Lyon-31874	1775 ± 40	-	1815 - 1570	1694
94.2 - 94.6	<i>Betula</i> wood	Lyon-7303	1930 ± 30	-	1945 - 1820	1877
112.5 - 113.5	<i>Betula</i> leaves fragments	Poz-37363	2250 ± 40	-	2345 - 2155	2247
125.8 - 126.8	Aquatic moss	Poz-30536	2930 ± 70	2620	2875 - 2490	2707
161.0 - 162.1	<i>Betula</i> leaf	Poz-37364	3070 ± 40	-	3170 - 3375	3288
189.9 - 190.9	Undetermined twig	Poz-30537	3740 ± 70	-	3895 - 4295	4104
206.3 - 206.8	Undetermined wood	Poz-35131	4250 ± 35	-	4650 - 4865	4806
206.9 - 208.3	Undetermined wood	Poz-37365	4110 ± 35	-	4520 - 4815	4654
241.4 - 243.4	Undetermined twig	Poz-37366	6970 ± 70	-	7679 - 7935	7804
248.4 - 248.6	Undetermined wood	Poz-35130	7440 ± 40	-	8180 - 8350	8266
252.0 - 253.0	Undetermined wood and leaves fragments	Poz-24710	7560 ± 50	-	8210 - 8445	8366
259.9 - 260.9	<i>Vaccinium</i> and <i>Betula</i> leaves fragments	Poz-37367	8350 ± 80	-	9130 - 9515	9339
270.4 - 271.4	<i>Ericacea</i> leaf	Poz-30538	8330 ± 60	-	9135 - 9475	9334
391.7 - 393.7	Herb rhizome epidermis	Poz-31634	8920 ± 190	-	9540 - 10430	9992

\* = Post-bomb radiocarbon activity expressed as a percentage of modern carbon

**Table 3.1** Radiocarbon dates from Lake Igaliku

'clam' R program (Blaauw 2010). All dates in this paper are given in calendar years BP (before 1950). Age information, including <sup>14</sup>C, <sup>210</sup>Pb, and <sup>137</sup>Cs, were compiled and processed using a Monte Carlo procedure to establish the age-depth model (Blaauw 2010). Considering the radically different lithology below and above 275 cm (Fig. 2), which reveals a major change in the sedimentation pattern, the age-depth model was

divided in to distinct sections: a smooth cubic spline regression was used on the upper part and a simple linear interpolation was used on the lower one.

The sediment accumulation rate (SAR, in cm yr<sup>-1</sup>) was derived from the age-depth model and the mass accumulation rates of minerogenic (MAR<sub>min</sub>), and organic matter (MAR<sub>org</sub>) were calculated using the following equations:

$$\text{MAR}_{\text{org}} [\text{mg cm}^{-2} \text{ yr}^{-1}] = \text{WBD} \cdot (1 - \text{WC}) \cdot \text{OM} \cdot \text{SAR}$$

$$\text{MAR}_{\text{min}} [\text{mg cm}^{-2} \text{ yr}^{-1}] = \text{WBD} \cdot (1 - \text{WC}) \cdot \text{MM} \cdot \text{SAR}$$

Where, OM and MM (1-OM) are, respectively, the organic-matter and mineral-matter content estimated on the whole sample set with the empirically determined relationship  $\text{OM} = 2.3 \times \text{TOC}$  ( $R^2 = 0.99$ ,  $p < 0.001$ ,  $n = 25$ ) (Massa *et al.* 2012).

### 3.3.4 Pollen analysis

Sediment samples were processed for pollen analysis using standard techniques (Moore *et al.* 1991). The estimation of pollen concentration for each sample was enabled by adding a *Lycopodium* spore tablet. A minimum of 400 pollen grains of terrestrial plants was counted in each sample, but below 243 cm, pollen grains were too rare to ensure statistical significance. Pollen grains were identified with the aid of a reference collection of Greenlandic modern pollen types and keys (Faegri and Iversen 1989; Moore *et al.* 1991), and photographs (Reille 1992; Beug 2004). *Oxyria digyna* and *Rumex acetosa/acetosella* were combined into the *Oxyria/Rumex*-type due to the difficulty of their distinction. The results are presented as percentages of the pollen sum, excluding aquatics, spores, algae, *Cyperaceae*, hygrophilous, exotics, and spores. Algae, aquatic plants, and the pollen sum are represented in accumulation rates.

### 3.3.5 Diatoms

Diatoms were prepared from wet sediments using standard oxidative protocols for large sample numbers (Battarbee and Kneen 1982; Renberg 1990). Slurries were mounted on coverslips using Naphrax mounting medium and an average of 400 valves were identified per slide using taxonomic reference literature from Greenland (Foged 1953, 1955, 1972, 1977) and Labrador (Fallu *et al.* 2000).

## 3.4 | Results and proxy interpretation<sup>1</sup>

### 3.4.1 Sediment composition and chronology

Throughout the sequence, the sedimentological parameters are remarkably consistent. Changes in MS and WBD are principally driven by the grain-size distribution and the minerogenic content (Figs. 2, 3).

<sup>1</sup> All of the data from Lake Igaliku presented in this study are available on-line through the World Data Center for Paleoclimatology (<http://www.ncdc.noaa.gov/paleo/pubs/jopl2012arctic/jopl2012arctic.html>).

In most cases, an increase in grain size is associated with higher mineral-matter content and higher MS and WBD.

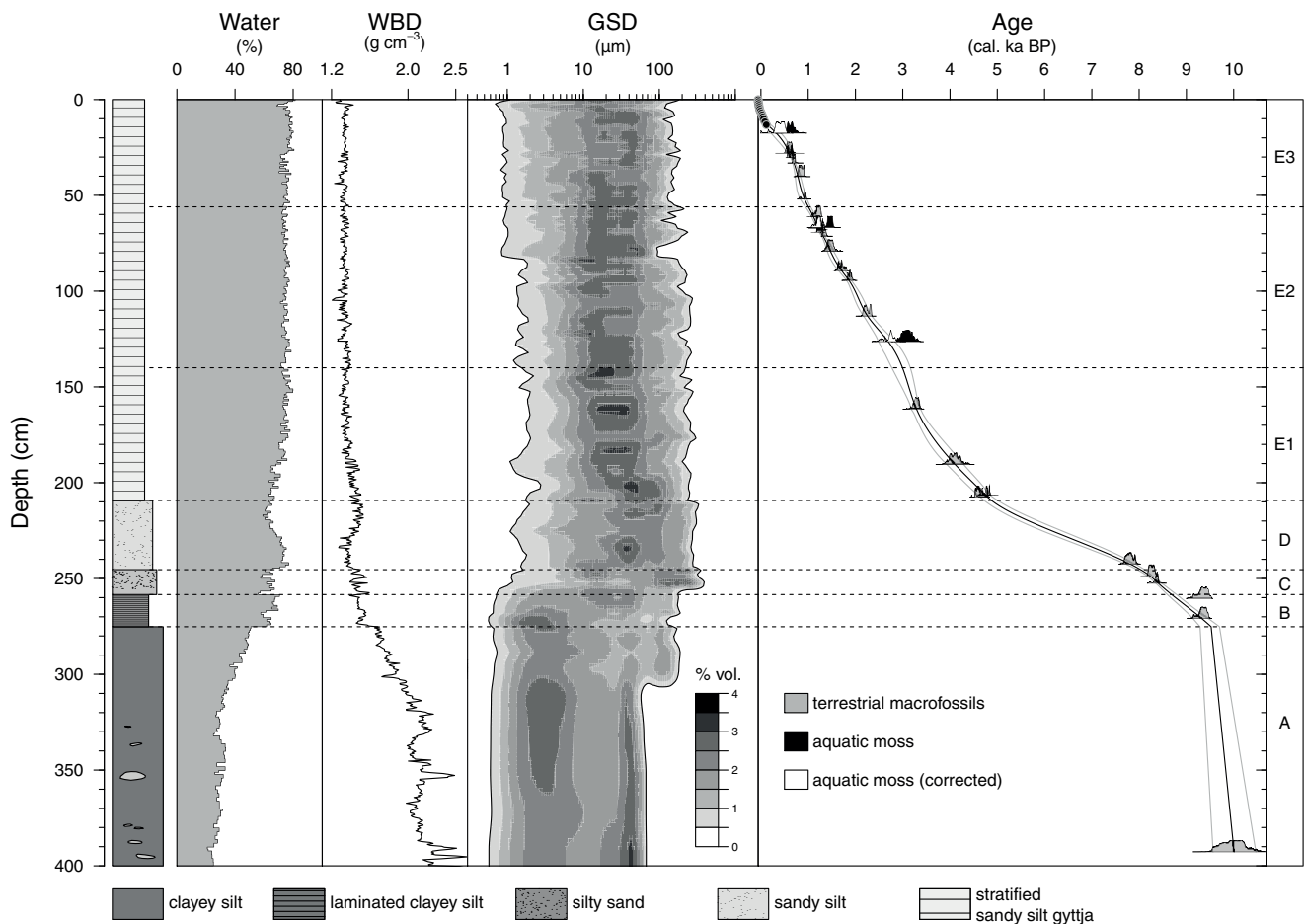
AMS <sup>14</sup>C measurements at the major lithological boundaries reveal large changes in sediment accumulation rate (Fig. 2). All the calibrated radiocarbon ages increase with increased depth, except at 252.5 cm (8350 ± 80 BP) and 260.4 cm (8330 ± 60 BP), which are coeval (Table 1). Rather than interpolate between these points, the upper of these two dates was removed because the finely laminated clayey Unit B is not consistent with high sedimentation rates and instead suggests a decrease in hydrological competence (see description below). Interpolating through the date would have neglected the abrupt lithological change from massive glacial minerogenic sediments (Unit A) to organic lacustrine gyttja (Unit B), which is often associated with decreasing sedimentation rates (e.g. Wagner *et al.* 2000; Kaplan *et al.* 2002). Erosion and redeposition of this macrofossil could have occurred as it was found just below an in-wash event (Unit C).

The X-radiographs reveal a continuous sedimentation with distinct lamina (~6 mm) and no mass-wasted deposit. Five major stratigraphic units can be distinguished from the visual core description and the sedimentological analyses. They are deposited under (1) Glacio-marine conditions (Unit A), and (2) lacustrine settings (Unit B through Unit E):

#### *Unit A (> 9.5 cal ka BP)*

The lowest unit consists of grey clayey silt and spans from 400 to 275 cm. It is massive with a stiff consistency, low WC (< 50%), low TOC content (< 1%), and high MS, WBD (2.0-2.5 g cm<sup>-3</sup>), minerogenic and organic MARs (respectively 4 and 200 mg cm<sup>-2</sup> yr<sup>-1</sup>). The sediments are poorly sorted and exhibit a wide range of particle sizes, from clay to sand, and two major modes at 3 and 40 μm. Near the bottom, pebbles are embedded in muddy matrix, and a 5 cm dropstone was found at 355 cm (Fig. 2). This facies is typical of marine sedimentation in the vicinity of an outlet glacier (Desloges *et al.* 2002; Nørgaard-Pedersen and Mikkelsen 2009). The very low TOC/TS value indicates high sulphur and likely marine conditions (Bernier and Raiswell 1984). The TOC/TN value of ~9 is similar of those of sediments from Spitsbergen fjord environments, which are characterized by terrigenous dominated organic material (Winkelmann and Knies 2005). Minerogenic sediments in these inner fjords have a TOC/TN value affected by inorganic nitrogen bound as ammonium into the lattice structure of the clay mineral, which can account for up to 70% of the total nitrogen content.





**Fig. 3.2** Lithology, water content, wet bulk density, grain-size distribution, and chronology of the composite sediment stratigraphy from Lake Igaliku

This is likely the case for the marine sediments of Unit A, with a low TOC/TN value despite predominantly allochthonous OM. Toward the top of the unit, the sediment is progressively enriched in OM with a rise in WC and a decrease in WBD and MS. The grain-size distribution reveals a concomitant shift, characterized by the appearance of a third, coarser mode at 120  $\mu\text{m}$ , which persists through the unit. This likely indicates an evolution of sediment sources, probably resulting from the depletion of the fine till fraction and from a more littoral setting.

#### Unit B (9.5 – 8.6 cal ka BP)

The lithology abruptly changes at 275 cm and marks the deposition of finely laminated grey to dark grey clayey silt up to 258 cm. Fine grain size likely reflects decreasing current velocities in favor of clay sedimentation and the establishment of lacustrine conditions. The laminae become faint towards the top of the unit as the TOC, TN, and TS increase (Fig. 3). The sediments also become yellowish with increasing silt content, suggesting the depletion of the glacial sediment source. The TS content

reaches its maximum ( $> 0.5\%$ ), suggesting an anoxic monimolimnion (Routh *et al.* 2004). This hypothesis is reinforced by several layers of purple sulphur bacteria at the bottom of the unit. The TOC/TN value increases from 10 to 12, interpreted as an increasing terrestrial contribution to the organic matter pool.

#### Unit C (8.6 – 8.0 cal ka BP)

Between 258 and 245 cm, the sediments include several detrital layers, and indicate reducing bottom-water conditions. The lowest detrital layer is fine grained, but the others consist of yellowish silty sand, with no evidence of glacial input. The coarse-grained sediment suggests enhanced wind activity as the deposition of clastic grains  $> 255 \mu\text{m}$  (Fig. 3) requires aeolian transport on a frozen lake surface or basal freezing at the shore and dropping of particles to the lake floor with spring ice melt (Andresen *et al.* 2006).

#### Unit D (8.0 – ~4.8 cal ka BP)

This unit consists in yellowish sandy silt from 245 to 209 cm. The TOC/TN value increases steadily throughout

Unit D, with small-scale variations pointing to an increasing proportion of land-derived organic matter into the sediments, whereas the TOC/TS value between 30 and 80 documents a shift to oxygen-saturated bottom water (Hedges and Keil 1995). The increase in grain size toward the top of the unit, associated with increasing minerogenic inflow, indicates higher transport energy.

#### Unit E (~4.8 cal ka BP – present)

This unit spans from 209 cm to the top of the sequence, and consists of an almost homogenous finely stratified brownish sandy silty gyttja with black layers rich in ferrous iron oxide and sulphur. These reduced layers match with relatively lower TOC/TS values around 200-170 cm (subzone E1) and 50-20 cm (subzone E3). The grain size is finer than in the underlying unit and decreases continuously towards the top of the sequence. This unit also has higher MAR of

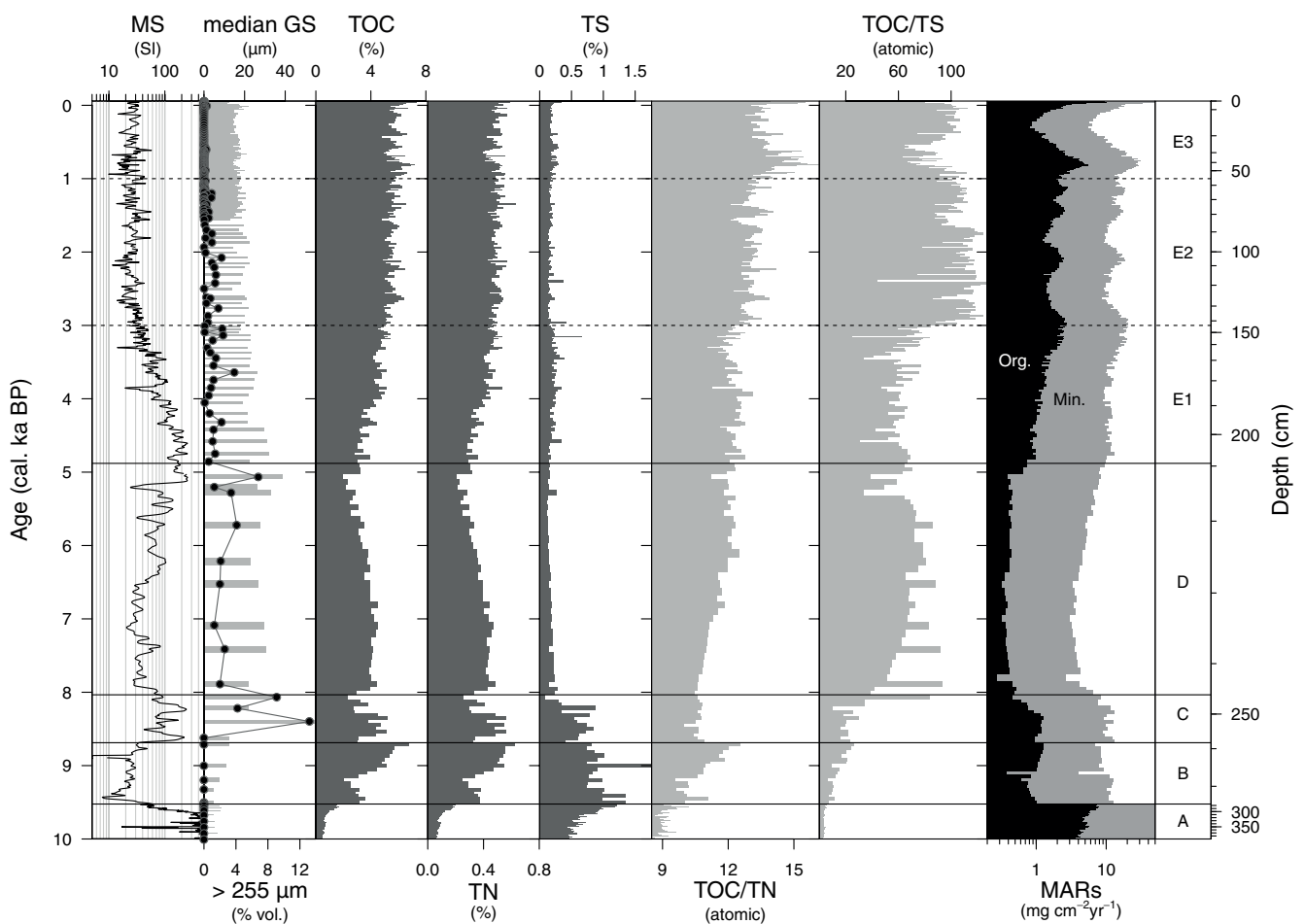
minerogenic and organic matter than the underlying unit. Above ~5 cm, the sandy silt gives way to black clayey silt associated with a high TOC/TN value and MAR (top of subzone E3).

#### 3.4.2 Pollen stratigraphy

The simplified pollen record (Fig. 4) reflects the sub-continental, subarctic vegetational zone of southern Greenland, where birch and willow copses cover most of the ground in protected areas (Feilberg 1984). The pollen diagram was divided into four main zones in which the major vegetation changes match the sediment evolution.

#### > 8.1 cal ka BP (Unit A to C)

The pollen concentration in Lake Igaliku sediments is insufficient for analysis below 243 cm. However,



**Fig. 3.3** Magnetic susceptibility (MS), median grain size (grey bars) and > 255 µm (black dots), total organic carbon (TOC), total nitrogen (TN) and sulphur (TS) and related molar ratio, mass accumulation rate of minerogenic (grey bars) and organic matter (black bars) from Lake Igaliku. Defined lithostratigraphic zones and sub-zones are represented on the right column with corresponding depth scale.

numerous algae were found, mainly *Tetraedron*, *Botryococcus*, *Volvocaceae* as well as dinoflagellate resting cysts, which suggest poorly developed vegetation around the lake and early productive lake conditions (Fredskild 1983).

#### 8.1 – ~4.8 cal ka BP (Unit D)

The bottom sample is characterized by dominant values of *Salix*, *Empetrum*, and *Thalictrum alpinum* consistent with the pioneer vegetation phase described by Fredskild (1973). This is immediately followed by a shift to a dry open heath dominated by *Juniperus communis* (20% to 40%) and with *Poaceae* and *Thalictrum* as the dominant herbaceous taxa. *Alnus* reached 10%, confirming it was present in southern Greenland until the mid-Holocene (Fréchette and de Vernal 2009). *Juniperus communis* is typical of poor soils and can survive dry conditions (García *et al.* 2000; Thomas *et al.* 2007b), but its dominance in the pollen assemblage also implies a warm climate during this period (Fredskild 1973). Around 8.0-7.8 and 5.3-4.8 cal ka BP, *Juniperus communis* reaches ~40% of the

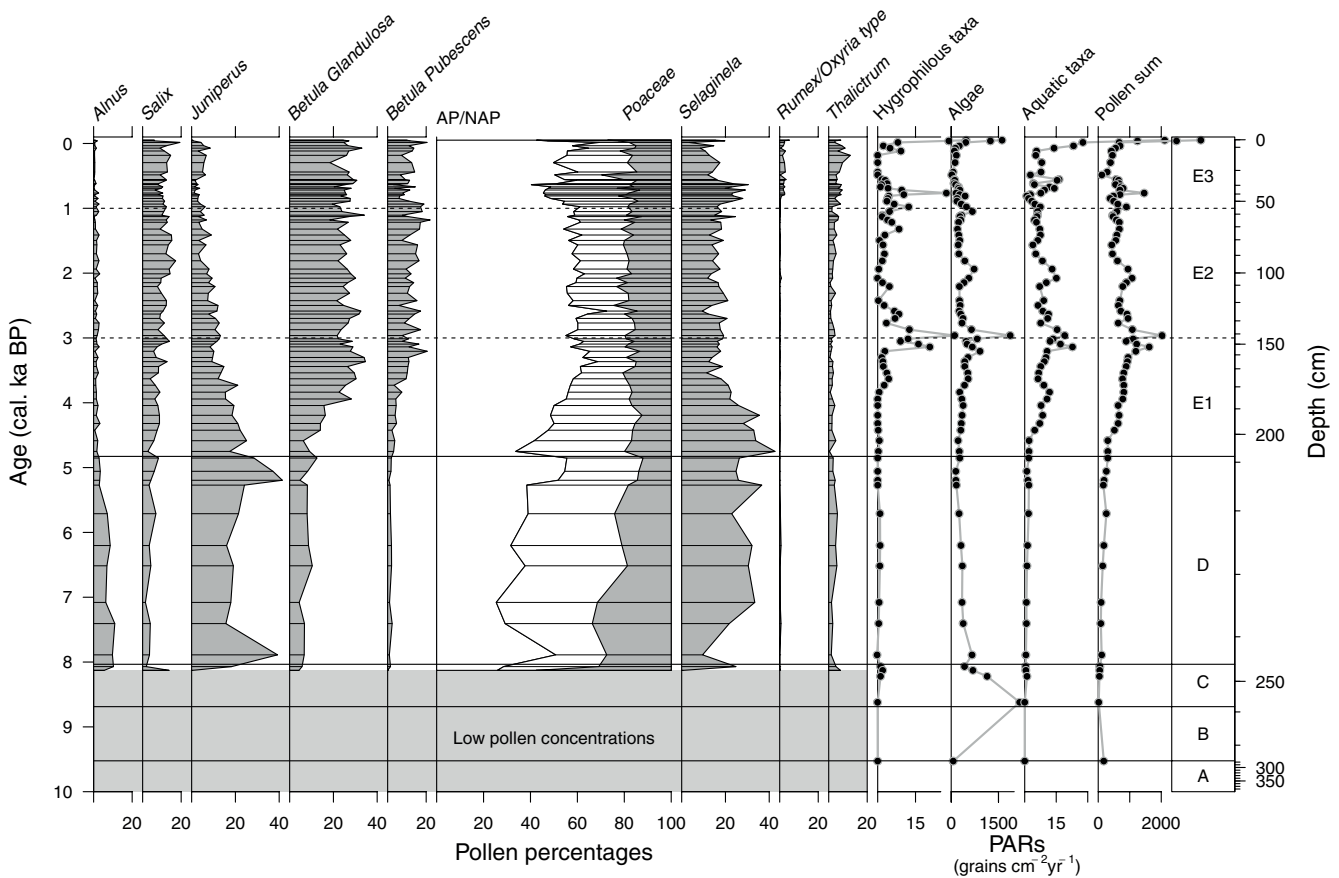
pollen total with a decrease in *Selaginella selaginoides* and *Thalictrum alpinum*, which suggest relatively drier conditions.

#### ~4.8 – 1.0 cal ka BP (Unit E1 and E2)

This zone marks the progressive replacement of the Juniper-tundra by a low dwarf shrub community dominated by *Betula glandulosa* (20-35%), *Betula pubescens* (10-20%), and *Salix* (10-18%). The heliophilous club moss, *Selaginella selaginoides*, decreases with the expansion of dwarf shrub. The expansion of *Betula pubescens*, a drought-intolerant tree (Atkinson 1992), together with a rise of hygrophilous taxa, suggests a wetter climate, quite similar to the present conditions. At this time, the terrestrial and aquatic pollen influxes reach maximum values. They begin to decrease after ~3.0 cal ka BP, suggesting cooler summers.

#### 1.0 cal ka BP – present (Unit E3)

After ~1.0 cal ka BP, the appearance of Norse apophytes such as *Rumex acetosa* provides evidence of Norse farmers in the region of Lake Igaliku (Gauthier



**Fig. 3.4** Simplified pollen diagram based on a relative percentages and accumulation rate. AP/NAP = arboreal/non-arboreal pollen

*et al.* 2010). *Betula glandulosa* and *Poaceae* values remain steady but *Betula pubescens* and *Juniperus communis* reach their lowest percentages until 0.5 cal ka BP, together with a subtle decrease of *Salix*. After ~0.5 cal ka BP, *S. selaginoïdes* decrease and shrubs are more abundant with the rise of *Salix* and *Juniperus*. Pollen accumulation rates (PAR) reach minima during the Little Ice Age (between ~1500 and 1920 AD), and then increase markedly to their maximum values.

### 3.4.3 Diatom assemblages

Diatoms are present and well preserved in all samples from Lake Igaliku sediments. Over 199 species were identified that constitute a largely oligotrophic Arctic flora, typical of small, dimictic lakes in Greenland (Perren *et al.* this volume; Cremer and Wagner 2004), as well as Labrador (Fallu *et al.* 2000) and Northern Scandinavia (Bigler *et al.* 2002). Five main zones can be identified from the diatom assemblages that are consistent with the stratigraphic units and pollen zones described above.

#### > 9.5 cal ka BP (Unit A)

This zone is marked by a marine diatom flora (*Chaetoceros* spp. resting cysts as well as marine species belonging to the genera *Plagiogramma*, *Biremis*, *Cocconeis*, *Fragilariopsis*, etc.) and is consistent with the earliest phase of post-glacial, isostatically uplifted isolation basin in West Greenland (Long *et al.* 1999).

#### 9.5 – 8.0 cal ka BP (Unit B and C)

These two zones mark the transition from marine to freshwater conditions and the probable establishment of meromixis, with a freshwater mixolimnion overlying trapped anoxic sea water. These zones are characterized by *Cyclotella radiosa*, *Epithemia* spp., as well as small *Fragilaria sensu lato* and are similar to other high-productivity meromictic environments in West Greenland (McGowan *et al.* 2003).

#### 8.0 – ~4.8 cal ka BP (Unit D)

The bottom of this zone marks the rapid transition to a completely freshwater oligotrophic environment dominated by small benthic *Fragilaria* s.l. (= *Staurosirella* spp., *Pseudostaurosira* spp.) and to growing representation of oligotrophic centric forms (e.g. *Cyclotella rossii* complex). Small *Fragilaria* species are cosmopolitan and tend to outcompete other species in alkaline and/or low-light environments. The dominance of benthic pioneering taxa until ~4.8 cal ka BP is typical of Holocene Greenland lake evolution (Perren *et al.* this volume) and likely reflects poor light quality as

well as high lake-water alkalinity resulting from weakly developed soils and sparse vegetation.

#### ~4.8 cal ka BP – present (Unit E)

This period represents a shift toward planktonic diatom dominance, especially by the centric diatom *Cyclotella stelligera* (= *Discostella stelligera*). The dominant modern flora was established ~4.8 cal ka BP. It has been relatively stable over the last 5000 years, with sub-millennial-scale variations, except after 1988 AD when the diatom flora show a dramatic increase in *Fragilaria tenera* and a rise in *Cyclotella stelligera*. The expansion of small planktonic species after ~4.8 cal ka BP likely reflects a combination of factors including reduced summer stratification and lower alkalinity.

## 3.5 | Discussion

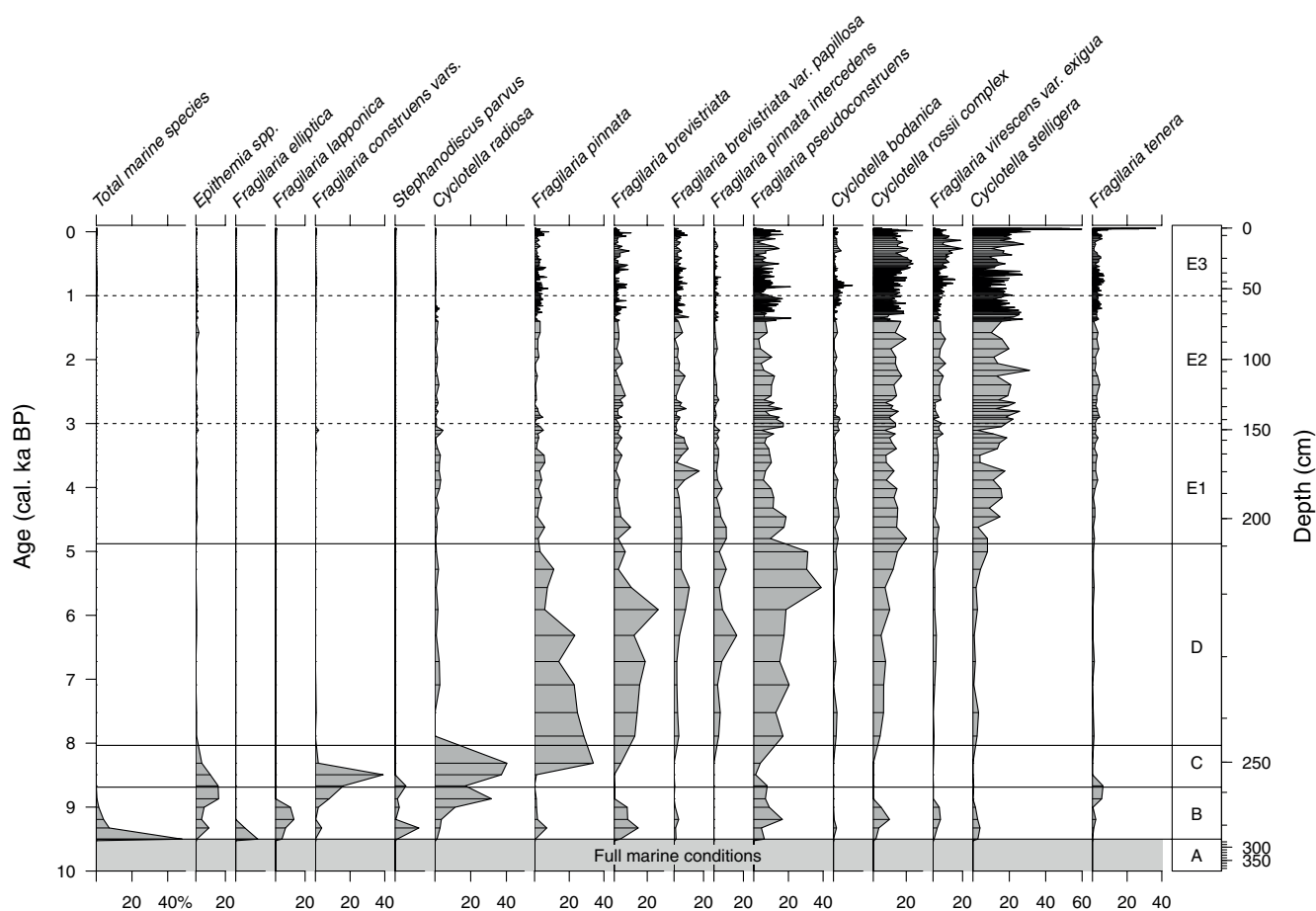
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### 3.5.1 Ice-proximal marine conditions (10 – 9.5 cal ka BP)

The deepest macrofossil from the Lake Igaliku core provides a minimum age of 10.4–9.5 cal ka BP for the deglaciation of the area, which broadly agrees with the deglacial history of southern Greenland (Weidick *et al.* 2004; Kelly and Lowell 2009). After the initial retreat of the inland ice, the basin of Lake Igaliku was part of an ice-proximal fjord with lingering ice in the fjord as documented by the marine diatom flora and ice-rafted debris. High organic and minerogenic MARs are similar of those of Spitsbergen fjord environments and are most likely introduced by meltwater discharge, coastal erosion and ice-rafted debris from nearby glaciers (Winkelmann and Knies 2005). Toward the top of the marine sediment unit, the rapid decrease in MS and the increase of organic material likely document a waning ice influence and the establishment of vegetation on the catchment landscape.

### 3.5.2 Basin isolation (9.5 – 8.1 cal ka BP)

Unit B documents the shift from marine conditions to the early stages of lacustrine development. The abrupt lithological change from the massive unsorted marine sediment to laminated lacustrine clayey gyttja marks the isostatic emergence of Lake Igaliku from nearby Igaliku Fjord and Tunulliarfik Fjord ~9.5 cal ka BP, consistent with the relative sea-level history of the region (Bennike *et al.* 2002; Weidick *et al.* 2004; Sparrenbom *et al.* 2006).



**Fig. 3.5** Stratigraphic diagram showing the relative abundance of important diatom taxa

The co-occurrence of both lacustrine (52%) and marine (48%) diatom taxa in the basin at the time Lake Igaliku was isolated from the sea suggests that the threshold level is close to the highest tide. The change in sediment grain size and detrital MAR mark the cessation of input to the basin from wave and tidal flow (Long *et al.* 2011). The disappearance of marine taxa indicates a complete disconnection from the sea at *ca.* 8.8 cal ka BP (Fig. 5).

The marine/lacustrine transition was then followed by a period of meromixis, a chemically stratified water column with higher salinity water underlying fresher water (Corner *et al.* 2001). Meromixis is indicated by high sulphur content and monimolimnetic anoxia, as well as a diverse diatom flora common to highly productive meromictic environments elsewhere in western Greenland (McGowan *et al.* 2008). The fine laminae are likely meromictic varves formed due to the strong stratification of the water column. In coastal Greenland, these laminations are typical of lacustrine sedimentation following the isostatic emergence (Bennike and Björck 2000; Long *et al.* 2011). The

sedimentation rate remains relatively high (Fig. 3), which might reflect erosion of unstable till deposits in the catchment.

The upward attenuation and disappearance of the laminae as well as the increasing values of TOC and TN suggest weakening stratification, enhanced productivity, and the progressive flushing of old sea water trapped at the bottom of the lake. At the same time, the increasing contribution of terrestrial organic matter likely indicates the development of soils and vegetation in the catchment, which point to a warming climate during the earliest lake history. After 8.1 cal ka BP, the complete transition to an oligotrophic freshwater diatom flora and mixis in the water column associated with TOC/TN > 20, indicate the absence of marine water trapped in the basin.

### 3.5.3 A cold and windy event 8.6 – 8.1 ka BP ?

A succession of coarse clastic pulses occurring ~8.6–8.1 ka BP is interpreted as a period of climatic instability. The sharp decrease of the TOC/TN value and the

lack of pollen indicate low input of terrestrial organic matter, suggesting a cold climate. The deposition of coarse clastic grains (up to 500 µm), is favored by dry and windy conditions (Lamoureux and Gilbert 2004; Andresen *et al.* 2006). These findings are consistent with a dry, cold and stormy period 8.4-8.0 cal ka BP, as has been inferred in southern Greenland from the sediments of lake N14 (Andresen *et al.* 2004), which can be interpreted as a response to the 8.2 cal ka BP event (Alley *et al.* 1997; Barber *et al.* 1999).

However, the timing of the meromictic/freshwater transition and early catchment evolution complicates this hypothesis. The diatom flora shows that the basin has not experienced significant marine incursion since ~9.5 cal ka BP, making marine influences during this period unlikely. Similarly, the coarse-grained deposits could have resulted from a shift in sediment source from glacial drift to regolith produced by the weathering of freshly exposed granitic bedrock. However, it cannot explain the transport of sand, which requires high energy and wind scouring that was facilitated by the near absence of vegetation cover.

Because of its proximity to the Irminger Current (Fig. 1), Lake Igaliku is sensitive to changes in the ocean circulation. We suggest that this detritic event in Lake Igaliku is climatic in origin and linked to the catastrophic drainage of meltwater from the Laurentide ice sheet into the Labrador Sea. The best date for the start of this event is 8.6 cal ka BP (8.7 – 8.5 cal ka BP). This pre-dates the cooling inferred from the Greenland ice core records (Thomas *et al.* 2007a) but falls within the age range of the Agassiz outburst floods into the Labrador Sea (Lewis *et al.* in press) as well as cooling inferred from stable isotope records in the North Atlantic region (Daley *et al.* 2011). Further analysis and chronological investigations are necessary to confirm the nature and the timing of the event observed at Lake Igaliku.

### 3.5.4 The Lake Igaliku expression of the Holocene thermal maximum

The record of the Holocene thermal maximum (HTM) is complicated at Lake Igaliku by the continuous evolution of the landscape that followed deglaciation. Immediately after the glacial retreat, soils were poorly developed and vegetation was scarce. Consequently, terrestrial and aquatic life was in a pioneering phase despite maximum summer insolation (Fig. 6). N-fixing *Alnus* was one of the earliest colonizers on the landscape at Igaliku, along with *Juniperus* (Figs. 4, 6), and is associated, in modern pollen assemblages, with high summer temperatures in Arctic Canada and Greenland

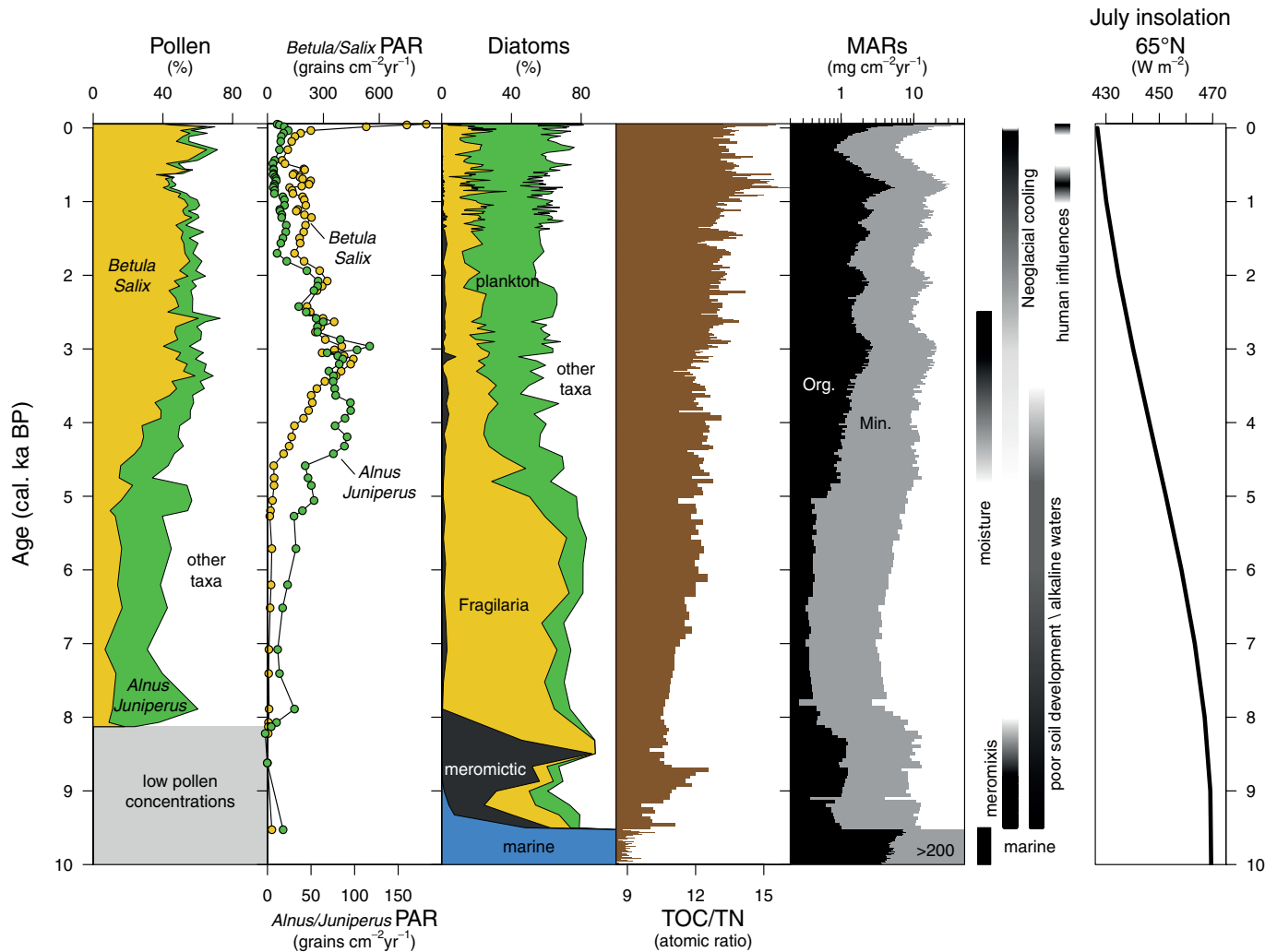
(Fréchette *et al.* 2008). In the lake, benthic *Fragilaria* diatom taxa dominated (Fig. 6). *Fragilaria*-dominated lake systems are rare in modern environments and are restricted to the north coasts of Greenland and Ellesmere Island and the high Alps in lakes that have strong seasonal ice regimes, poorly developed catchment soils and vegetation, and relatively high pH (Perren, unpublished data; Antoniadou *et al.* 2007). The allochthonous inputs were lowest on this part of the stratigraphy and the dominance of *Fragilaria* here therefore suggests that edaphic factors exert a strong control on early species distribution. Summer aridity until ~4.8 cal ka BP may have prolonged this pioneer phase. Indeed, the stabilization of the TOC/TN value at ~6 cal ka BP indicates that both soils and vegetation reached equilibrium with the climatic conditions that prevailed until then.

From these competing factors, it is difficult to characterize the HTM initiation, although evidence of warmth is present as early as ~9 cal ka BP as indicated by TOC values. Even if it is assumed that pollen assemblages of the entire postglacial development should not be interpreted as only climatically driven, the presence of *Alnus* and *Juniperus* suggests that warm temperatures have prevailed at least until ~4.8 cal ka BP.

Between 5.3 and 4.8 ka BP, a rise in *Juniperus* taxa and a decrease in *Selaginella selaginoides* points to a brief period of drier conditions. At the same time, increase in grain size and detrital inflow (Fig. 6) suggests an increase in the aeolian activity that occurs during times of aridity. This event is consistent with an important climate reversal around 5.5-5.0 cal ka BP characterized by windy conditions recognized in southern Greenland (Andresen *et al.* 2004), east Greenland (Wagner *et al.* 2000), and Iceland (Jackson *et al.* 2005). Change in sea salt and terrestrial dust influx to the ice sheet (O'Brien *et al.* 1995), as well as increased exotic pollen transport to the coast of west and south Greenland (Fredskild 1984) also suggest major atmospheric circulation changes over the Arctic around 5.5-5.0 cal ka BP.

### 3.5.5 HTM-Neoglacial transition (~4.8 cal ka BP)

After approximately 4.8 cal ka BP, a major environmental transition is recorded in the pollen, diatoms, and sediments of Lake Igaliku. The open *Juniperus* heath progressively became a dense cover of *Betula glandulosa* with lesser components of *Betula pubescens* and *Salix*, and with some residual *Juniperus*. The spread of *Betula pubescens*, a drought-intolerant shrub (Atkinson 1992), may signal wetter conditions,



**Fig. 3.6** Summary of the major environmental changes inferred from Lake Igaliku sediments. Insolation (Berger and Loutre 1991) is shown for comparison

quite similar to the present day. *Betula glandulosa* is associated with humus-rich soil (Fredskild 1973, 1991; De Groot *et al.* 1997) and its spread was likely enabled by *Juniperus communis*, a pioneer plant that can grow on poor soil (Thomas *et al.* 2007b). Common juniper in tundra ecosystems increases soil fertility by locally increasing N and P and may facilitate the growth of other plant communities (DeLuca and Zackrisson 2007). Accordingly, the *Juniperus/Betula* succession is probably influenced by climate as well as edaphic and ecological factors.

The shift to almost homogeneous gyttja and the decrease in median sediment grain size after ~4.8 cal ka BP suggest that increased moisture and vegetation change also had a strong influence on soil evolution and sediment transfers to the lake. Increased precipitation and surface runoff are likely reflected in the rise of both minerogenic and organic terrestrial inputs (Fig. 6). The denser *Betula* cover would have protected soils and diminished the availability and transport of

coarse clastic material to the lake. The transition from evergreen *Juniperus* tundra to a highly productive deciduous shrub cover (Shaver and Chapin 1991) would have enhanced the accumulations of organic matter via litterfall on the surface soil.

The shift from benthic to planktonic diatoms at ~4.8 cal ka BP is consistent with the shift in catchment vegetation and sediment input suggesting tight climate/catchment/lake linkages. The retention of cations and nutrients within the developing terrestrial ecosystem would have led to increasing acidification and oligotrophication in the lake over time (Engstrom *et al.* 2000). The increasing input of dissolved organic carbon from maturing soils was probably another source of long-term acidification (Anderson and Stedmon 2007). Reduced stratification from cooling summers and slight acidification may have allowed for the growth of the modern *Cyclotella*-dominated planktonic diatom assemblage after ~4.8 cal ka BP (see also Perren *et al.* this volume).

The timing of the *Betula-Cyclotella* shift at Lake Igaliku is contemporaneous with the shift in western Greenland toward moister conditions (McGowan *et al.* 2003; Aebly and Fritz 2009), a change in the moisture source at the summit of the ice sheet (Masson-Delmotte *et al.* 2005), and an increase in polar water in the East Greenland Current (Jennings *et al.* 2011). Closer to Lake Igaliku, climate reconstructions indicate the first sign of Neoglaciation at about 4.7–4.8 cal ka BP (Andresen *et al.* 2004; Nørgaard-Pedersen and Mikkelsen 2009). This timing suggests a strong climatic control on the onset of these ontogenetic shifts.

### 3.5.6 Cooler Neoglacial phase (after ~3 cal ka BP)

While the Neoglacial cooling is often characterized in Greenland lakes by a decrease in organic-matter content (e.g. Willemse and Törnqvist 1999; Wagner *et al.* 2000; Kaplan *et al.* 2002), increased supplies of soil organic matter allowed for predominantly organic sedimentation to reach its maximum at Lake Igaliku during the late Holocene, in apparent contradiction with insolation trend (Fig. 6). PAR (Fig. 6) is interpreted to reflect growing-season productivity, partly dependent upon temperature. Early Holocene aridity and weakly developed soil can explain the relatively low PAR before 4.8 cal ka BP. With more favorable conditions, the pollen production of *Juniperus* rose and attained a maximum between 4.5 and 3.0 cal ka BP. Because of the vegetation shift, maximum pollen production of the *Betula/Salix* community was delayed until ~3 ka (Fig. 6), which is well after other records indicate HTM conditions in south Greenland (Kaplan *et al.* 2002; Fréchette and de Vernal 2009). PAR started to decrease from ~3 cal ka BP, and may indicate the onset of the cooler phase of the Neoglacial at Lake Igaliku. Decreasing pollen accumulation is accompanied by increasing TOC/TN values, which may reflect decreasing autochthonous OM production. Decreasing lake productivity is also supported by the concomitant decrease in algae and aquatic pollen accumulation rates (Fig. 4). This probably caused a decrease in oxygen consumption for the decomposition of OM that likely lead to oxygenated bottom water and high TOC/TS values (Fig. 3). Reduced summer stratification due to colder conditions may also have increased the hypolimnetic oxygen concentrations. The timing of the cooling at Lake Igaliku is consistent with a clear local glacial advance (Larsen *et al.* 2011), and a significant cooling inferred from opal concentrations in lake sediments of south Greenland (Kaplan *et al.* 2002; Andresen *et al.* 2004). This cooling is coeval with diminished northward advection of the

Irminger Current after 3.5 cal ka BP (Jennings *et al.* 2011), suggesting that oceanic forcing played a major role in air temperatures of south Greenland.

Increasing moisture after 4.8 cal ka BP preceded the register of a significant cooling at Lake Igaliku. Similarly, Wagner *et al.* (2000) described a decoupling in moisture and temperature change in east Greenland, with increasing moisture preceding the Neoglacial cooling by 1000 years. A similar pattern was also observed in west Greenland, where the onset of moister conditions pre-dates the end of the maximum warming (McGowan *et al.* 2003; Presthus Heggen *et al.* 2010).

Despite the possible influence of land use, pollen accumulation appears to document climatic changes of the last millennia nonetheless. PAR reached minimum values during the Little Ice Age from 1500 to 1920 AD, consistent with maximum glacial re-advance at Qipisarqo (Kaplan *et al.* 2002) and elsewhere in south Greenland (Weidick *et al.* 2004; Larsen *et al.* 2011). It is also coeval with high rates of isostatically driven transgression, which caused the inundation of a Norse graveyard at Herjolfsnæs (Mikkelsen *et al.* 2008). The sharp increase of *Salix/Betula* pollen accumulation rate after 1920 AD (Fig. 6) suggests a rapid warming, which reversed the Neoglacial cooling trend similar to other locations in the Arctic (Kaufman *et al.* 2009).

### 3.5.7 Human influences

Norse farmers settled southern Greenland ~985 AD (Jones 1986) including the area around Lake Igaliku, which was used for grazing and hay production. Following the disappearance of the Norse ~1450 AD, Igaliku was resettled during the 18th century (Arneborg 2007) and large-scale agriculture, based on sheep farming, was developed in the 1920s (Austrheim *et al.* 2008). Consequently, the response to climate change over the last millennium was overprinted by land-use effects (Perren *et al.* in press; Gauthier *et al.* 2010; Massa *et al.* 2012). However, the consideration of human-induced changes at Lake Igaliku in light of the entire Holocene ecosystem development provides new insights about their magnitude.

Relative to the preceding Holocene shifts, the vegetation was slightly impacted by land clearance and grazing, and exhibits a small decrease in woody taxa abundance (from 60% to 45%). Until ~1335 AD, the related soil erosion, documented by high TOC/TN and MAR values, clearly compounds the long-term increasing trend (Fig. 6). Contrary to the other studied variables, the diatom assemblages indicate that the lake ecology was not significantly impacted, and that



the changes are within the range of natural Holocene variability.

Both in terms of lake ecology and soil erosion, the period since 1988 AD is likewise unprecedented in the context of the Holocene by a magnitude and rate of change greater than the previous 9500 years. The digging of drainage ditches for hayfields caused a dramatic increase in MAR, which reached unprecedented values. The use of nitrogen fertilizers on these fields (200-250 kg ha<sup>-1</sup> yr<sup>-1</sup> of N, Miki Egede pers. commun.) have outpaced the natural buffering capacity of Lake Igaliku, resulting in a sharp rise in the mesotrophic diatom, *Fragilaria tenera*.

### **3.6 | Synthesis and conclusion**

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The multiproxy approach used in this study highlights the interplay of ontogenetic processes (e.g. marine isolation, catchment maturation, soil and lake development, plant colonization) with overarching climatic factors (e.g. early Holocene aridity, Neoglacial cooling). Anthropogenic influences, which began with the Norse colonization around 1000 AD, preclude paleoclimatic interpretation during the last millennium.

The early Holocene climate record from Lake Igaliku is overprinted by the marine, meromictic, and freshwater phases of basin isolation until ~8.1 ka BP. Despite the difficulty in interpreting Lake Igaliku sediments solely

in terms of climate change, the record suggests early Holocene warmth, which was interrupted by a cold, dry and windy event between 8.6 and 8.1 cal ka BP. From ~8 to ~4.8 cal BP, the establishment of an open heath with *Juniperus* and *Alnus* documents dry and warm conditions. The dry and windy event at ~5.3-4.8 cal ka BP could be related to an initial phase of the atmospheric circulation change (Andresen *et al.* 2004). Increased moisture and the beginning of a cooling are documented after ~4.8 cal ka BP, which could mark atmospheric reorganization in the North Atlantic region. As in other locations in south Greenland, a more significant cooling is recorded ~3 ka BP, with a decreasing pollen accumulation culminating with the end of Little Ice Age. This long-term cooling trend was reversed during the 1920s by recent warming.

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## Chapitre 4

# **Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland**





## Chapitre 4



# Pollen and non-pollen palynomorph evidence of medieval farming activities in southwestern Greenland

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## Abstract

Radiocarbon dating, pollen and non-pollen palynomorph analyses from a lake core were used to establish the timing and effects of farming activities around Lake Igaliku, Eastern Settlement, Greenland. The absence of agro-pastoral impact before the medieval colonization by Europeans provides an opportunity to understand the development of farming activity in a pristine landscape. The results show that the first phase of clearance and grazing pressure, without the expansion of the Norse apophyte (native plant, in habitats created by humans) *Rumex acetosa* type, could have occurred in the 9–10th century A.D. The presence of Norse settlers and livestock is clearly recorded from the 11–12th century A.D. with increasing frequencies of the Norse apophytes *Rumex acetosa* type and *Ranunculus acris* type, and coprophilous fungi. This colonization phase is followed by a period of decreasing human impact at the beginning of the 14th century, with a decrease in weeds, apophytes and coprophilous fungi suggesting a reduced grazing pressure. The regrowth of *Salix* and *Betula* and the disappearance of anthropogenic indicators except *Rumex acetosa* type between the 15th and 18th century demonstrate the abandonment of the settlement, until the development of contemporary agriculture in the 20th century.

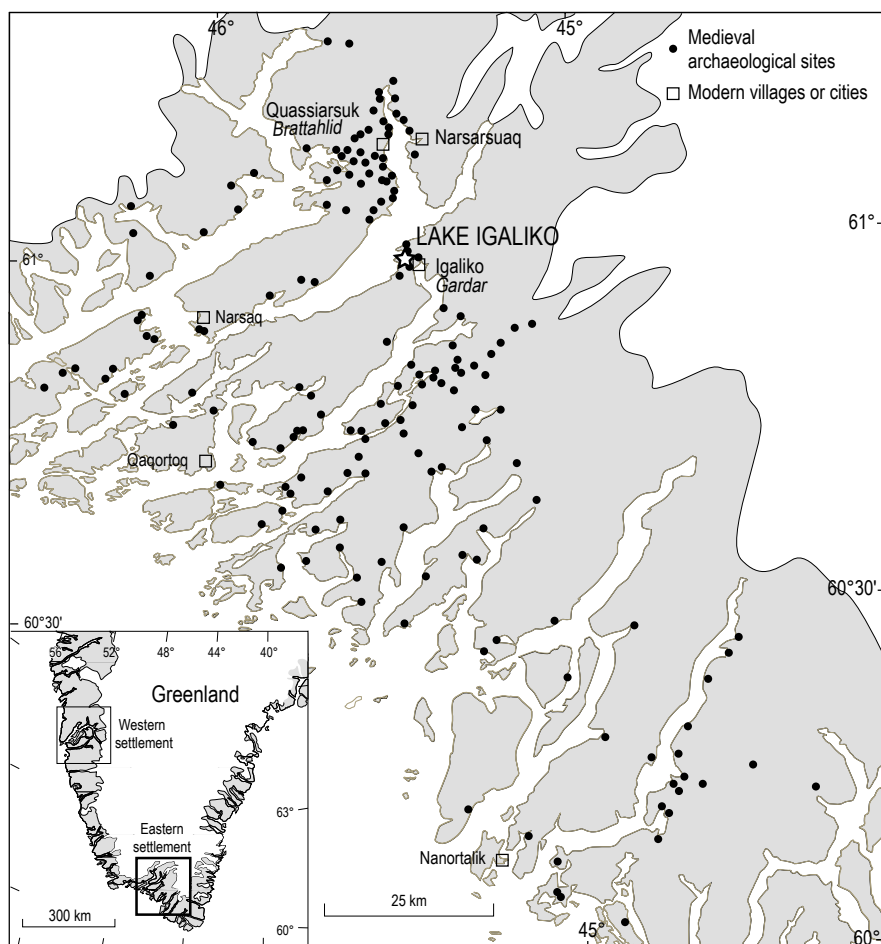
**Keywords:** *Non-pollen palynomorphs, Palynology, Grazing pressure, Greenland*

## 4.1 | Introduction

The Norse settlement of Greenland from A.D. 985 to ca. 1450 has been particularly studied by archaeologists and palaeoecologists with a particular interest in agro-pastoral practices (Arneborg 2005; Dugmore *et al.* 2005; Commisso and Nelson 2008; Buckland *et al.* 2009), demography (McGovern 1991; Lynnerup 1996) and the analysis of individual sites (Algreen-Møller and Madsen 2006; Guldager *et al.* 2002). According to historians, the Norse colonization began in A.D. 985 with Erikrur Rauðe Þorvaldsson (Erik the Red). It developed on the basis of an agro-pastoral economy

and, at its height, supported a population ranging from 3,000 to 6,000 inhabitants (Lynnerup 1996; McGovern 1991). Farmers spread out over three parts of west Greenland with the two most important settlements situated at 60°N, Østerbygden, district of Narsaq, the so-called Eastern Settlement, and 64°N Vesterbygden, district of Nuuk, the so-called Western Settlement (Fig. 1). Farmers raised cattle, sheep, goats, horses, pigs and dogs, but they also hunted seal and caribou as well as fishing (Dugmore *et al.* 2005). In order to extend pastures and managed hay fields, they cleared the sparse arctic shrubs intensely (Fredskild 1992) and





**Fig. 4.1** Map of the Norse Eastern Settlement in southwest Greenland (historical data according to Kuijpers *et al.* 1999)

fertilized the grasslands with manure (Commisso and Nelson 2007, 2008; Ross and Zutter 2007; Buckland *et al.* 2009) and practiced irrigation (Arneborg 2005; Adderley and Simpson 2006).

The chronology of the abandonment of these colonies is unclear and the way in which it happened is still the subject of debate. The only point on which the authors agree is the role of the climatic change of the Little Ice Age (Dansgaard *et al.* 1975; Stuiver *et al.* 1995; Barlow *et al.* 1997) which isolated the community and caused a decline in agricultural yields (Barlow *et al.* 1997). In spite of a change in activity with more hunting and fishing (Arneborg *et al.* 1999, 2002), Norse society of south Greenland collapsed during the 15th century and all the farms were abandoned. It was not until the 18th century that the medieval Norse territories in the southwest of Greenland were partially reoccupied again by European migrants (Keller 1990), as well as in the 1920s for the redevelopment of agro-pastoral activities (Guldager *et al.* 2002), within the very center of the former Norse agricultural areas.

The impact of Norse activities on the arctic environment, following the *landnám* or settlement, from Old Norse,

“land-take”, is mainly shown by archaeobotanical analyses on archaeological sites or offsite in ponds and peat deposits but close to groups of ruins. Fredskild (1973, 1978, 1992) established a biochronology for the Holocene in Greenland and, more particularly, in the Eastern Settlement in the Qassiarsuk area, from two ponds and four peat-filled hollows. Fredskild’s investigations have revealed the arrival of Norse farmers in the 10th century and their perceptible impact on the environment from scrub clearance, the creation of hay meadows and the introduction of non-indigenous taxa. Radiocarbon dates in Fredskild’s studies are few in number and sometime imprecise (1973, 1978; Sandgren and Fredskild 1991). In order to improve these first results and to provide high resolution palaeoecological data, Schofield *et al.* (2007a) and Edwards *et al.* (2008) have studied two other peat deposits in the same area, in Qorlortoq valley and Tassiusak. Pollen analyses show human impact from the 10th century, but the first millennium A.D. is poorly recorded in the studied sequences due to sedimentological hiatuses from peat cutting, or a low sediment accumulation rate. These recent investigations also attempted to provide a good

chronology of the Norse occupation during the first half of the 2nd millennium A.D. Most recently, Buckland *et al.* (2009) have analyzed drainage ditches containing clay-rich peat which were located close to the settlement ruins of *Garðar*, about 2 km from Lake Igaliku. Pollen, insect analyses, as well as AMS radiocarbon dates on seeds revealed evidence for manuring and irrigation for the period of ca. A.D. 1110–1370.

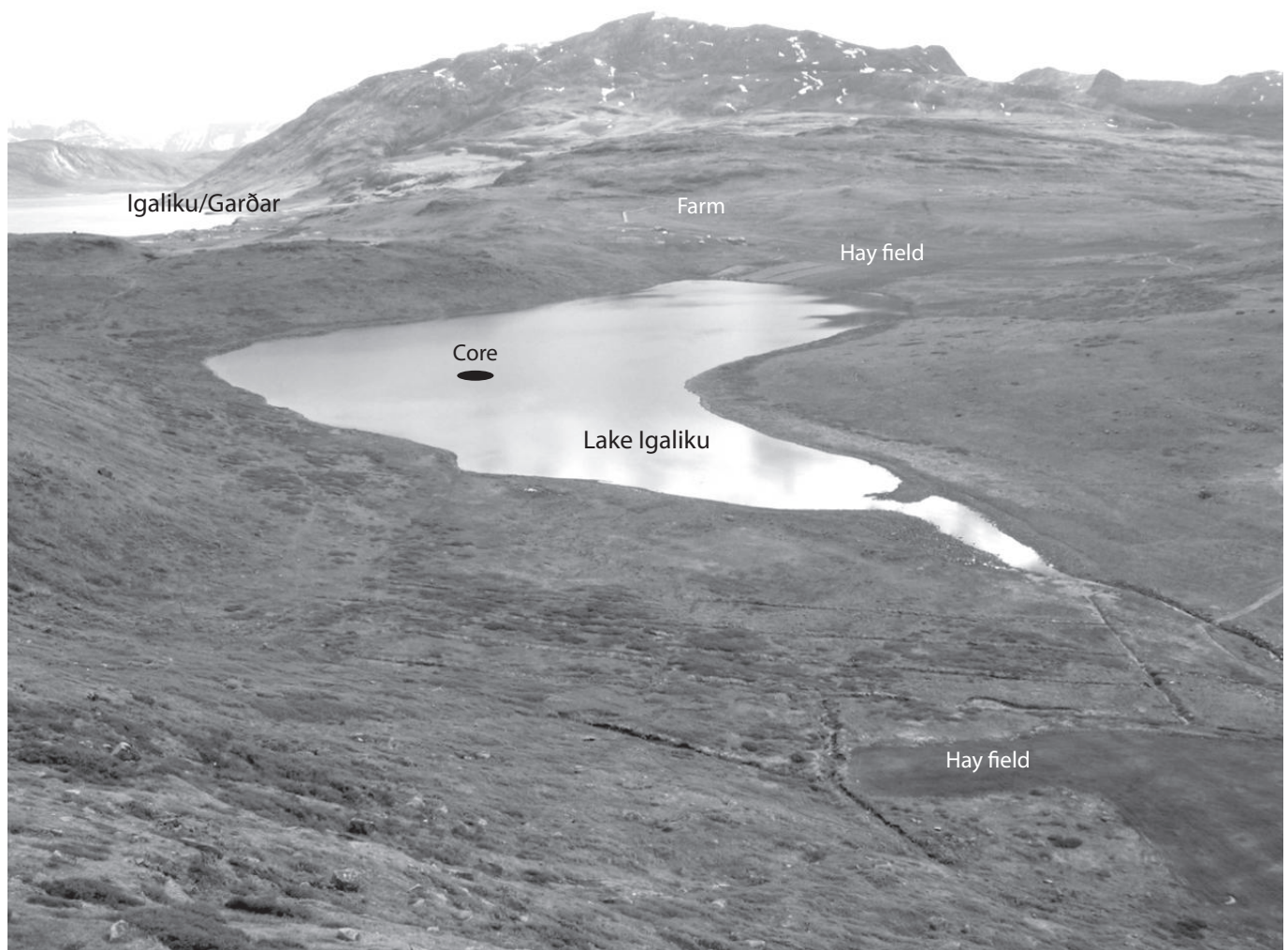
In light of these previous studies mentioned above, and in order to overcome the difficulties encountered such as with the sedimentation rate and peat cutting, we investigated continuous palaeoenvironmental archives in mid-lake sediments from Igaliku, near the *Garðar* archaeological site. This research aims to assess the transition between a pristine landscape and a cultural one, and is based on an approach using pollen and non-pollen palynomorph (NPPs) proxies and AMS radiocarbon dates of the sequence. NPPs are a great help in demonstrating the different phases of grazing

pressure. Results from fossil assemblages are also compared with those found in samples of modern sheep and horse dung.

## 4.2 | Materials and methods

### 4.2.1 Location and vegetation around Lake Igaliku

Igaliku, the Norse *Garðar*, is located at the head of the Igaliku Fjord and was at the center of the Eastern Settlement (Fig. 1). The first settler of the area accompanied Erik the Red from Iceland (Buckland *et al.* 2009). Later, *Garðar* became the episcopal residence; the first bishop, Arnald, arrived in 1126 and had the largest medieval farms of Greenland, showing its economic importance and activity. At Igaliku, 52 Norse archaeological structures are recorded, including large byre-barn complexes, animal pens and enclosures,



**Fig. 4.2** View of Lake Igaliku in southwest Greenland, with the coring location and farmed surroundings (photo towards the north, by V. Bichet 2007)

sheep/goat houses and an irrigation system for fodder production (Norlund 1929). The *Ping*, general assembly for Greenland, was located in *Garðar*. Lake Igaliku (informal name) is situated about 2 km northwest from *Garðar* and is easily accessible for farmers or livestock (Fig. 2).

Today, the north shore of the lake is overlooked by slopes where patches of *Salix glauca* (grey willow), *Betula glandulosa* (dwarf birch) and *Juniperus communis* (juniper) grow (Fig. 2). The south shore is a managed agricultural landscape used for hay meadow. *Ranunculus acris*, *Rumex acetosa* and *Taraxacum officinale* grow around the farms and sheep graze in the entire area.

The deepest part of the lake was cored from a floating platform (61°00'24"N–45°26'30"W, 30 m a.s.l.). A sandy and silty Holocene sequence of 400 cm was sampled with a piston corer in June 2007 and the upper 65 cm were also cored with a gravity corer.

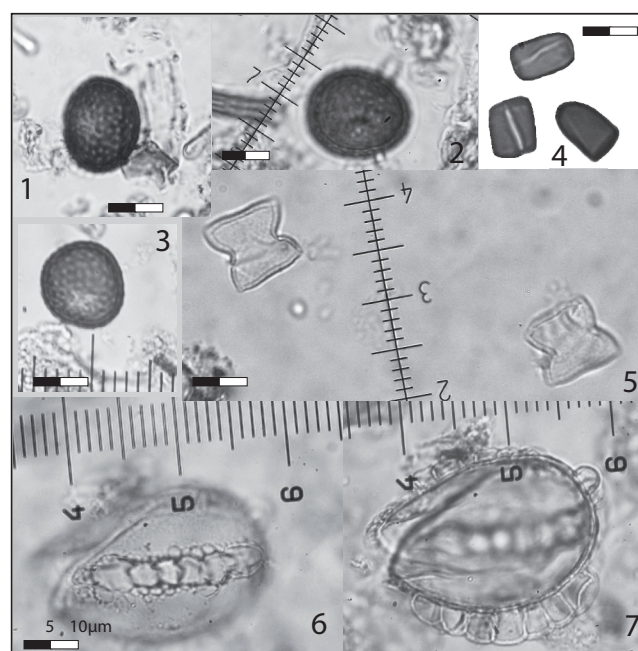
Modern sheep and horse dung samples were collected in July 2007 and September 2008. July samples were collected in pasture around Qassiarsuk and September samples were collected in pastures around a farm in Søndre Igaliku, south of Igaliku. We have chosen sheep and horse dung because they are nowadays the most common herbivores in southern Greenland. Cows are very rare; pigs, goats and reindeer are absent. The kind of livestock is not of great importance: most coprophilous fungi grow indiscriminately on any herbivore dung (Bell 2005).

Sediment samples and dung samples of 1 cm<sup>3</sup> each were processed for pollen and non-pollen palynomorph (NPP) analysis using standard techniques (Moore *et al.* 1991). They were treated with HCl (10%), NaOH (10%), HF (40%), ZnCl<sub>2</sub> and acetolysis (8 min). A minimum of 400 pollen grains of terrestrial plants was counted in each sample to ensure statistical significance. *Cyperaceae*, hygrophilous plants such as *Menyanthes trifoliata* and *Equisetum*, and aquatic taxa, exotic taxa, spores and nonpollen palynomorphs were excluded from the pollen sum.

Pollen grains were identified with the aid of a reference collection of Greenlandic modern pollen types and keys (Fægri and Iversen 1989; Moore *et al.* 1991), photographs (Reille 1992; Beug 2004). In accordance with Fredskild (1973), *Betula* grains larger than 20 µm were assigned to *B. pubescens* and the remainder assigned to *B. glandulosa*. Pollen preservation was systematically recorded for each *Betula* grain encountered, in order to observe evidence of degradation. The pollen diagram was drawn using TILIA and TGView software (Grimm

1991). Pollen zones were delimited with the help of CONISS (Grimm 1987).

Non-pollen palynomorphs (Fig. 3) were identified according to Bell (1983), Jankovská and Komárek (2000), Turton and McAndrews (2006), van Geel (1978, 2001), van Geel *et al.* (2003) and van Geel and Aptroot (2006), and percentages were calculated on the basis of the same pollen sum used for the pollen diagram (van Geel *et al.* 1981).



**Fig. 4.3** Non-pollen palynomorphs from Igaliku, southwest Greenland. 1-3, IGA1, an unknown globose microfossil, 16-22 µm in diameter; 4, HdV-113, Sporormiella, ascospore, 6-9 x 10-13 µm; 5, HdV-371, Tetraedron sp. Algae, hyaline, quadratic and cushion shaped microfossil, 17-19x19-21 µm; 6-7, Filinia resting eggs, 35-40 x 50-55 µm. Abbreviations: HdV: Hugo-de-Vries Laboratory, University of Amsterdam; IGA: Igaliku

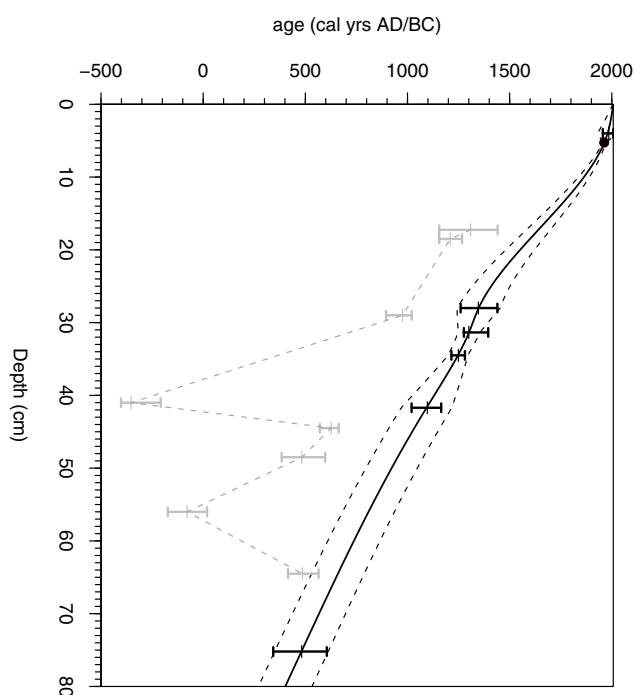
#### 4.2.2 Radiocarbon dating and age–depth model

The chronology of the sequence is established by accelerator mass spectrometry (AMS) <sup>14</sup>C measurements along the upper 125 cm of the core and completed by Cesium measurements for the most recent sediment (Table 1; Fig. 4). <sup>137</sup>Cs activity was measured on 0.5 cm thick samples in the upper 10 cm.

Plant macrofossils were present in small quantities, so eight samples of unidentified and mixed plant remains and six samples of well-preserved terrestrial plant

Dating method	Depth (cm)	Lab. Code	Material	Radiocarbon age (B.P. $\pm 1\sigma$ )	Calibrated age (1 $\sigma$ -range)	Calibrated age (2 $\sigma$ -range)
<sup>14</sup> C	<b>3,5-4,5</b>	<b>Poz-24707</b>	<b>Mixed plant remains</b>	<b>107,11 <math>\pm</math> 0,36 pMC</b>		<b>A.D. 1956-2007</b>
<sup>137</sup> Cs	<b>5,5</b>		<b>Bulk sediment</b>			<b>1963</b>
<sup>14</sup> C	17-17,5	Poz-31628	Indet. Bryophyte	680 $\pm$ 100	A.D. 1258-1399	A.D. 1155-1441
<sup>14</sup> C	18-19	Poz-25024	Mixed plant remains	835 $\pm$ 30	A.D. 1175-1251	A.D. 1156-1267
<sup>14</sup> C	<b>27,5-28,5</b>	<b>Poz-31632</b>	<b>Betula leaf</b>	<b>620 <math>\pm</math> 80</b>	<b>A.D. 1293-1398</b>	<b>A.D. 1260-1440</b>
<sup>14</sup> C	28,5-29,5	Poz-26851	Mixed plant remains	1070 $\pm$ 30	A.D. 902-1015	A.D. 895-1021
<sup>14</sup> C	31-31,7	<b>Poz-31629</b>	<b>Betula bark</b>	<b>655 <math>\pm</math> 35</b>	<b>A.D. 1276-1328</b>	<b>A.D. 1276-1395</b>
<sup>14</sup> C	<b>34,5</b>	<b>Poz-26852</b>	<b>Salix glauca leaf</b>	<b>775 <math>\pm</math> 30</b>	<b>A.D. 1225-1271</b>	<b>A.D. 1215-1281</b>
<sup>14</sup> C	40,5-41,5	Poz-26883	Mixed plant remains	2280 $\pm$ 35	397-235 B.C.	402-208 B.C.
<sup>14</sup> C	<b>41,3-42,1</b>	<b>Poz-31630</b>	<b>Betula twig</b>	<b>945 <math>\pm</math> 35</b>	<b>A.D. 1030-1152</b>	<b>A.D. 1020-1165</b>
<sup>14</sup> C	44-45	Poz-24708	Mixed plant remains	1420 $\pm$ 35	A.D. 608-652	A.D. 571-663
<sup>14</sup> C	47,5-49,5	Beta-246872	Mixed plant remains	1580 $\pm$ 50	A.D. 429-535	A.D. 384-597
<sup>14</sup> C	55,5-56,5	Poz-24709	Mixed plant remains	2060 $\pm$ 35	157-3 B.C.	173 B.C.-A.D. 19
<sup>14</sup> C	64-65	Poz-30535	Indet. Bryophyte	1570 $\pm$ 35	A.D. 434-537	A.D. 415-565
<sup>14</sup> C	<b>74,6-75,8</b>	<b>Poz-31633</b>	<b>Betula leaf</b>	<b>1580 <math>\pm</math> 60</b>	<b>A.D. 418-544</b>	<b>A.D. 343-605</b>

**Table 4.1** AMS radiocarbon dates and <sup>137</sup>Cs results from Igaliku. Dates used in the age-depth model are in bold type. pMC means percentages of modern carbon



**Fig. 4.4** Age-depth diagram for the lake sediments of Igaliku based on AMS radiocarbon dates from terrestrial plant macrofossils and a <sup>137</sup>Cs measurement (dot)

remains, such as *Betula* leaf, bark or twig, were dated. The dates obtained on terrestrial plant remains are generally later than the dates on samples with mixed remains of seeds and bryophytes (Table 1; Fig. 4). There is no carbonate around the lake, so there is no hard-water effect. This offset of about 400 years (Fig. 4) can

be explained by the reworking of <sup>14</sup>C-depleted organic matter from the watershed and also by a particular reservoir effect which affects arctic lakes due to the recycling of old carbon (Abbott and Stafford 1996). Old dates were also reported by several authors after paired analyses of terrestrial macrofossils and bulk sediments or humic acid fractions at the same depth (Sandgren and Fredskild 1991; Kaplan *et al.* 2002; Edwards *et al.* 2008). So our samples of mixed plant remains probably contained aquatic plant fragments and/or old organic material remobilized by soil erosion and thus these dates were rejected (Fig. 4). Radiocarbon dates were calibrated to calendar years using the atmospheric calibration dataset IntCal04 (Reimer *et al.* 2004) by means of the OxCal 4.0 program (Bronk Ramsey 1995, 2001). Then, age-depth modeling, including the 1963 <sup>137</sup>Cs peak at 5.25 cm depth, was performed using a weighted regression procedure in the framework of generalized additive models (Heegaard *et al.* 2005). According to the <sup>14</sup>C calibration model, this depth-age curve is provided with a mean uncertainty close to  $\pm 70$  calibrated years.

The depth-age model shows a continuous and roughly linear sedimentation rate of 0.05 cm year<sup>-1</sup>, with a slight increase to 0.065 cm year<sup>-1</sup> between 28 and 35 cm. Taken that the sediment surface reaches the present, the sediment accumulation above 10 cm, over the last 100 years, progressively increases to a maximum of 0.15 cm year<sup>-1</sup>, which is probably an overestimate here because of the reduced compaction towards the sediment surface.

## 4.3 | Results

### 4.3.1 Pollen and non-pollen palynomorph diagram

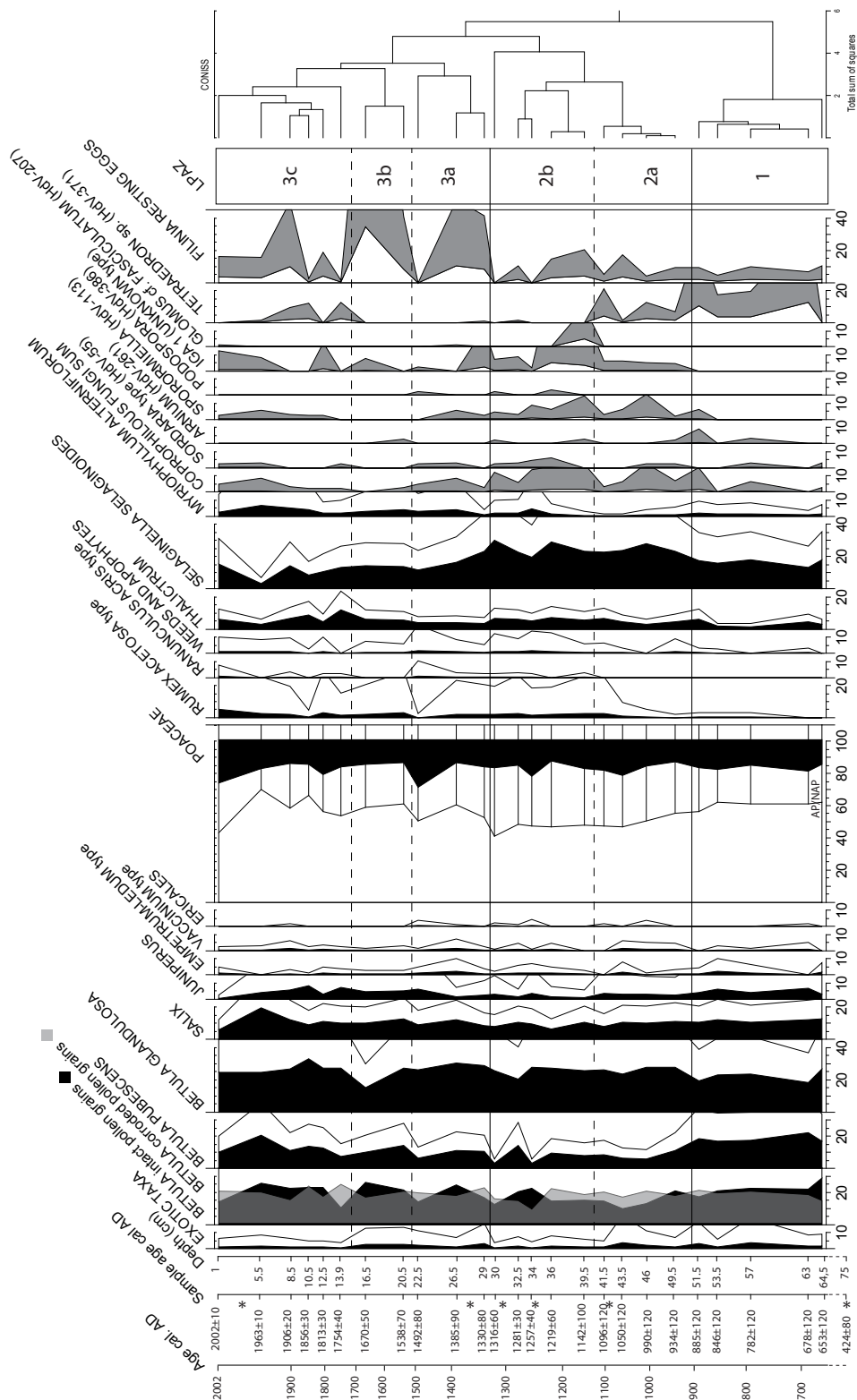
A simplified percentage diagram with selected curves of pollen and non-pollen palynomorph taxa (NPP) is presented in Fig. 5.

In Zone 1, regular pollen frequencies of *Betula pubescens* 20% (tree birch) and *Salix* 12%, *Betula glandulosa* 20%, *Juniperus* 5 - 8%, *Vaccinium* type, and *Empetrum-Ledum* type (willow/birch/juniper/heath scrub) are recorded and suggest the growth of these taxa in the catchment area. *Empetrum-Ledum* type and *Vaccinium* type (Ericaceous dwarf shrubs) are certainly under-represented in the fossil pollen assemblage in comparison to birch and willow, which are overrepresented (Schofield *et al.* 2007b). This arctic cover allowed the expansion of *Selaginella selaginoïdes* (15–20%). *Rumex acetosa* type appears in this first zone, with very low percentages. Occurrences are scarce among coprophilous fungi (*Sordaria* and *Arnium*). *Filinia* resting eggs have low values (2 - 3%). *Tetraedron* (5–12%), a small green alga, is characteristic of eu-mesotrophic conditions (Jankovská and Komárek 2000; Fig. 3), however, it can be observed in oligo-mesotrophic cold water and on lake littorals (Rybníčková and Rybníček 2006). *Myriophyllum alterniflorum* (2% - water milfoil) is an aquatic plant, tolerant of oligotrophic acid water such as boggy pool and is also characteristic of oligo-mesotrophic conditions.

The decrease in *Betula pubescens* (from 20 to 10%) and the rising values of *Selaginella selaginoïdes* (25%) and *Thalictrum* (4%) in LPAZ 2a suggest a more open area. Pollen evidence of moderate grazing pressure is recorded here, with a slight decrease in *Juniperus* (from 5 to 2%) and an increase in weeds/apophytes, and in corroded *Betula* pollen grains and in coprophilous fungi. The decrease in *Juniperus* has often been interpreted as an effect of grazing (Fredskild 1973). This shrub usually grows in places with only a slight snow-cover and is especially exposed to the attack of hungry herbivores. Increase in corroded *Betula* pollen grains could also be related to grazing pressure, as soil erosion under a cover of shallow-rooted permanent pasture may have caused an increase in the proportion of corroded pollen derived from eroded catchment soils (Lawson *et al.* 2007). The fungal spores of coprophilous fungi (*Sordaria*, *Sporormiella* and *Arnium*) indicate the presence of herbivore dung around the lake (van Geel and Aptroot 2006; Davis and Shafer 2006; Fig. 3). An unknown NPP appears (IGA 1; Fig. 3). The origin of

this microfossil remains difficult to determinate, and it could be a coprophilous ascospore or a spore of another origin, such as a bryophyte. Liverworts related to grazing and dung inputs are recorded in Greenland, *Riccia sorocarpa* Bisch. or *Marchantia alpestris* (Nees) Burgeff, for example. *Riccia* species grow abundantly in the emergent surfaces of regional mountain waters within areas of intense grazing (Carrión 2002a; Carrión *et al.* 2003). The use of bryophyte spores in pollen analyses has been demonstrated, however, the spore morphology of IGA 1 is very different, and as this type was also found in recent dung (see below) there is a good chance that the IGA 1 originates from dung. *Myriophyllum alterniflorum* and *Tetraedron* decrease, suggesting changes in water quality or lake level fluctuations (Jankovská and Komárek 2000). At the end of LPAZ 2a, *Poaceae* and *Rumex acetosa* frequencies increase together with a perceptible decline of coprophilous fungi.

Vegetation change takes place in Zone 2b, with a slight decrease of willow and *Juniperus*, and increasing frequencies of *Rumex acetosa* type (Fig. 5). *Poaceae* representation is slightly reduced and *Ranunculus acris* type, another Norse apophyte very common today around farms and in pastures (Fredskild 1973, 1978) occurs for the first time. *Juniperus* reaches its lowest values (1%). *Selaginella selaginoïdes* is an acidophilic taxon and its rising frequencies (25–30%) suggest that the soils around the lake became increasingly leached over time, perhaps as a consequence of scrub clearance and grazing (Lawson *et al.* 2007). In combination with pollen data, the fungal record of coprophilous fungi, with the first occurrence of *Podospora*, suggests a high density of domesticated herbivores in the area under study. The unknown spore, IGA 1, increases suddenly; this unidentified microfossil obviously has the same trend as coprophilous fungi. *Tetraedron* nearly disappears. At the same time, the frequencies of *Filinia* resting eggs slightly increase (3–4%). The occurrence of *Glomus* cf. *fasciculatum* is correlated with the increased frequencies of corroded pollen grains of *Betula* sp. (Lawson *et al.* 2007). *Glomus* is found on the roots of a variety of host plants including *Betula* (van Geel 2001). *Chlamydo*spores of *Glomus* observed in lake deposits, as well as corroded pollen grains, are indicative of soil erosion in the catchment of the lake. Coprophilous fungi decrease at the end of Zone 2b, suggesting a declining grazing pressure. Zone 3a witnesses the steady decrease of coprophilous fungi. The slight regeneration of juniper and willow scrub constitutes a response to reduced grazing intensity. Coprophilous fungi nearly disappear in Zone



**Fig. 4.5** Simplified pollen and non-pollen palynomorph (NPP) diagram based on a relative percentage calculation. Exaggeration curves x2 for *Salix*, *Juniperus*, *Selaginella selaginoides*, *Thalicttrum* and *Filinia* resting eggs, x5 for exotic taxa, *Vaccinium* type, *Empetrum-Ledum* type, *Ericales*, *Myriophyllum alterniflorum*, *Glomus* (HdV-201) and *Tetraedron* sp., x10 for all other taxa. Exotic taxa: *Abies*, *Picea*, *Pinus*, *Carpinus*, *Corylus*, *Fagus*, *Fraxinus*, *Quercus*, *Ulmus*, *Ambrosia* and *Artemisia*. On the left, the age with the total standard deviation is given for each sample; asterisk denotes position of radiocarbon dates used for the age interpolation

3b, contrary to *Rumex acetosa* type. Percentages of *Filinia* resting eggs and *Tetraëdron* are very irregular in Zone 3 and these fluctuations are difficult to interpret. Sometimes it seems to be related to human impact (van Geel 2001), but the highest values of *Filinia* occurred during a phase of decreasing human impact. In an attempt to explain the changes in the *Filinia* and *Tetraedron* records, we can suggest climatic oscillations of water temperature, duration of ice cover, trophic state, and perhaps some ecological causes such as the abilities of individual plants to spread and reproduce, or competition between taxa. The development of recent agriculture (LPAZ 3c) is linked to a new increase in *Rumex acetosa* type, weeds, coprophilous fungi and IGA 1.

#### 4.3.2 Pollen and NPP analyses from dung

Pollen extracted from dung samples represents what was consumed by herbivores as well as airborne pollen. Moe (1983) studied pollen from sheep feces in Norway and concluded that it provides virtually no information about the quantitative composition of the vegetation of the sheep's environment, but it does provide valuable information about their diet. According to Carrión (2002b), dung pollen spectra represent ingested plant material from a local area. However, each leaf surface eaten by an herbivore may contain regional pollen rain. Coprophilous fungi recorded in samples grow in dung, but they could also have been ingested, if wind-dispersed ascospores were present on the grazed plants (Aptroot and van Geel 2006).

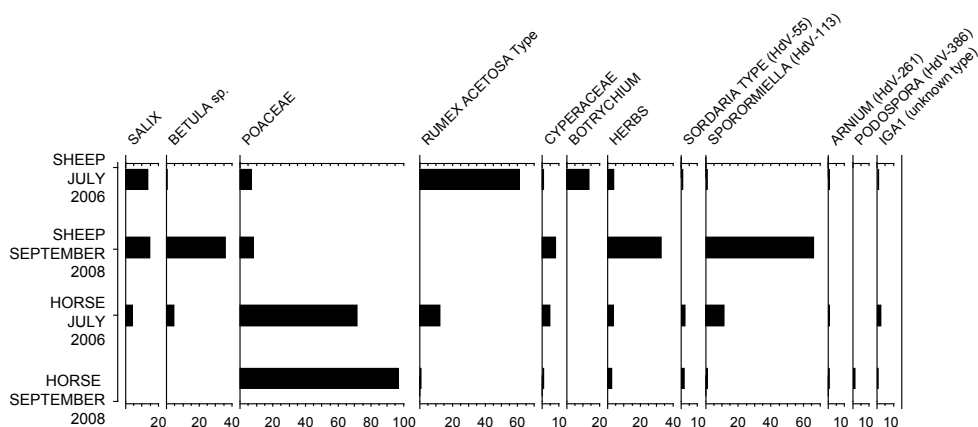
##### Sheep

The modern economy in southern Greenland is dependent upon sheep farming. Sheep graze almost everywhere, except in areas reserved for hay-making.

Pollen analysis shows differences between July and September (Fig. 6). In the July sample, *Rumex acetosa* type is dominant (60%). However, the grazing of *Rumex* remains doubtful because the plant contains oxalates which are toxic for livestock. The analyses of pollen rain in Qassiarsuk (Schofield *et al.* 2007b) have shown very high frequencies of *Rumex acetosa* type (40%) in some of the field assemblages. The high frequencies encountered in our study are more the result of an overrepresentation of *Rumex* than from grazing it, for its pollen is present everywhere in the air, the vegetation and the water. Pollen of *Betula*, *Salix* and *Poaceae* are also frequently overrepresented in Schofield's study (2007b). Only *Betula* reaches high values in our September sample and could be overrepresented. The season for *Betula* pollination is finished in September, but sheep are known to appreciate shrub leaves. This is a factor in limiting tree and shrub growth (Fredskild 1973; Schofield *et al.* 2007a). The *Betula* pollen frequency from the September sample is probably related to leaf grazing and the ingestion of pollen grains remaining on shrubs. The record of coprophilous fungi shows occurrences of *Sordaria*, *Sporormiella* and *Arnium*, the very same taxa recorded in the fossil sediment samples. *Sporormiella* is the dominant taxon in the September dung sample. IGA 1 type, the unknown taxon, is also present but it seems a little more abundant in horse dung.

##### Horses

They often live close to farms, and they are of invaluable assistance at the end of summer, when Greenlandic farmers use them to bring in the sheep which are scattered across large areas. High frequencies of *Poaceae* (70 and 95%; Fig. 6) are probably related to the fodder given to the horses by farmers because pollen dispersal by *Poaceae* is quite weak by September.



**Fig. 4.6** Pollen and non-pollen palynomorph analyses of modern sheep and horse dung samples from the Igaliku area, Greenland, on a relative percentage calculation

There is no dominant taxon among the coprophilous fungi, and all the taxa found in sheep dung also occur in horse dung with low frequencies.

#### 4.4 | Discussion

LPAZ 1 covers the period prior to the arrival of farmers (ca. A.D. 650–900; Fig. 5). Low arboreal and dwarf-shrub pollen frequencies indicate a regionally open landscape without any evidence of human activities until A.D. 900. Discreet occurrences of *Rumex acetosa* type are recorded and could result from long-distance pollen transport from Europe or America. This taxon has also been reported in a pre-settlement phase at Coramum SØ (Fredskild 1973). The pollen type includes *Rumex acetosa*, *R. acetosella* and *Oxyria digyna* pollen grains (Beug 2004). The latter is native to Greenland but *R. acetosa* and *R. acetosella* are, according to Fredskild (1973), Norse apophytes. However, there are two ecologically different strains of *R. acetosella* in Greenland, the first one an indigenous strain, distributed in west Greenland south of ca. 71° and towards northeast Greenland between 70 and 75°, while the other, hemerophilous, strain is only found in Norse settlements (Fredskild 1973). Occurrences of local *Oxyria digyna*, or *R. acetosella* indigenous strain, an anemophilous and prolific pollen producer (Fredskild 1973), do not seem exceptional in these conditions.

LPAZ 2a is dated between ca. A.D. 900 and 1100, which is within the Medieval Warm Period (MWP) ca. A.D. 885–1235, according to Lassen *et al.* (2004). The westward expansion of Norse settlers into the wider North Atlantic region took place precisely during this period, and the first farmers are supposed to have arrived in Greenland by the end of the 10th century A.D. (Amorosi *et al.* 1997). The environmental changes in the pollen diagram, an increase in coprophilous fungi at ca. A.D. 900 and a decline of *Betula pubescens* after A.D. 950, could be related to the first stage of the colonization (Fig. 5). However *R. acetosa* type remains scarce. Previous studies have often dated the increasing frequencies of *R. acetosa* type in the Eastern Settlement from the time of the very beginning of colonization (Fredskild 1973, 1978; Schofield *et al.* 2007a; Edwards *et al.* 2008; Buckland *et al.* 2009). Our age–depth model suggests that the discrepancy between the fall of *Betula pubescens*, maybe if birchwood was used domestically for cooking or heating purposes, and the expansion of *R. acetosa* type, may have been in the order of 100 years. What could be the reasons for such an event: a pre-Norse human impact

without introduction of *R. acetosa* type (the age–depth model allows this hypothesis)? Was it a delay in the acclimatization of *R. acetosa* type? Was it grazing by wild herbivores with an increase in coprophilous fungi, or was climatic change responsible?

The warming conditions of this period (Crowley 2000; Lassen *et al.* 2004) cannot explain all the changes in the vegetation. For instance, the decrease in *Betula pubescens*, which only grows in southern Greenland, is in contradiction with a warming climate. Climate change does not support the decline in *Myriophyllum spicatum* either. Isarin and Bohncke (1999) mention that the presence of this aquatic plant indicates a minimum mean July temperature of 9°C. Igaliku is close to this ecological limit with a mean July temperature of 10.3°C from 1961 to 1990 at Narsarsuaq (Cappelen *et al.* 2001). The decrease in *Myriophyllum alterniflorum* could be caused by a climate cooling but Zone 2a occurs during the MWP (Crowley 2000; Lassen *et al.* 2004; Moberg *et al.* 2005). *M. alterniflorum* percentages do not seem to be affected during the Little Ice Age (LIA) period (\*A.D. 1350–1850) in Zone 3. Thus we assume that the decrease of *M. alterniflorum* is more likely due to changes in water quality than to a climatic change.

The clearance of birch trees creates open habitats suitable for grazing by herbivores, and the rise in ascospores of coprophilous fungi is generally attributed to the presence of dung from livestock in the catchment area. We have to underline that coprophilous fungi grow in the dung of all herbivores, and wild herbivores overgrazing the area could also have transformed the environment. However, we are in a period of warmer climate and this would not favor a large population of reindeer. Reindeer calves are born in spring when nutritious plants are growing. The earlier appearance of greengrowth accompanies warmer spring temperatures, but the timing of caribou/reindeer calving has not shifted to correspond with peak forage availability (Post and Forchhammer 2008). Mother and calf are not able to exploit high-quality forage during a period of high energetic requirements, taxing female body condition and consequently lowering calf production (Post and Forchhammer 2008; Vors and Boyce 2009). So, natural causes such as climate change and wild herbivore grazing cannot really explain the environmental change in LPAZ 2a. In spite of the scarcity of *Rumex acetosa* type, the recorded change in the pollen diagram could be linked with pastoral activities.

Human activities could be responsible, but the Norse apophyte *R. acetosa* type keeps low values. Could we consider a pre-Norse settlement, without the introduction of *R. acetosa* type? The standard deviation of



the depth–age model ( $\pm 120$  years) as shown does not provide evidence of human impact earlier than the date given by historical sources. Nevertheless, previous studies have recorded early agricultural impact in the Eastern Settlement. At Galium Kaer, human impacts appear at A.D. 660–1030 (K-1647; 2r) (Fredskild 1973), and at Søndre Igaliku anthropogenic indicators appear from at A.D. 596–877 (B-5311; 2r) (Sandgren and Fredskild 1991). However, these dates were rejected by the above authors because they did not concur with the chronology of the historical sagas. We have also rejected older radiocarbon dates because of reservoir effects. Early settlements, earlier than the historical data, have been observed in North Atlantic Islands. The Faeroe Isles were settled, according to historical texts, by ca. A.D. 860 (Amorosi *et al.* 1997). Hannon and Bradshaw (2000) have established a different chronology. They show the first occurrence of cultivated crops as early as the 6th century A.D. and the introduction of domestic animals by ca. A.D. 700.

Concerning the expansion of *R. acetosa* type, Edwards *et al.* (2008) suggested a delay of about 30 years between the first clear evidence for human impact and a sustained rise in the *R. acetosa* type pollen curve. In the Igaliku pollen diagram, the age–depth model suggests a delay of about 100 years. According to historical sources, a Norse farmer recorded as accompanying Erik the Red from Iceland was the first settler of Igaliku/*Garðar* (Buckland *et al.* 2009). Erik the Red's daughter also lived in Igaliku, but the settlement grew from A.D. 1124 when the episcopal seat of *Garðar* was created. In the pollen diagram, the maximum percentages of *R. acetosa* type are precisely dated to ca. A.D. 1100. The vegetation change in phase 2a could also be the result of the first historical settlement, before the expansion of *Garðar* and the delay in the expansion of *R. acetosa* type was maybe longer than expected.

Recorded events in Zone LPAZ 2b (ca. A.D. 1140–1320; Fig. 5) correspond to the well-known Norse *landnám*: the increased pollen from likely Norse apophytes such as *R. acetosa* type and *Ranunculus acris* type and NPPs with a peak of *Glomus cf. fasciculatum* and an increase in *Sporormiella*, *Sordaria*, *Arnium* and IGA 1 do not leave any doubt about grazing pressure and human impact. Coprophilous fungi reach their maximum values and, among these fungal remains, *Podospora* occurs for the first time, and could be related to the first presence of cows, as this phenomenon is known from sites in Austria, the Azores and Tibet (Jean Nicolas Haas and Jacqueline van Leeuwen, personal communication). The increasing proportion of livestock (cows, pigs, sheep and goats) as well as the spread of midden

material on hayfields in order to improve yields (Graf and Chmura 2006; Buckland *et al.* 2009) may have brought a large amount of ascospores into the lake sediments. The general trend of declining coprophilous fungi and corroded *Betula* pollen grain values is evident at the end of LPAZ 2b (ca. A.D. 1260–1320) and suggest a decreasing grazing pressure and/or manuring of hay fields. According to the archaeological data and isotopic studies by Arneborg *et al.* (1999, 2002), the average diet of the Norse people progressively changed from 20% marine food around A.D. 1200 to 80% marine food at the end of the settlement around A.D. 1450. This change with time is probably due to an adaptation to the changing climate. This decrease in grazing pressure seems to be linked with an economic change most probably caused by the climatic transition from the Medieval Warm Period to the Little Ice Age.

In LPAZ 3a (ca. A.D. 1330–1500; Fig. 5) frequencies of *Thalictrum*, weeds and apophytes, *Selaginella selaginoides* and coprophilous fungi all decline. Reduced farming activity is the prelude to the end of the settlement in the beginning of the 15th century A.D. This date is consistent with historical data and pollen analyses (Schofield *et al.* 2007a; Buckland *et al.* 2009), and coincides approximately with the evidence for the onset of the Little Ice Age. Effects of the LIA on the vegetation are not evident in this pollen diagram (LPAZ 3a and b). *R. acetosa* type seems to hold its ground to some extent but it does not seem to be a very good anthropogenic indicator. It could occur before any settlement (LPAZ 1 - long distance transport or indigenous strain), it maybe needed a delay to really adapt to the harsh Greenlandic climate (LPAZ 2a), and it does not disappear after the abandonment of the site (LPAZ 3). Coprophilous fungi seem here to be the most reliable indicators for farming activities and grazing pressure.

## 4.5 | Conclusions

– According to our pollen and non palynomorph data, the first colonization may have been around A.D. 885  $\pm 120$ . The standard deviation of the depth–age model does not allow us to suggest a human impact earlier than the date given by historical sources. The first settler of Igaliku/*Garðar* accompanied Erik the Red in A.D. 985. From ca. A.D. 1100 the development of farming activities did exert a perceptible impact on the environment.

– The palynological signal shows an increase in coprophilous fungi and the clearance of *Betula*

*pubescens*, however there is a clear discrepancy of about 100 years between this first human impact and the expansion of the likely Norse apophyte *Rumex acetosa* type. The delay between the introduction and the expansion of *R. acetosa* type was maybe longer than expected.

– The first colonization phase is followed by a period of decreasing human impact in the beginning of the 14th century A.D. The regrowth of birch and the disappearance of anthropogenic indicators except *R. acetosa* type between the 15th and 18th century demonstrate the abandonment of the settlement, until the development of modern agriculture in the 20th century.

– The same ascospores from coprophilous fungi and those related to animal husbandry are recorded in lake sediments and modern dung samples. The unknown spore IGA 1 is of particular interest: its curve has the same trend as those of other coprophilous taxa and it also occurs in the dung samples. Non-pollen palynomorphs are of invaluable help here in demonstrating the introduction of domesticated herbivores, inferred

grazing pressure and/or spread of manure in order to fertilize. Coprophilous fungi provide an accurate vision of the historical colonization of Greenland, complementing historical and archaeological knowledge.

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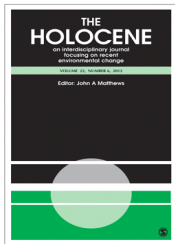
## Chapitre 5

# **A Paleoecological Perspective on 1450 years of Human Impacts from a Lake in Southern Greenland**





## Chapitre 5



# A Paleoecological Perspective on 1450 years of Human Impacts from a Lake in Southern Greenland

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## Abstract

A multiproxy sedimentary record from Lake Igaliku in southern Greenland documents 1450 years of human impacts on the landscape. Diatoms, scaled chrysophytes, and C and N geochemistry show perturbations consistent with recent agricultural activities (post-ad 1980), superimposed upon long-term environmental variability. While the response to Norse agriculture (~ad 986–1450) is weak, the biological response to the last 30 years of modern sheep farming is marked, with drastic changes in diatom taxa,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotopic ratios, and a sharp increase in scaled chrysophytes. Indeed, current conditions in the lake during the last 30 years are unprecedented in the context of the last 1450 years. The dominant driver for recent changes is likely an intensification of agricultural practices combined with warming summer temperatures. Warm temperatures and agricultural disturbance together during Norse Landnám did not lead to the marked changes seen in the modern lake environment over the last 30 years. The synergistic response between increased climate warming and agriculture will likely have unanticipated effects. These findings confirm the sensitivity of Arctic lakes to external anthropogenic forcing and are the first analyses of their kind for the effects of agriculture in Greenland.

**Keywords:** Agriculture, climate change,  $\delta^{15}\text{N}$ , diatoms, Greenland, Norse

## 5.1 | Introduction

Arctic ecosystems are subject to an increasing number of stressors. The effects of climate change are becoming increasingly evident in the circumpolar North in the form of accelerating glacier melt (Zwally *et al.*, 2002), reduced Arctic Ocean summer sea ice extent (Serreze *et al.*, 2009), and marked biological shifts in both aquatic and terrestrial ecosystems (Post *et al.*, 2009; Smol *et al.*, 2005). Operating at the same time is

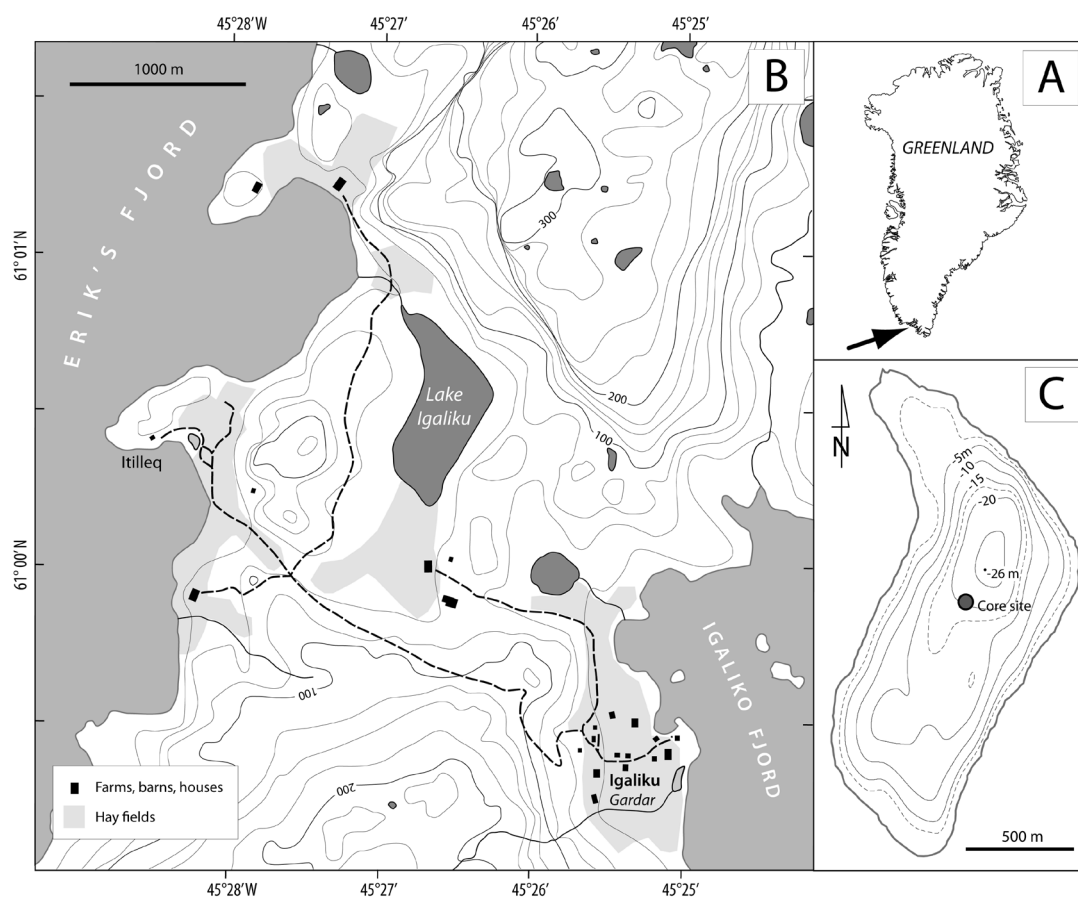
a range of anthropogenic stressors (e.g. atmospheric deposition of nutrients, persistent organic pollutants (POPs), mercury) whose ecological implications are still largely unknown (Arctic Monitoring and Assessment Programme (AMAP), 2009). Adaptation to current and future climate change requires understanding not only of the range of natural climate variability and scenarios for the future, but also the response of ecosystems and civilizations to multiple stressors.



The south coastal region of Greenland is situated within a key geographic area for understanding North Atlantic climate variability, and occupies an important place in human history. The Norse settled southern Greenland ~ad 986, and the population at the peak of their colony is estimated to have been between 2000–3000 (Lynnerup, 2000) and 4000–6000 (Berglund, 1986), in approximately 500 farms within the inner fjords centered near Narsarsuaq (Østerbygd) and Nuuk (Vesterbygd). Norse subsistence was based on both terrestrial animal husbandry as well as marine resources, with community-organized seal hunts accounting for larger proportions of the economy through time (Dugmore *et al.*, 2009). Following the disappearance of the Norse, the region around the Igaliku was resettled in the 1700s and large-scale agriculture, principally sheep farming, was reintroduced in the 1920s coincident with warmer post-Little Ice Age (LIA) temperatures (Vinther *et al.*, 2010). Currently, the agricultural sector in southern Greenland is expected to grow with increased summer

temperatures, extended growing seasons and more efficient farming practices (Greenland Agriculture Advisory Board, 2009).

The establishment of the Norse farms in Greenland is thought to be aided by the favourable climatic conditions of the Medieval period. The cause of the collapse of their colony however, has been the source of much speculation (McGovern, 2000). One reason is thought to be largely climate-driven: As the climate cooled with the beginning of the LIA (ad 1400–1900) and storm frequency increased (Dugmore *et al.*, 2007a), their finely adapted lifestyle became increasingly difficult to maintain, agricultural productivity faltered, the fjords and sea routes became ice-choked, seals disappeared as migration patterns changed, and access to raw materials (i.e. iron, wood) became strained, all of which hastened the collapse of the colony (Dugmore *et al.*, 2007b, 2009; McGovern, 2000). Another hypothesis is that the demise of the Norse in Greenland was partly self-induced: The grazing pressure of livestock on



**Fig. 5.1** Map showing (a) the location of Lake Igaliku on Greenland, (b) the region around Lake Igaliku including roads (dashed lines), buildings (black rectangles) and current (post-1960) hay fields (grey shaded areas) as well as the archaeological site of *Gardar*, and (c) the bathymetry of the lake and coring location.

fragile heath tundra vegetation exceeded the resilience of the landscape and the fields became progressively denuded, erosion increased and carrying capacity fell, and the pastoral economy failed leading to the collapse of the colony (Fredskild, 1988; Jakobsen, 1991; McGovern, 2000).

The paleoenvironment of Norse sites in the North Atlantic has been studied extensively using pollen (e.g. Edwards *et al.*, 2008; Fredskild, 1988; Gauthier *et al.*, 2010; Schofield *et al.*, 2008, 2010) and sedimentological analyses (Sandgren and Fredskild, 1991). While a few studies have investigated the impact of Norse activities via changes in-lake ecology using the remains of chironomids elsewhere in the North Atlantic (e.g. Faroes: Gathorne-Hardy *et al.*, 2007; Iceland: Lawson *et al.*, 2007), to date, no studies have used either sedimentary diatoms or carbon and nitrogen stable isotopes in lake sediments to investigate the environmental impacts of the Norse. This is despite the wide use of these paleolimnological proxies in other paleoenvironmental applications (Smol and Stoermer, 2010). Diatoms, in particular, have been successfully used to trace the nature of human impacts on the landscape as early as the Neolithic and Bronze Age (Bradshaw *et al.*, 2005; Fritz, 1989) and for disentangling the relative impacts of early human settlement patterns in boreal and temperate regions (Anderson *et al.*, 1995; Ekdahl *et al.*, 2004). In the Arctic, diatoms are commonly used to trace environmental responses to Holocene climate variability as well as recent warming (Smol *et al.*, 2005; Wolfe, 2002). They have also been used to investigate other prehistoric and historic cultural impacts in the Arctic (i.e. from whaling cultures (Douglas *et al.*, 2004) and sewage treatment (Douglas and Smol, 2000)) but have not yet been used to investigate agricultural impacts.

Despite the fact that Greenland Norse colonies are commonly thought to have been influenced by late-Holocene climate variability, to date not a single continuous, high-resolution, multiproxy paleoenvironmental record has been generated within immediate proximity of a Norse site in Greenland. Therefore, the patterns of late-Holocene natural variability are unknown at these sites, as is the extent to which Norse farming caused the purported environmental destruction often claimed. Here we present a high-resolution multiproxy biological and geochemical record from Lake Igaliku that explicitly tests the magnitude of Norse landscape impacts relative to the natural variability of the last 1450 years, and compares the period of Norse tenure (ad 986–1450) with that of modern agricultural activities

(after ad 1920). This is the first analysis of this kind for Greenland and the first use of diatoms to investigate the interaction between man and the environment in this key geographic and archaeological region of southern Greenland.

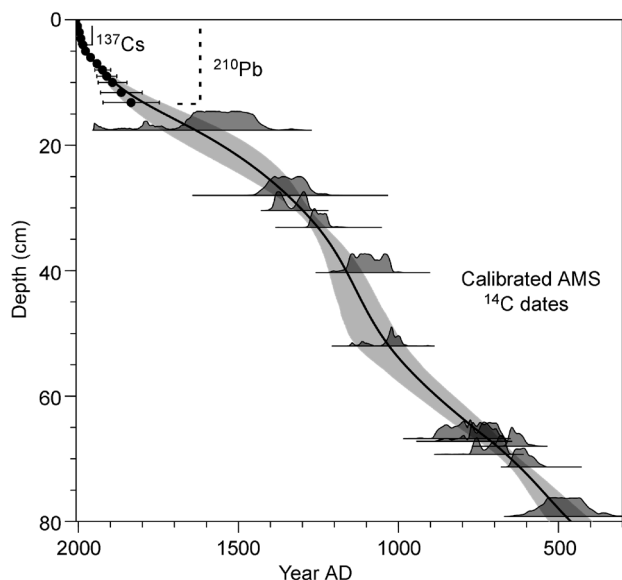
## 5.2 | Methods

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### 5.2.1 Study area

Lake Igaliku (61°00'N, 45°26'W, 30 m a.s.l.) occupies a low valley between the head of Igalikup Kangerlua (Igaliku Fjord) and Tunulliarfik fjord (Erik's Fjord) in southern Greenland (Figure 1). The catchment area of the lake (3.1 km<sup>2</sup>) is of relatively low relief with a modern farm and pastures close to the lake and bedrock hills reaching 300 m a.s.l. to the south. The bedrock of the region is composed of Ketilidian Proterozoic crystalline granite overlain by the volcano-sedimentary rocks of the Eriksfjord formation, which outcrops in the hills to the northwest. This region of southern Greenland is classified as low Arctic, where permafrost is discontinuous, and birch and alder copses grow locally in the innermost sheltered fjords. Mean annual temperature is 0.9°C, with July and January means of 10.3°C and -6.8°C, respectively. The lake is 34 ha in area and 26 m deep. It has one outflow, but no major inflow

From archaeological and written accounts, Igaliku was one of Norse Greenland's most prosperous farm regions. Originally settled by Erik the Red's daughter, Freydis, at the beginning of the Norse Landnám, it was given to the bishop in 1126 and became the site of the cathedral as well as the *Thing* (assembly) for the Eastern Settlement of Greenland (Jones, 1986; Sanmark, 2009). The farms are estimated to have housed between 75 and 100 cattle, in addition to sheep, and thus would have required extensive use of the surrounding land for grazing as well as hay production (Nørlund, 1936). The catchment of Lake Igaliku was never the site of a Norse farm but would have been used for grazing livestock. The modern community consists of 60 permanent inhabitants and was founded in the late 1700s. Agricultural practices resumed in the 1920s, at the same time that the climate of southern Greenland reached its recent maximum (Box *et al.*, 2009). Current sheep farming in the catchment is limited to one farm, established in the early 1960s, which has a barn for wintering sheep and summer hay production on a 30 ha field. A small ditch currently drains effluent from the barn into the nearby lake. The farm currently deploys 750–900 kg N fertilizer per year within the



**Fig. 5.2** Age–depth model showing the dates, probabilities of radiocarbon dates and the 95% confidence interval for the age–depth model (grey band).

lake catchment to boost yields for winter fodder (Mikki Egede, personal communication, 2011).

Pollen and non-pollen palynomorph (NPP) studies from Lake Igaliku sediments reflect agricultural impacts on the landscape during Norse occupation. A decline in arboreal birch pollen c. ad 1000, corresponds to an increase in exotic weed taxa (e.g. *Rumex acetosa/acetosella*) and a peak in coprophilous fungi, which suggest that initial birch clearance was concomitant with the use of pastures for grazing, and that sheep and cows were likely grazing in proximity of the lake during the period of Norse occupation (Gauthier *et al.*, 2010). Following the abandonment of the settlement, the landscape did not revert to a pristine state, but retained the vegetation changes initiated by the Norse.

### 5.2.2 Cores and chronology

A suite of sediment cores was retrieved using piston and gravity cores from the deepest part of Lake Igaliku in June 2007 (see Figure 1). The 4 m composite sequence captures the entire Holocene (c. 10,000 years), including the marine to lacustrine transition c. 9500 yr BP; however, only the upper core is discussed here (the last ~1450 years). The chronology for the core is based on 13 birch macrofossil  $^{14}\text{C}$  dates (twigs and leaves), a  $^{137}\text{Cs}$  peak (ad 1963), and  $^{210}\text{Pb}$  measurements using  $\alpha$  spectroscopy and the constant rate of supply (CRS) method (Appleby and Oldfield,

1978). Radiocarbon measurements were made by the Poznan Radiocarbon Laboratory and at the Université Claude Bernard 1, Lyon and were calibrated using Intcal09 (Reimer *et al.*, 2009). Ages are reported in cal. yr BP or yr ad and an age–depth model (Figure 2) was produced using a cubic spline following Blaauw (2010). The sampling strategy reflected sedimentological characteristics (visible laminae) and 104 continuous samples (between 2 and 32 years per sample) are reported here.

### 5.2.3 Diatoms and chrysophytes

Diatoms and chrysophytes were prepared from wet sediments using a standard protocol for large sample numbers (Renberg, 1990). 5–10 ml 30% hydrogen peroxide was added to the ~0.3 g samples and heated until the reaction subsided, followed by the addition of several milliliters of 10% HCl. Samples were then rinsed with distilled water and a known quantity of Divinyl Benzene (DVB) microspheres was added to the slurries (Battarbee and Kneen, 1982), which were then dried on coverslips and mounted using Naphrax mounting medium. Using a transmitted light microscopy under oil immersion, at least 350 diatom valves were identified and enumerated from the slides as well as chrysophyte cysts and scales. Identification of diatoms was aided by reference literature from Greenland (Foged, 1953, 1972, 1977) and Labrador (Fallu *et al.*, 2000).

### 5.2.4 Stable Isotopes and geochemistry

Core samples for stable isotope and geochemistry measurements were dried and ground to fine powder prior to analysis. The total carbon and total nitrogen contents were measured by total combustion in a Vario Max CNS elemental analyser (Elementar, Germany). Mass loss of the samples was negligible after combustion at 950°C, and thus the total carbon measured is interpreted to be organic. The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotopic analyses were performed in triplicate on an elemental analyser NA 1500 NCS (Carlo Erba Instruments, Milan, Italy) coupled in continuous flow mode to a stable isotope ratio mass spectrometer VG Isochrom (Micromass, Manchester, UK). The results are presented in standard delta notation. Standard errors for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  measurements are < 0.2‰ and < 0.5‰, respectively.  $\delta^{13}\text{C}$  measurements since ad 1840 were corrected for the Seuss effect (Friedli *et al.*, 1986) by subtracting the anthropogenic  $\delta^{13}\text{C}$  offset according to Schelske and Hodell (1995).

### 5.2.5 Numerical analysis

Principle components analysis (PCA) was performed on a covariance matrix of diatom taxa with relative frequencies >1%. PCA was chosen because the species assemblages form a short primary gradient established by detrended correspondence analysis (DCA; 1.67 SD).

A second PCA was performed on a correlation matrix of selected diatom taxa from the initial PCA (i.e. those with the highest scores: *Cyclotella stelligera*, *Fragilaria tenera*, *Cyclotella rossii* complex), chrysophyte scales, and geochemical data (C, N, C/N,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ). These proxies were analysed together in order to generate an overall ecological response to landscape disturbance and natural variability over the last 1450 years.

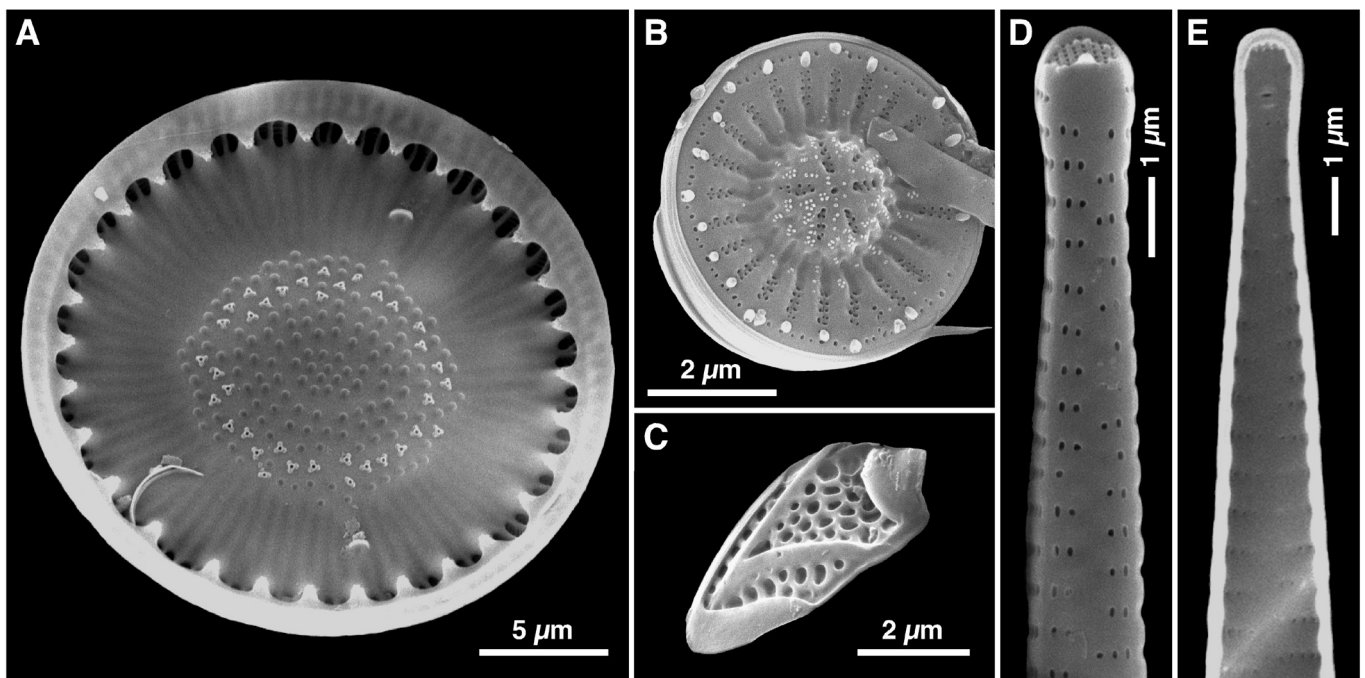
## 5.3 | Results

### 5.3.1 Diatoms and chrysophytes

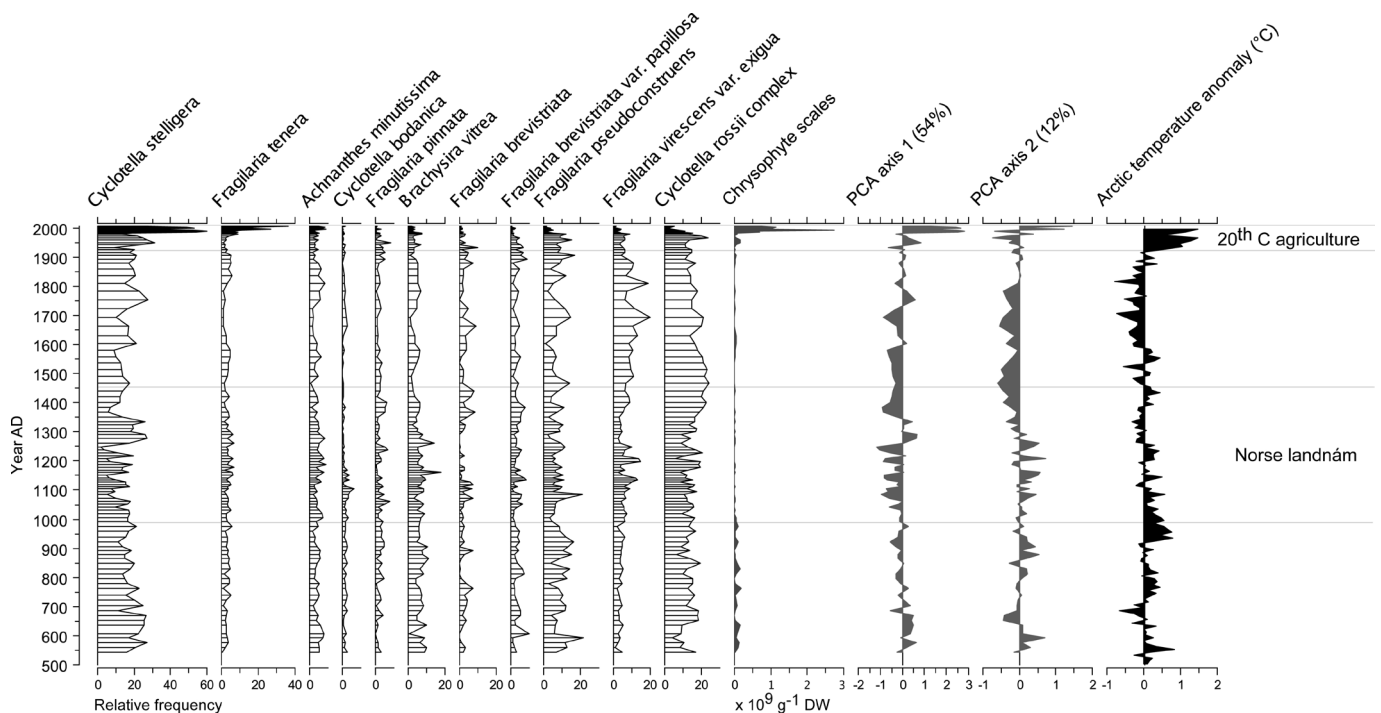
Over 140 species of diatoms from 25 genera were identified from the sediments of Lake Igaliku. Scanning electron microscope images of several of the key taxa

are shown in Figure 3. The flora is typical of dimictic, circumneutral, oligotrophic West Greenlandic lakes (Perren, 2007). *Cyclotella stelligera* (= *Discostella stelligera*) and the complex belonging to variants of *Cyclotella rossii*, *C. comensis*, *C. tripartita*, and *C. ocellata* (henceforth called *Cyclotella rossii* complex) dominate the planktonic component and are identical to those found along the west coast of Greenland (Perren *et al.*, 2009) as well as those described from northeast Greenland (*Cyclotella* sp. A: Cremer and Wagner, 2004). *Brachysira vitrea*, small *Achnanthes* and *Achnantheidium* spp., and *Fragilaria sensu lato* (= *Staurosira*, *Staurosirella*, *Pseudostaurosira*, *Fragilaria-forma* spp.) are the dominant benthic taxa. Lesser quantities of representatives of the genera *Cymbella*, *Eunotia*, *Navicula*, and *Nitzschia* are also present.

The stratigraphy of dominant diatom taxa is shown in Figure 4. The diatom assemblages are remarkably stable over the last 1450 years. The most notable exception is in the last 30 years, when *Cyclotella stelligera* and *Fragilaria tenera* increase dramatically (to maxima of 60% and 37%, respectively) at the expense of the *Cyclotella rossii* complex. Chrysophyte scales, belonging principally to the genera *Synura*



**Fig. 5.3** Scanning electron micrographs of key diatom and chrysophyte taxa from Lake Igaliku sediments. (a) Inner valve view of *Cyclotella bodanica* (= *Puncticulata bodanica*) showing central and marginal fultoportulae and two rimoportulae; (b) *Cyclotella stelligera* (= *Discostella stelligera*) showing the stellate arrangement of alveoli in the colliculate central area of the valve; (c) chrysophyte scale belonging to *Mallomonas crassisquama*; external (d) and internal (e) views of *Fragilaria tenera* showing the apical pore field and single rimportula, respectively.



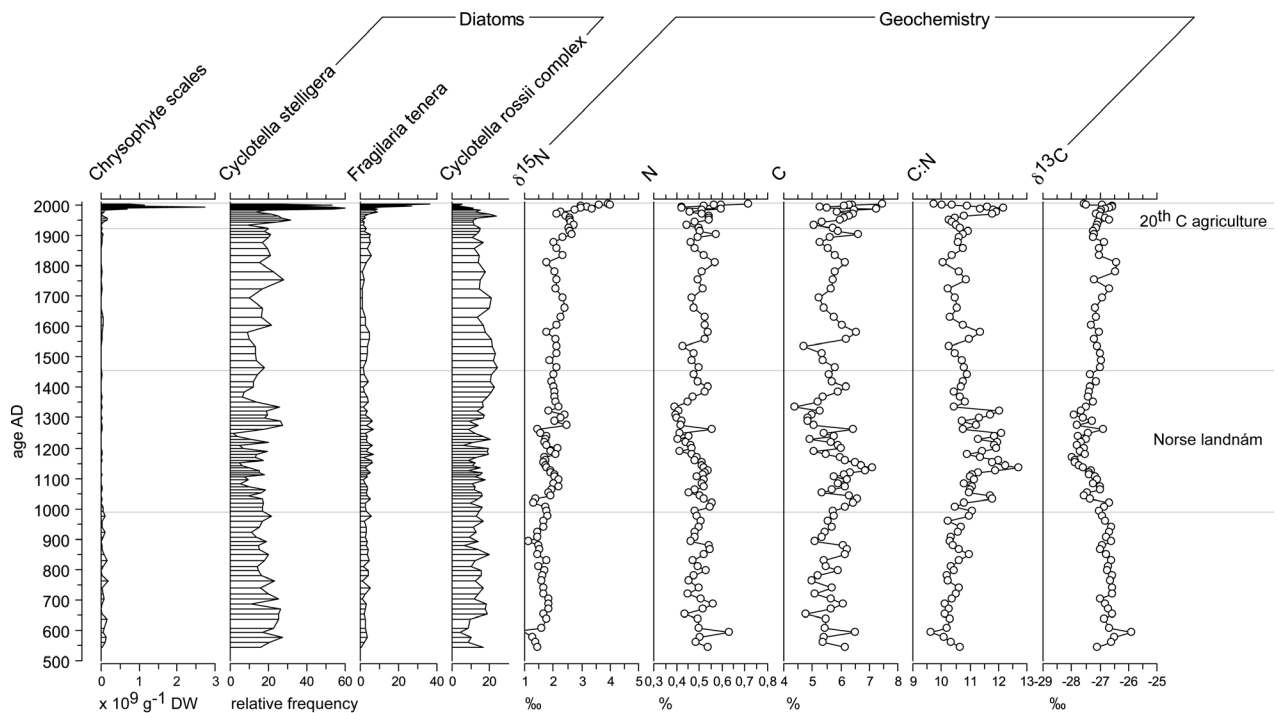
**Fig. 5.4** Stratigraphic diagram showing the relative frequency of important diatom taxa, the concentration of scaled chrysophytes, the first 2 PCA axes and the Arctic temperature anomaly reconstruction from Kaufman *et al.* (2009). The periods of Norse Landnám and 20th century agriculture are shown.

and *Mallomonas*, also increase to over  $10^9$  scales/g sediment at the surface against a steady background concentration of between  $0-10^3$  scales/g sediment. Recent changes (post-ad 1980) mimic the changes seen in lakes elsewhere in the Arctic and at temperate latitudes over the last century, namely with an increase in small *Cyclotella* species (i.e. *C. stelligera*; Rühland *et al.*, 2008) and an increase in scaled chrysophytes (Perren *et al.*, 2009; Wolfe and Perren, 2001). Although reductions in the average cell size of *Cyclotella* populations (towards smaller species such as *C. stelligera*) have been linked to climate warming through prolongation and strengthening of stratification patterns (Winder *et al.*, 2009), it is yet unknown what impact slight nutrient additions may have on their distribution as well. The highest values of *C. stelligera* occur in the period following ad 1980, with lesser peaks briefly at ~ad 1750, and between ~ad 1250 and 1350 (Figure 4). *Fragilaria tenera*, a spindle-shaped planktonic taxon, occurs in only the most nutrient-enriched West Greenland lakes (Perren, 2007) and its increase here likely marks a shift towards nutrient enrichment within the last 30 years. The marked shift in scaled chrysophytes has been reported from lakes elsewhere and they have been linked to warmer conditions in Arctic lakes (Wolfe and Perren, 2001); however, their response to nutrient enrichment is unknown.

The PCA of diatom results show two major features: a major shift in lake ecology ~ad 1980 as registered in the PCA axis 1, and an underlying, century-scale variability captured by the second axis (Figure 4). PCA axis 1 captures profound change in beginning ad 1980, which is the major feature of the diatom record. PCA axis 1 also shows lesser positive excursions at ~ad 1250–1350, coeval with the latter part of the Norse Landnám, and in the earliest part of the record prior to ~ad 750. PCA axis 2 mirrors the major modes of century-scale Arctic climate variability (Kaufman *et al.*, 2009) with positive values between ~ad 800 and ~1300 and negative values during the LIA ~ad 1300–1900. However, post-ad 1920 warming trends in Kaufman *et al.* (2009) are not mirrored by the Igaliku PCA axis 2. Rather, the major inflection in the PCA axis 2 occurs in the period since ad 1980.

### 5.3.2 Geochemistry

Stable carbon and nitrogen isotopes and geochemical stratigraphies are shown alongside the principal diatom and chrysophyte stratigraphies in Figure 5. Nitrogen content values oscillate between 0.4% and 0.7% dry mass with the lowest values between ad 1200 and 1400 and at ad 1500. The highest values occur in the last 10 years. Similarly, total carbon reaches its highest values in the last decade with oscillations between



**Fig. 5.5** Stratigraphic diagram showing the proxies used in the synthesis PCA: chrysophyte scales, key diatom taxa, and geochemistry parameters. The periods of Norse settlement and modern agriculture are shown.

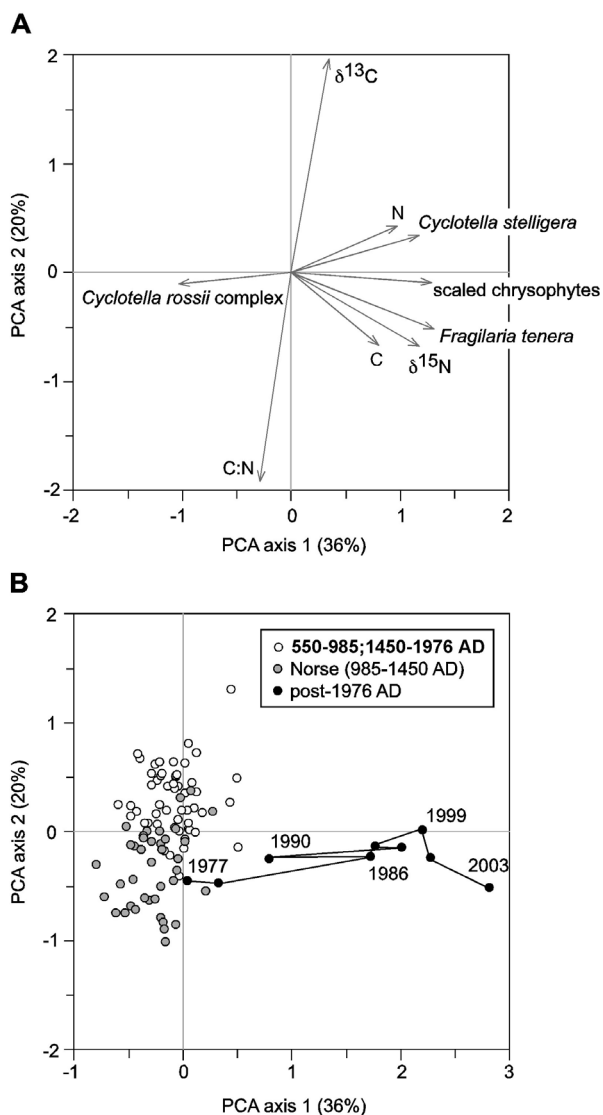
4.4% and 7.5% through the last 1450 years. The C/N molar ratio is variable throughout the record ranging between 9.5 and 12.5, but highest during the period ad 1100 and 1350 and between ad 1970 and 2000. The  $\delta^{13}\text{C}$  record is relatively stable throughout the 1450 year sedimentary profile, ranging between  $-28\text{‰}$  and  $-26\text{‰}$  with a distinct minimum between ad 1000 and 1450, and in the last decade. The  $\delta^{15}\text{N}$  slowly increases throughout the record from  $0.9\text{‰}$  at the beginning of the record to  $4.0\text{‰}$  in the uppermost sample with a slight stepwise increase beginning ad 1275, and the major inflection at ad 1980.

The enrichment of  $^{15}\text{N}$  in Igaliku is the inverse of observed recent trends in  $\delta^{15}\text{N}$ . In Greenland Ice Sheet snow and in Arctic lake sediments,  $\delta^{15}\text{N}$  values decline since ad 1950 owing to the widespread atmospheric deposition of N from anthropogenic sources (Hastings *et al.*, 2009; Wolfe *et al.*, 2006). Changes to  $\delta^{15}\text{N}$  can occur in lakes as a result of either internal mechanisms or changing source material. In lakes that are N-limited,  $\delta^{15}\text{N}$  will increase with increased in-lake production as the source pool of N gets progressively used (Hodell and Schelske, 1998).  $\delta^{15}\text{N}$  also increases in lakes that receive external N loading from enriched sources (e.g. manure, sewage, industrial fertilizers; Teranes and Bernasconi, 2000). The rise in  $\delta^{15}\text{N}$  in Igaliku is likely a result of the addition of fertilizers from manure and industrial sources, but some component

of internal utilization of N, such as enhanced sediment denitrification, cannot be ruled out.

### 5.3.3 Synthesis of multiple proxies

The PCA integrating diatoms, chrysophytes, and N and C geochemistry demonstrates the coherence of the individual proxies with each other (Figure 6a). The first and second axes explain, respectively, 36% and 20% of the variance of the data set. The first axis is strongly associated with N, *Cyclotella stelligera*, the concentration of scaled chrysophytes, *Fragilaria tenera*, and  $\delta^{15}\text{N}$ . The diatom complex of *Cyclotella rossii* dominates the negative end of the first axis. The second axis is dominated by the  $\delta^{13}\text{C}$  values on the positive side, and by C/N ratio on the negative end. The PCA biplot of samples in Figure 6b demonstrates the degree to which recent changes in Lake Igaliku are unprecedented. Norse samples cluster within the range of natural background values (ad 500–986; ad 1450–1976) near the origin on the negative side of both the first and second axis. Samples since ad 1976, however, display a marked shift reflecting changes in the biological and geochemical proxies, demonstrating that the ecological state of the lake beginning in the 1980s is unprecedented within the context of the 1450 year record at Igaliku.



**Fig. 5.6** Synthesis PCA results. (a) PCA biplot showing the scores of the proxies used in the analysis (arrows); (b) PCA biplot of the downcore sample scores from the analysis (circles).

## 5.4 | Discussion

The biogeochemical response of Lake Igaliku documents subtle environmental changes over the last 1450 years, until *c.* ad 1980 when a dramatic shift occurred. In contrast with the archaeological and glaciological evidence for regional change in conditions, the biogeochemical response of the lake does not exhibit threshold-type responses to Norse farming, Medieval climate warming, or to the LIA, but rather shows low-amplitude fluctuations in an otherwise stable lake ecosystem. The relative stability of the diatom flora at Igaliku suggests that until ad 1980, the magnitude of both climatic (LIA and Medieval) and anthropogenic

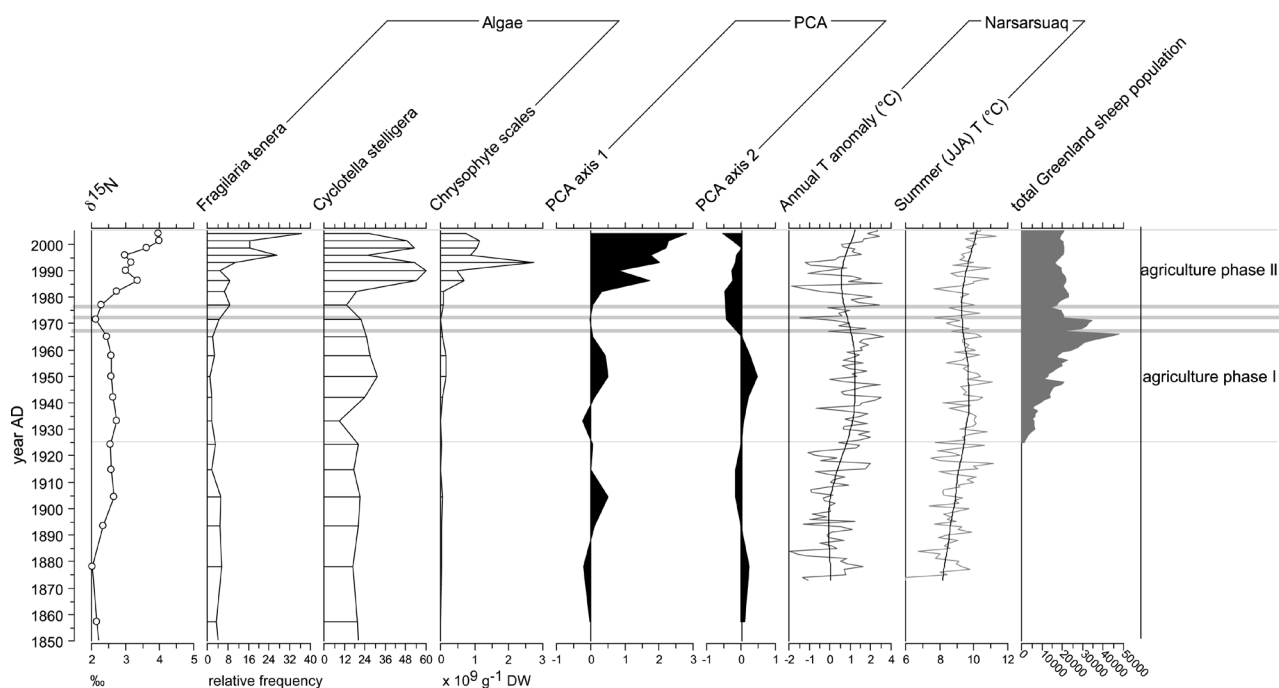
stressors (Norse) were not sufficient to drastically alter the biological dynamics of the lake.

### 5.4.1 Scant environmental impact from Norse farming

At Igaliku, the Norse period is registered in the sediments as slightly higher relative frequencies of the diatom taxon *Cyclotella stelligera*, slightly higher  $\delta^{15}\text{N}$  values (both a proxy for increased production), high C/N ratios, depleted  $\delta^{13}\text{C}$  values, as well as the lowest values of C and N in the last 1450 years. Sedimentological analyses (Massa *et al.*, 2012) demonstrate a higher flux of minerogenic materials during this time, which is consistent with the C and N values shown here and with a possible soil erosion source. The peak of this signal is constrained to the period *c.* ad 1280–1350, a time that marks the peak of the population of Norse Greenland (Lynnerup, 2000), but also the end of the Western Settlement, the beginning of the transition to colder temperatures of the LIA (Barlow *et al.*, 1997; Jensen *et al.*, 2004; Ogilvie *et al.*, 2009) as well as the transition to a more marine resource-based diet (Arneborg *et al.*, 1999). It is not possible to determine whether the subtle environmental changes are due to climate cooling, land use, or some combination of the two during this time, but it is important to note that Norse farming did not leave a significant impact on these environmental proxies.

It is an unexpected result that nearly 500 years of Norse agricultural activities are barely registered in the ecology of adjacent lake sediments. Elsewhere in the Northern Hemisphere, diatoms document nutrient enrichment in response to early agriculture by Anderson *et al.* (1995); Bradshaw *et al.* (2005); Ekdahl *et al.* (2004); Fritz (1989). In southern Greenland, widespread evidence from a number of nearby peat, soil, and lake sediment paleoenvironmental studies documents abrupt vegetation change (Fredskild, 1988; Schofield *et al.*, 2008, 2010), as well as erosion and soil degradation (Jakobsen, 1991; Sandgren and Fredskild, 1991) consistent with the timing of the Norse Landnám. Entomological and  $\delta^{15}\text{N}$  isotopic evidence from infields also document extensive manuring and irrigation to maximize hay production (Buckland *et al.*, 2009; Commisso and Nelson, 2008), which would be consistent with large landscape-level disturbance and the potential for soil erosion.

The extent to which the Norse caused the systematic regional degradation of the landscape, can be questioned. Our findings echo those from the Sandøy, on the Faroe Islands, which show limited paleoenvironmental



**Fig. 5.7** Stratigraphic diagram showing variations in  $\delta^{15}\text{N}$ , *Fragilaria tenera*, *Cyclotella stelligera*, and chrysophyte scales, the synthesis PCA axes 1 and 2, the mean annual temperature anomaly from the Narsarsuaq meteorological station, June, July and August (JJA) temperature from Narsarsuaq, and the total population of sheep in Greenland for the last 150 years. Grey bands mark the recent documented sheep population crises.

evidence of Norse landscape degradation (Gathorne-Hardy *et al.*, 2007). Although there is little doubt from coprophilous fungal and sedimentological evidence (Gauthier *et al.*, 2010; Massa *et al.*, 2011) that the catchment and immediate shore of Lake Igaliku were used for grazing and therefore subject to some degree of erosion; the overall ecological impact of the Norse settlement was probably very localized.

#### 5.4.2 The minimal role of climate at Lake Igaliku

Paleoclimatic archives from the circumpolar North suggest that the last 2000 years encapsulates both the warmest and coldest climates of the late Holocene (Bradley, 2000). Although warmth during the Medieval time (~ad 1000–1200) is by no means hemispheric or global in nature (Bradley *et al.*, 2003), it is well expressed in southern Greenland from a number of paleoclimatic proxies (Dahl-Jensen *et al.*, 1998; Jensen *et al.*, 2004; Kaplan *et al.*, 2002). Few paleoclimatic archives exist in Greenland with which to compare the magnitude of most recent warming (post-2005) with Medieval warmth, although warmest Medieval winter temperatures are purported to be on par with those of the warmest part of the middle 20th century (Vinther *et al.*, 2010). The results presented here suggest no limnological response to warmer medieval temperatures.

The LIA is expressed along the southwestern Greenland margin and the inland ice as a period of extreme cold, dustiness, and drought (Andersen *et al.*, 2006; Dahl-Jensen *et al.*, 1998; Kaplan *et al.*, 2002), with local glaciers achieving their late-Holocene maxima (Weidick *et al.*, 2004). The LIA at Igaliku is marked by greater proportions of large planktonic *Cyclotella* species (e.g. *C. rossii* complex) and by *Fragilaria virescens* v. *exigua*. These shifts are consistent with a temperature-driven phytoplankton size-fraction response found by Winder *et al.* (2009), where warm conditions favour small phytoplankton (i.e. *Cyclotella stelligera*) and vice versa. The geochemical data, on the other hand, show highly variable values with no clear trend during the LIA.

#### 5.4.3 Medieval versus modern farming impacts: An historical analogue?

A good historical analogue for the impact of Norse sheep farming exists: From 1920 to 1976, sheep farming in southern Greenland used methods not entirely dissimilar from the Norse. Sheep were left to forage in winter and minimal amounts of fodder were produced. The period prior to 1976 is unremarkable in the biogeochemical proxies at Lake Igaliku despite large sheep populations (upwards of 50,000 in S Greenland) on the land. However, beginning in 1976, the method of farming



shifted towards fodder production and higher yields at slaughter which introduced fertilizers (250–300 kg/ha per yr) and effluent from winter sheep stables into the local landscape and lake (Figure 7: agricultural phase II; Greenland Agriculture Advisory Board, 2009). After 1976, sediments from Igaliku show a rise in planktonic diatoms (*Cyclotella stelligera*, *Fragilaria tenera*), as well as chrysophyte scales,  $\delta^{15}\text{N}$ , and N, reflecting increased nutrient additions and the beginning of industrialized agriculture. These effects supercede all changes associated with the Norse Landnám.

The Norse-modern farming analogue also demonstrates the sensitivity of Arctic agriculture. In good years, between 1920 and 1976, the sheep yields in southern Greenland were high. In bad years, such as the cold, snowy spring of 1967, nearly 60% of the sheep population perished from starvation (Greenland Agriculture Advisory Board, 2009), with a similar situation again in 1971 and 1976 (Figure 7; Austrheim *et al.*, 2008). The mean annual temperature for these years is 1–2°C below the 1873–2005 average (Figure 7; Carstensen and Jørgensen, 2010), yet had catastrophic consequences for sheep farming in Greenland. Although the Norse sheep populations were likely far smaller than those of today, two or three consecutive years with late snowy springs, as are known to have occurred throughout the last several millennia (Barlow *et al.*, 1997; Ogilvie, 1991), could have easily crippled subsistence farming in Greenland, putting added reliance on marine resources and decreasing the resilience of the Norse in Greenland.

#### 5.4.4 The last 30 years at Igaliku: Multiple stressors (double trouble?)

Determining the relative influence of climatic forcing versus land use changes on aquatic ecosystems is a difficult task, especially when the two phases of human settlement on the land coincide with the warmest periods of the last 2000 years. This is especially difficult in the Arctic, where enhanced warming will likely alter nutrient cycling dynamics. Recent climate warming since ~1960 is widely documented from a number of sites in the Arctic (Arctic Climate Impact Assessment (ACIA), 2005) and Arctic temperature trends exceed global averages two to threefold over the last century (Trenberth *et al.*, 2007). Despite this, warming is a relatively recent phenomenon in southern Greenland (Box *et al.*, 2009). Meteorological records from the nearest weather station at Narsarsuaq, Greenland (1873–present; Figure 7), show that only the most recent years, since 2005, attain the mean annual

temperature maxima of the 1920–1950s, which were the warmest period of the instrumental record (Box *et al.*, 2009; Carstensen and Jørgensen, 2010). Summer temperatures (JJA), however, show steady warming over the instrumental period with a larger increase since the 1980s (Figure 7). The fact that the well-dated upper sequence at Igaliku does not show a shift in the decades following the 1920s, but at ad 1980, concomitant with the shift in regional farming practices, strongly suggests that agriculture is the principal driver of ecological changes in the lake. However, the role of warming summer temperatures during this period cannot be completely ruled out.

## 5.5 | Conclusions

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The microfossil and geochemical proxy records from the last 1450 years at Lake Igaliku do not support the hypothesis that the Norse strongly impacted their environment. The five centuries of Norse farming in southern Greenland are registered in the sedimentary biological and chemical proxies as subtle deviations from long-term means, as opposed to the marked shifts documented since the advent of mechanized farming in ~1976. Similarly, the natural environmental variability of the last 1450 years is eclipsed by the recent changes seen in Lake Igaliku.

Despite subtle historical impacts, recent changes in Lake Igaliku, evidenced by marked shifts in diatoms, scaled chrysophytes, and  $\delta^{15}\text{N}$ , suggest that the lake is sensitive to changing land use. Recent farming activities have outpaced the geochemical and biological resilience of the lake and have likely heightened its sensitivity to future stressors. Under climate change scenarios, South Greenland is expected to warm 3–6°C over the next 100 years (ACIA, 2005). With additional pressure from the agricultural sector, these stressors will likely result in unanticipated new ecological states in the future. These findings confirm the sensitivity of Arctic lakes to external anthropogenic forcing and contribute to the understanding of the relative differences between the historic and modern impacts of agriculture in the North and their sensitivity to future stressors.

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**Chapitre 6**

**A 2500 year record of natural and anthropogenic soil erosion in South Greenland**





## Chapitre 6



# A 2500 year record of natural and anthropogenic soil erosion in South Greenland

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## Abstract

The environmental impact of the Norse landnám (colonization) in Greenland has been studied extensively. But to date, no study has quantified the soil erosion that Norse agricultural practices are believed to have caused. To resolve this problem, a high resolution sedimentary record from Lake Igaliku in South Greenland is used to quantitatively reconstruct 2500 years of soil erosion driven by climate and historical land use. An accurate chronology, established on 18 AMS <sup>14</sup>C, and <sup>210</sup>Pb and <sup>137</sup>Cs dates, allows for the estimation of detritic fluxes and their uncertainties. Land clearance and the introduction of grazing livestock by the Norse around 1010 AD caused an acceleration of soil erosion up to ~8 mm century<sup>-1</sup> in 1180 AD which is two-fold higher than the natural pre-landnám background. From 1335 AD to the end of the Norse Eastern Settlement (in the mid-fifteenth century), the vegetation began to recover from initial disturbance and soil erosion decreased. After an initial phase of modern sheep breeding similar to the medieval one, the mechanization of agriculture in the 1980's caused an unprecedented soil erosion rate of up to ~21 mm century<sup>-1</sup>, five times the pre-anthropogenic levels. Independently, a suite of biological and geochemical proxies (including Ti and diatom concentrations, C:N ratio, δ<sup>13</sup>C and δ<sup>15</sup>N of organic matter) confirm that the medieval and modern anthropogenic erosion far exceeds any natural erosion over the last 2500 years. Our findings question the veracity of the catastrophic scenario of overgrazing and land degradation considered to have been the major factor responsible for Norse settlement demise. They also shed light on the sustainability of modern practices and their consequences for the future of agriculture in Greenland.

**Keywords:** Greenland; Norse; Eastern Settlement; landnám; Agriculture; Soil erosion

## 6.1 | Introduction

Understanding the interactions between climate and human impact on lake sediments has become an important issue of paleolimnology (Dearing *et al.*, 2008; Battarbee and Bennion, 2010). In this framework,

the westward migration of the Scandinavian settlers (Norse) across the North Atlantic region during the 8<sup>th</sup>-10<sup>th</sup> centuries is an ideal case study for understanding the interactions between human societies and their environment. The absence of established agricultural



systems in Greenland before the Norse colonization (*landnám*), well documented by the archaeological and medieval literature, namely “the Sagas” (for an in-depth review see Dugmore *et al.*, 2005 and references therein), provides a unique opportunity to study the human impacts through a rapid colonisation of a pristine landscape (eg. Fredskild, 1973; Gauthier *et al.*, 2010; Schofield and Edwards, 2011). The history of the Greenland settlements (the “Eastern Settlement” in the far south and the “Western Settlement” in modern Nuuk district further north), from the end of the 10th century to the late 15th century, is also an iconic example of the impact of changing climate on human population (McGovern, 1991; Barlow *et al.*, 1997; Dugmore *et al.*, 2007). The chronology of the abandonment is unclear as are its causes. The only consensus is the role of the deteriorating climatic conditions of the ‘Little Ice Age’ which likely isolated the community and reduced agricultural yields (eg. Dansgaard *et al.*, 1975; Stuiver *et al.*, 1995; Barlow *et al.*, 1997; Patterson *et al.*, 2010). Among the many reasons proposed to explain the disappearance of the Norse from Greenland, overgrazing and excessive soil erosion may have led to a dramatic decrease of grassland and fodder production crucial to Norse animal husbandry (eg. Gad, 1970; Jacobsen and Jakobsen, 1986; Jacobsen, 1987; Fredskild, 1988; Hansen, 1991; Jakobsen, 1991; Fredskild, 1992; Mainland, 2006). Apart from one exception (Rutherford, 1995), increased soil erosion is documented from all investigations of Norse farming impacts. Severe soil erosion was also observed in a few areas of South Greenland during the 1970’s and Fredskild (1988) suggested that the Norse settlers could be responsible for its initiation. Concerned about a possible adverse environmental impact comparable to that postulated for the Norse, the Danish authorities conducted an extensive study of the impacts of sheep grazing on vegetation and soils (Hansen, 1991; Sandgren and Fredskild, 1991; Fredskild, 1992). Afterwards it turned out that the only substantial eroded area (ca. 10 km<sup>2</sup>) is situated near Igaliku Kujalleq (Søndre Igaliku, figure 1a). Moreover, some authors argued that the extensive sand horizons observed in lakes and soil profiles of this area could be the result of aeolian inputs as well as sediment influx from erosion and transportation in the immediate catchments (Mikkelsen *et al.*, 2001; Andresen *et al.*, 2004; Lassen *et al.*, 2004; Kuijpers and Mikkelsen, 2009).

To assess the problem of soil erosion in Greenland, it must be directly estimated through the calculation of sediment yield, before, during and after the medieval occupation. Lake reservoirs have been widely used in to quantify erosion rates and to determine changes in

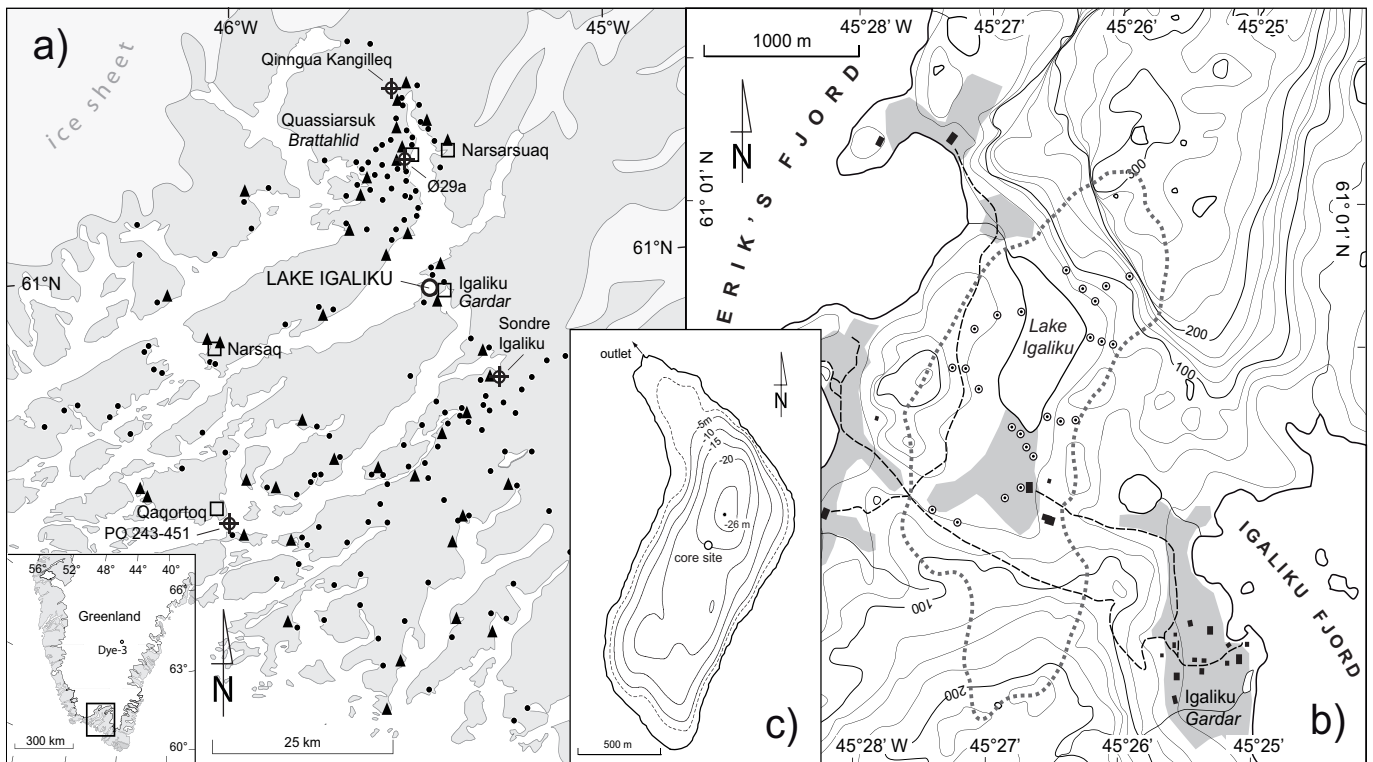
sediment yield due to agriculture (e.g. Dearing, 1992; Chiverrell, 2006; Enters *et al.*, 2008; Boyle *et al.*, 2011). To date there is no reliable quantification of erosion in the Greenland settlements that could support the mass erosion hypothesis. Fredskild’s pioneering work showed strong evidence of soil erosion (Sandgren and Fredskild, 1991; Fredskild, 1992) but poor chronological control does not allow the sediment yield to be estimated. Recent efforts on peat deposits (Edwards *et al.*, 2008; Schofield and Edwards, 2011), soil sections (Buckland *et al.*, 2009) and archaeological trenches (Schofield *et al.*, 2008) have produced high-resolution records of the impact of Norse farming, with reliable chronology through AMS dating of terrestrial plant macrofossils. However, systematic sedimentological hiatuses due to peat cutting or low sediment accumulation rates do not adequately place the records in a late-Holocene palaeoclimatic context. In light of the previous studies mentioned above, nothing definitive can be said as to whether the Norse agricultural practices caused widespread land degradation.

Here, we present a quantified reconstruction of past soil erosion based on the analysis of a well dated lacustrine sediment record from Igaliku, near the major archaeological site of *Garðar*, in South Greenland. The objective of the present study is to estimate soil erosion within the catchment area of Lake Igaliku using the detritic and organic inputs into the lake. The reliability of our estimate is controlled by a set of geochemical and ecological parameters including, titanium content, bulk organic matter geochemistry and diatom valve concentration. As sheep farming was reintroduced at a large scale in the area during the 1920’s, we have also compared medieval and recent soil erosion to place the Norse impacts in a modern context. Both erosion rates and sedimentological proxies were interpreted in the context of past arctic climate and historical land-use. This work builds on paleoecological data obtained from the same core (Perren *et al.*, 2012; Gauthier *et al.*, 2010) and constitutes a comprehensive reconstruction of human impact on an area of prime importance during the Norse period.

## 6.2 | Study Area

### 6.2.1 The Igaliku lake system

Lake Igaliku (unofficial name, 61°00’N - 45°26’W, 15 m asl) is located in a low valley between the head of Igalikup Kangerlua (Igaliku fjord) and Tunulliarfik fjord (Erik’s fjord) (figure 1a,b). It is a north-south oriented lake with a surface area of 34.6 ha (figure 1c). The



**Fig. 6.1** (a) Map of the Norse Eastern Settlement showing the location of Igaliku/Garðar, Norse ruins groups (dots), modern farms (triangles); core PO 243-451 in outer Igaliku Fjord (Jensen *et al.*, 2004; Lassen *et al.*, 2004) and ruin group Ø39 and Ø29b (crossed circles). The inset map displays the regional setting of the study area and the location of the Dye-3 ice core (modified from Mikkelsen *et al.*, 2001). (b) The region around Lake Igaliku including roads (dashed lines), buildings (black rectangles), current hay fields (shaded area), the soil samples (dotted circles) and the archaeological site of Garðar. The catchment delimitation is drawn in dotted line. (c) The bathymetry of Lake Igaliku and coring location.

catchment area is 3.55 km<sup>2</sup>, without an inlet but a small outlet on the northern shore drains into the Tunulliarfik fjord. The local topography is characterized by a gently sloped large plain (3.1 km<sup>2</sup>) surrounded in the western part by a low rounded hill (130 m asl). The slope is considerably steeper to the northeast where the highest relief reaches 300 m asl. The rocks underlying most of the catchment are Proterozoic granites of the Julianehåb batholith (Upton *et al.*, 2003) that are partly covered by arkosic sandstones and lavas of the Mesoproterozoic Eriksfjord Formation which outcrops on the hills.

The study area is situated in the subcontinental, subarctic climatic and vegetational zone of southern Greenland (Feilberg, 1984). Towards the innermost and sheltered fjords, the climate gradually changes from maritime to more continental conditions reflected in the vegetation by an increase in dwarf-shrub heath or scrub which tends to cover most of the ground. The meteorological standard normals 1961-1990 (Cappelen *et al.*, 2001) at the station of Narsarsuaq (17 km north of Igaliku, figure 1a) record a mean annual temperature of 0.9°C, with a maximum in July of 10 -11°C, 194.8 days/yr with frost and a yearly precipitation of 615 mm.

The area is windy, with a mean wind speed of 3.8 m/s, and strong desiccating foehn winds blowing from the Ice Cap are frequent year round.

### 6.2.2 History of land use in the Igaliku area

The town of Igaliku - the Norse *Garðar* - is located on a fertile plain at the head of Igaliku Fjord which lies strategically in the centre of the Eastern Settlement. According to the *Groenlendinga Saga* (Saga of the Greenlanders), the area was settled by the daughter of Erik the Red soon after the *landnám* (Gad, 1970; Jones, 1986). *Garðar* became the Episcopal seat of Greenland in 1124 AD, consecrated two years later by the arrival of the first bishop (Krogh, 1967). It is also thought to have been an assembly site of prime importance in the administrative system of Norse society (Sanmark, 2009). For these reasons *Garðar* was a high status farmstead: 52 Norse archaeological structures were recorded, including large byre-barn complexes, animal pens and enclosures, sheep/goat houses and an irrigation system attached to fodder production (Nørlund and Rousell, 1929). The bishop's farms

could host over 100 head of cattle, in addition to goats and sheep (Christensen-Bojsen, 1991), probably making *Garðar*, by far, the largest holding of livestock in Norse Greenland. Buckland *et al.* (2009) showed paleoecological evidence for manuring and irrigation to enhance the productivity of *Garðar*'s infields. As the 15 ha of land at *Garðar* were likely insufficient to raise a large livestock (Christensen-Bojsen, 1991), animals would have been kept from grazing in the infield and the total vegetated landscape of the area would have been utilized. This includes the catchment of Lake Igaliku, although neither ruins nor vestiges of fenced areas have been found.

The last bishop known to have resided at *Garðar* died in 1378 AD (Arneborg, 2007) and the last written account attesting the presence of the Norse in Greenland is a letter dated from 1409 AD that announced a wedding at the Hvalsey church (figure 1a) the year before (Gad, 1970). These elements do not allow the exact timing of the abandonment to be determined, but it is generally accepted that it must have occurred sometime in the mid to late 15<sup>th</sup> century (Dugmore *et al.*, 2009).

A Danish farmer settled the site of *Garðar* in the 18<sup>th</sup> century and a few domestic animals were kept in the region until the early 20<sup>th</sup> century (Arneborg, 2007). The modern grazing management began in 1915 with 250 sheep (Austrheim *et al.*, 2008) and was intensified in 1924 under the impetus of the Danish government (Hansen, 1991). Until 1976, sheep farming was based on extensive all year round grazing, with small supplements of winter fodder and occasional stabling. The number of sheep increased up to a maximum of 47 800 in 1966 but heavy snow and strong frost during the winter 1966/67 starved to death nearly 60 % of the herds. Similar disasters occurred in the winters of 1971/72 and 1976/77 (Greenland Agriculture Advisory Board, 2009). Consequently, a new plan for sheep management was presented (Egede, 1982): henceforth, sheep should graze 5 months on the outlying fields and be stall fed during the 7 months of the Greenland winters, requiring a considerable amount of fodder. Nowadays, there is one single farm in the catchment of Lake Igaliku and the lake surroundings are freely grazed by a few hundred sheep during the summer season. Two areas of land on the south and north shores of the lake are cultivated to produce winter fodder for stabling (figure 1b), on which N fertilizer are deployed (200-250 kg ha<sup>-1</sup> yr<sup>-1</sup> of N, Miki Egede, personal communication). Also, a small stream drains effluent from the barn into the nearby lake.

## 6.3 | Methods

### 6.3.1 Fieldwork

A 4 m-long sediment succession was sampled from the centre of Lake Igaliku (figure 1c) using gravity and piston corers equipped with Ø 63 mm PVC liners (both from UWITEC Co., Austria). The sediment water interface was properly recovered by using the gravity corer (Wagner *et al.*, 2008). The sequence spans the entire post glacial history (ca. 10 000 yrs) but only the top 120 cm are presented here. Twenty five volumetric samples of near-surface soils (upper 5 cm) were taken in the catchment of Lake Igaliku to determine dry bulk density (figure 1b). The soil samples were processed for loss on ignition at 550°C to calculate the bulk mineral content (BMC). An average BMC of 420 mg cm<sup>-3</sup> was estimated for the whole catchment.

### 6.3.2 Non-destructive laboratory analyses

An X-ray radiography was obtained using the Scopix system (Migeon *et al.*, 1999) followed by laboratory X-Ray Fluorescence (XRF) core scanner measurements (Avaatech, Netherlands). Analysis was continuously performed every 2 mm with a counting time of 30 s and a 10 kV acceleration intensity. Because the sediment matrix is characterized by variable water content and grain size distributions the XRF scanner only provides a relative estimation of geochemical variables (e.g. Tjallingii *et al.*, 2007). A normalization of element counts to the total count numbers was operated because it may partially correct drifts (Revel *et al.*, 2010). The relative opal content was assessed using XRF-derived Si:Ti ratio (Peinerud *et al.*, 2001) and compared to diatom valve concentrations (see Perren *et al.*, 2012, for methodological details).

### 6.3.3 Sampling method

The top 10 cm were sampled in 0.5 cm slices and below 10 cm, sampling intervals were chosen by using the X-ray image to ensure that the varying lithology is well represented and to provide homogenous samples. The subsamples (157) were separated into different sets. Volumetric samples (1 cm<sup>3</sup>) were taken with cut plastic syringes, weighed and kept cold for biological analysis (Perren *et al.*, 2012; Gauthier *et al.*, 2010). The others were gently dried at 60°C until constant weight to obtain sediment water content (WC, w/w). The dried sediment was ground to < 63 µm with an agate ball micromiller (Retsch, Germany) and homogenized.

### 6.3.4 Organic matter, elemental and isotopic analyses

The total organic nitrogen and carbon (TOC) concentrations were determined with a vario MAX CNS analyser (Elementar, Germany) using ~170 mg of dried material. The large sample size led to a relative standard error < 1 % for both elements. A subset of 25 samples were also measured for loss on ignition (LOI) at 550°C and 950°C to estimate organic matter content (OM), carbonate mineral content and mineral matter content (MM) in sediments (Santisteban *et al.*, 2004). TOC and LOI<sub>550°C</sub> appeared to be strongly correlated (LOI<sub>550°C</sub> = 2.3 x TOC, R<sup>2</sup> = 0.99, *p* < 0.001). Using this regression (slope = 2.3), OM and MM (100-OM) were estimated on the whole sample set.

About 6 mg of dried sediment of the upper 75 cm (n=104) were loaded in tin capsules and the stable isotopic composition of organic carbon and total nitrogen was determined on an elemental analyser NA 1500 NCS (Carlo Erba Instruments, Milan, Italy) coupled in continuous flow mode to a stable isotope ratio mass spectrometer VG Isochrom (Micromass, Manchester, England). No significant loss of weight at 950°C revealed that carbonate content is negligible for the Igaliku samples. Therefore, the sedimentary carbon is assumed to be organic and no removal of carbonate carbon was necessary before δ<sup>13</sup>C measurements. All

subsamples were triplicated and the 95% confidence interval of the mean is reported. Results are expressed in standard delta notation.

### 6.3.5 ICP-AES geochemistry and calibration of XRF scanner results

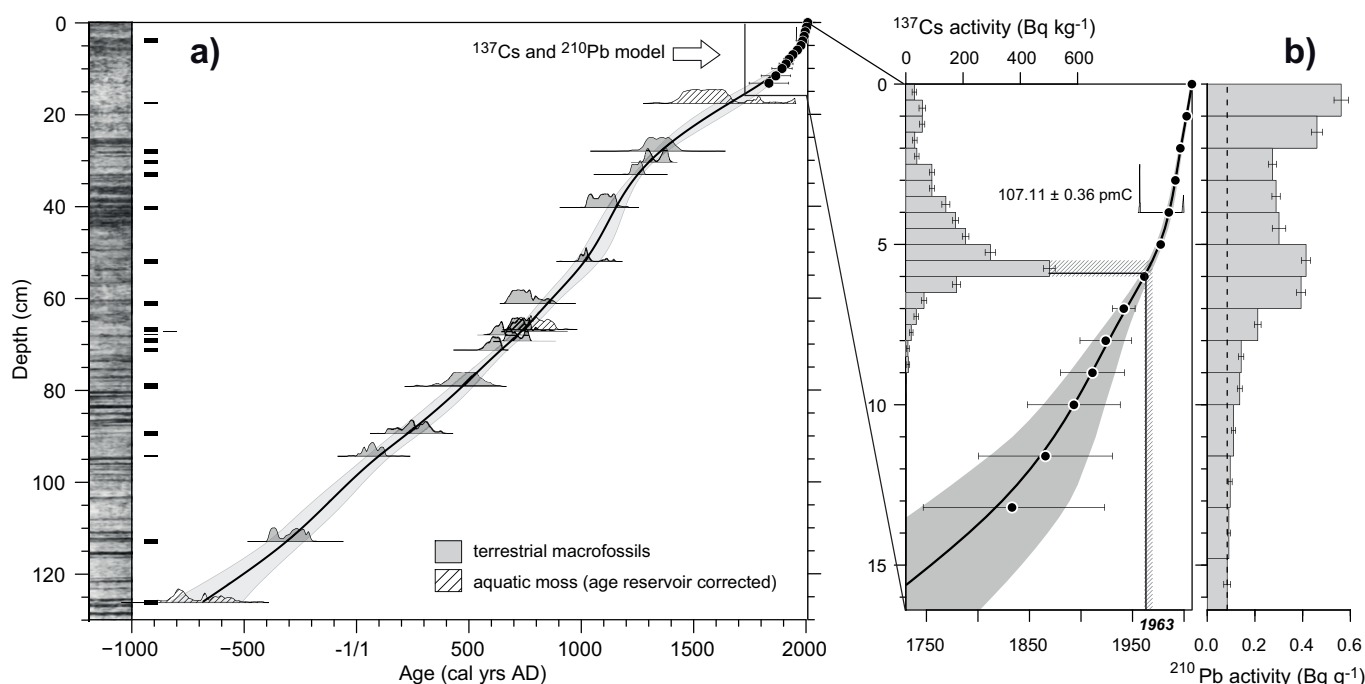
Fifty six samples were processed for inductively coupled plasma-atomic emission spectrometry (ICP-AES) measurements. About 70 mg of accurately weighed sediment were totally dissolved under pressure on a hotplate using a mixture of 1 mL each suprapure grade HCl, HNO<sub>3</sub> and HF (Merck, Germany). After evaporation, the residues were retaken with HNO<sub>3</sub> and appropriately diluted with MilliQ water. Certified reference material (BCR-2, BCSS-1, JSD-1, PACS-1) and 3 duplicates were added to the set of samples. The error of Ti concentration did not exceed ±8%. XRF-normalized Ti contents closely follow those obtained by ICP-AES (r=0.83, n=53, *p* < 0.001). Linear regression parameters were used to estimate Ti content along the whole section.

### 6.3.6 Core chronology

The age control of the upper 120 cm of the Igaliku core is based on 18 Atomic Mass Spectrometry (AMS) <sup>14</sup>C-measurements on hand-picked and mechanically cleaned plant remains (table 1, figure 2a), carried out at the Poznań Radiocarbon Laboratory (Poland) and at the

Depth (cm)	Material	Lab code	C yr BP (±1σ)	corrected <sup>14</sup> C age	cal BC/AD (2σ range)	cal BC/AD (weighed mean)
3.5 - 4.5	Undetermined plant remains	Poz-24707	*107.11 ± 0.36	-	AD 1956 minimum	-
17.4 - 17.7	Aquatic moss	Poz-31628	680 ± 100	370	AD 1395 - 1950	1559
27.5 - 28.5	<i>Betula</i> leaf	Poz-31632	620 ± 80	-	AD 1265 - 1435	1347
30.0 - 30.7	<i>Betula</i> bark fragment	Poz-31629	655 ± 35	-	AD 1280 - 1395	1337
32.6 - 33.6	<i>Salix</i> leaf	Poz-26852	775 ± 30	-	AD 1215 - 1280	1248
39.9 - 40.7	Twig	Poz-31630	945 ± 35	-	AD 1020 - 1165	1095
51.5 - 52.5	Wood	Poz-35136	1005 ± 30	-	AD 980 - 1150	1035
60.7 - 61.7	1 <i>Salix</i> and 2 <i>Betula</i> leaves	Poz-38952	1260 ± 40	-	AD 670 - 870	753
66.3 - 67.3	Aquatic moss	Poz-30535	1570 ± 35	1260	AD 670 - 865	749
67.1 - 67.3	Wood	Lyon-7300	1265 ± 30	-	AD 665 - 860	739
67.9 - 68.1	Wood	Lyon-7301	1410 ± 30	-	AD 595 - 665	631
68.8 - 69.8	Twig	Poz-35135	1305 ± 30	-	AD 660 - 770	712
71.0 - 71.7	<i>Betula</i> leaf	Lyon-7302	1450 ± 30	-	AD 565 - 650	609
78.6 - 79.8	Leaf	Poz-31633	1580 ± 60	-	AD 345 - 605	480
89.0 - 90.0	<i>Betula</i> wood	Lyon-31874	1775 ± 40	-	AD 135 - 380	256
94.2 - 94.6	<i>Betula</i> wood	Lyon-7303	1930 ± 30	-	AD 5 - 130	73
112.5 - 113.5	<i>Betula</i> leaves fragments	Poz-37363	2250 ± 40	-	BC 395 - 205	-297
125.8 - 126.8	Aquatic moss	Poz-30536	2930 ± 70	2620	BC 925 - 540	-757

**Table 6.1** Radiocarbon dates from the sediment archive of lake Igaliku. The post-bomb radiocarbon activity (marked\*) is expressed as a percentage of modern carbon (pmC).



**Fig. 6.2** (a) Age-depth model of the Lake Igaliku core with the probability distributions of calibrated <sup>14</sup>C ages and <sup>210</sup>Pb age estimates (points). (b) Bulk sediment <sup>137</sup>Cs and <sup>210</sup>Pb activity plotted on the upper part of the age-depth model. The sample corresponding to the Northern Hemisphere fall-out peak in 1963 AD is marked in grey. The black line marks 1963 AD from the age depth model. Horizontal error bars are expressed as 95% confidence level.

Lyon Radiocarbon Laboratory (France). The bryophyte date at 66.3-67.3 cm is 310 years too old compared to the result of the two terrestrial macrofossils that closely surround it. This phenomenon is due to a particular reservoir effect which affects arctic lakes due to the in-lake recycling of carbon (Abbott and Stafford Jr, 1996). Thus a reservoir correction of 310 years was applied to all <sup>14</sup>C age of aquatic mosses before calibration (eg. Kaplan *et al.*, 2002; Klug *et al.*, 2009).

The chronology for the last 150 years was established with <sup>210</sup>Pb and <sup>137</sup>Cs dating (figure 2b). The 20 samples from the top 10 cm of the core (~2 g of dried sediment) were measured for <sup>137</sup>Cs activity by gamma spectrometry in a calibrated geometry using a high-purity Ge well-type detector. The total <sup>210</sup>Pb activity of the top 16.4 cm (14 contiguous samples 1.0-1.6 cm each) was measured using alpha spectroscopy at MyCore Scientific Inc. in Ontario, Canada. Ages were determined using the constant rate of supply (CRS) model, which assumes a constant rate of unsupported <sup>210</sup>Pb from atmospheric fallout but allows sediment accumulation to vary (Appleby and Oldfield, 1978). The supported activity was determined from the basal section of <sup>210</sup>Pb data (figure 2b).

Results from radiocarbon and short-lived radio-isotopes were combined to produce an age-depth model for the whole sequence using a smooth cubic spline model and following the Monte Carlo approach provided

by Blaauw (2010). This method ('Clam') allows robust uncertainties to be computed and takes into account the entire probability distribution of the calibrated radiocarbon dates, avoiding any arbitrary choice.

### 6.3.7 From sediment accumulation rate to soil erosion

The sediment accumulation rate (SAR, expressed in cm yr<sup>-1</sup>), as well as its uncertainty, was computed by adapting the 'Clam' function to calculate the first derivative of the n-bootstrapped age-depth models and then, from these multiple SAR, the weighted average and 95% confidence interval. Then, mass accumulation rates of organic and minerogenic matter were calculated as follows:

$$\begin{aligned} \text{MAR}_{\text{org}} [\text{mg cm}^{-2} \text{ yr}^{-1}] &= \text{WBD} \cdot (1 - \text{WC}) \cdot \text{OM} \cdot \text{SAR} \\ \text{MAR}_{\text{min}} [\text{mg cm}^{-2} \text{ yr}^{-1}] &= \text{WBD} \cdot (1 - \text{WC}) \cdot \text{MM} \cdot \text{SAR} \end{aligned}$$

WBD being the wet bulk density (mg cm<sup>-3</sup>) assessed using WC, OM and MM (Sugai *et al.*, 1994). Using the obtained  $\text{MAR}_{\text{min}}$ , an estimation of soil erosion through the calculation of a mean denudation rates (DR) is proposed, basically assuming that the sediment is equally distributed on the entire surface area of the lake (Enters *et al.*, 2008) and with a bulk mineral content (BMC) of 420 mg cm<sup>-3</sup> for eroded soil (surface horizon):

$$\text{DR} [\text{mm century}^{-1}] = \text{MAR}_{\text{min}} \cdot \text{lake area} / \text{catchment area} / \text{BMC} \cdot 1000$$

## 6.4 | Results

### 6.4.1 Lithology and chronology

The upper 130 cm of the lake Igaliku core are composed of very finely stratified brownish sandy silt with black horizons rich in ferrous iron oxide. From ~5 cm, the sandy silts give way to black clayey silts until water-sediment interface. The X-radiographs reveal a continuous sedimentation with distinct lamina (~6 mm), indicating that sediments were not continuously mixed by bioturbation.

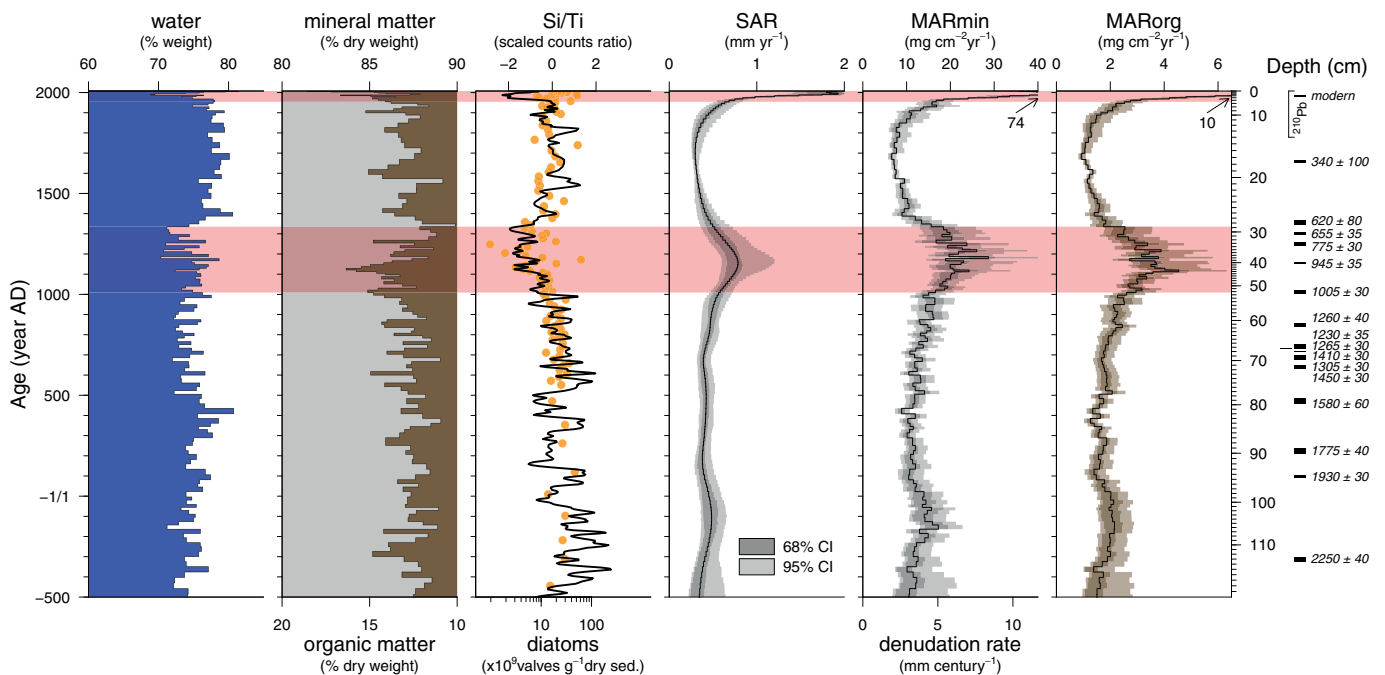
The age-depth model is almost linear until ~1010 AD (figure 2a) with a mean SAR of ~0.4 mm.yr<sup>-1</sup>. Then, the SAR continuously rises to a maximum of 0.8 mm.yr<sup>-1</sup>, around 1150 AD, and decreases gradually after that date. A sharp increase in the SAR, up to 1.9 mm.yr<sup>-1</sup>, is noted during the 20<sup>th</sup> century. Six AMS dates were targeted before 1000 AD to reduce the uncertainty resulting from a plateau in the calibration curve around the *landnám* period (Dugmore *et al.*, 2005). The narrower uncertainty of the <sup>14</sup>C part of the model is obtained for the period 1200 – 1350 AD (± 25 yr) with 3 closely spaced dates whereas the <sup>210</sup>Pb part of the model is very accurate with an error that range between ± 25 to 1.5 yr for the 20<sup>th</sup> century (figure 2b).

The <sup>137</sup>Cs peak at 5.5 - 6.0 cm depth (500 Bq.kg<sup>-1</sup>) clearly represents the main fall-out peak of 1963

AD in the Northern Hemisphere due to atmospheric nuclear weapon tests (Pennington *et al.*, 1973) and is in agreement with the <sup>210</sup>Pb CRS model (figure 2b). The low <sup>137</sup>Cs activity measured before the 1950's can be explained by a slight downward diffusion of the radionuclide in the sediment. The <sup>14</sup>C date at 4 cm (Poz-24707, table 1) gives a clear post-bomb radiocarbon activity of 107.11 ± 0.36 pmC (figure 2b). Calibrated with the Bomb04NH1 calibration curve of Hua and Barbetti (2004), it gives a minimum age of AD 1956 which fits with the <sup>210</sup>Pb model.

### 6.4.2 Mass accumulation rates and sediment composition

As there is no marked change in the sediment composition (figure 3), the SAR controls 89% and 97% (n=157, p<0.001) of the total minerogenic and organic MAR variance respectively. Thus, error in MAR is mainly due to lack of accuracy in the core chronology. The two major increases in sediment supply, towards 1150 AD and at end in the 20<sup>th</sup> century, are characterized by the highest levels of OM with 16% and 19% respectively. The inferred contribution of biogenic silica is positively proportioned to the diatoms concentration (figure 3). There is no significant linear relationship between diatom concentration and MM (r=-0.02, n=114, p=0.80) indicating that most of the silica in the sediment is of



**Fig. 6.3** Water content, organic and minerogenic matter content, diatom concentration and Si/Ti XRF scaled count ratio, sediment accumulation rate (SAR), minerogenic (MAR<sub>min</sub>) and organic (MAR<sub>org</sub>) masse accumulation rates plotted versus time (left axis) and depth (right axis). The grey shaded areas mark the periods of medieval (1010-1335 AD) and recent (after 1960 AD) agricultural impacts recorded in the Igaliku core.

mineral source. The diatom concentration is inversely proportioned to  $MAR_{min}$ , except for the uppermost part of the core where the two parameters reach their maximum values of  $74 \text{ mg cm}^{-2} \text{ yr}^{-1}$  and  $50 \times 10^9 \text{ valves g}^{-1}$  (figure 3). However, these high diatom concentrations do not increase the opal content as they are mainly due to a sharp increase in *Cyclotella stelligera*, a small species, which constitute ~60% of the diatom assemblage on this part of the core (Perren *et al.*, 2012).

### 6.4.3 Geochemical profiles

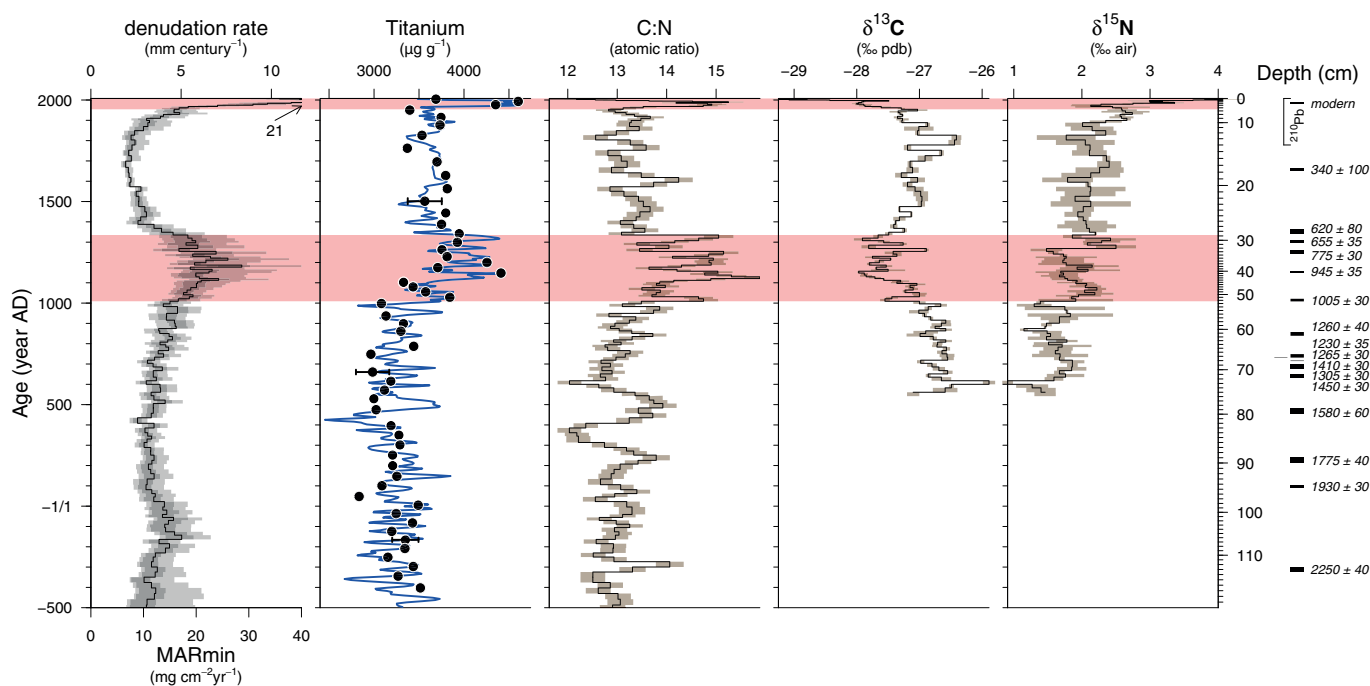
The Ti profile remains relatively stable before 1010 AD with an average value of 3200 ppm (figure 4). The concentration increases then up to 4400 ppm with peak values between 1010 AD and 1335 AD. Then, Ti concentrations fall to an average of 3650 ppm, which is 14% more than the pre-*landnám* baseline. Above ~1960 AD the titanium content increases sharply to reach the maximum values of the profile around 4600 ppm. C:N ratio coevals greatly with Ti content both for general trends and decadal scale variations, but unlike Ti, the C:N ratio does not show significantly higher values in the period of 1335 – 1960 AD than before 1010 AD (Student's t test,  $p=0.28$ ). The four uppermost samples, after 1997 AD, are clearly outlying the general geochemical composition of organic matter, and exhibit high  $\delta^{15}\text{N}$ , low C:N ratios and low  $\delta^{13}\text{C}$  values (figure

5ab). Except for these samples, a strong linear and negative relationship links the C:N ratio and the bulk  $\delta^{13}\text{C}$  ( $r=-0.80$ ,  $n=104$ ,  $p<0.001$ ) (figure 5b). The relationship between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  is more complicated: the two isotope ratios are negatively correlated ( $r=-0.73$ ,  $n=84$ ,  $p<0.001$ ), except for the period 1030 – 1230 AD during which the correlation is strongly positive ( $r=0.78$ ,  $n=20$ ,  $p<0.001$ ) (figure 5a).

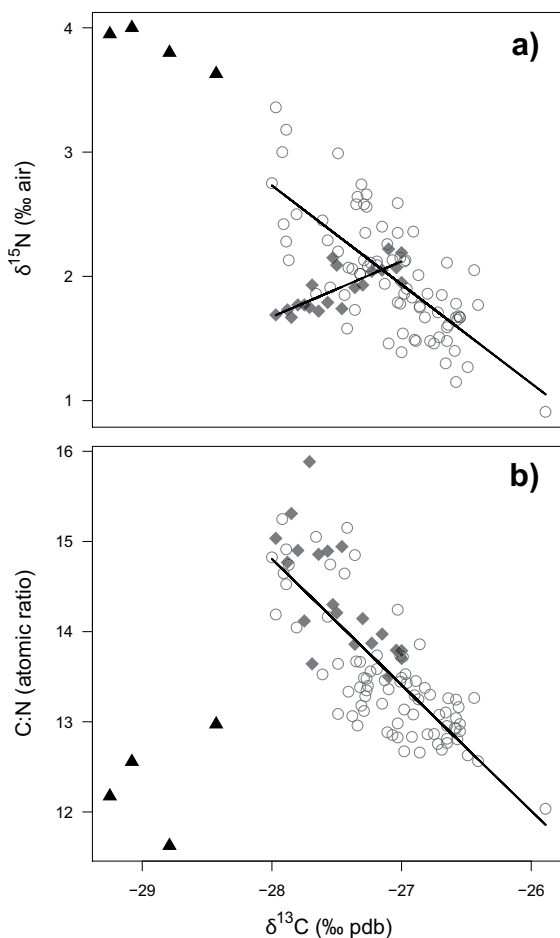
### 6.4.4 Assessing soil erosion

The calculated detritic inflows can be biased and overestimated by the presence of autochthonous silica. Especially when considering that in Greenland lakes, biogenic silica can contribute up to 35% of the total minerogenic matter content and can explain more than 40% of its variance (Willemse, 2002). However the absence of significant relationship between MM and diatom concentration indicates that changes in allochthonous MM (linked to soil erosion) drive the total MM fluctuations at the Igaliku Lake. Moreover, the lower diatom concentrations coincide with the periods of maximum sediment yield around 1010 – 1335 AD and after ~1960 AD which clearly indicate that opal production is diluted by the detritic inputs.

The titanium is a conservative lithogenic element that participates in very few biogeochemical processes (Kaupilla and Salonen, 1997; Koinig *et al.*, 2003). So



**Fig. 6.4** Mass accumulation rate of minerogenic matter ( $MAR_{min}$ ), soil denudation rate, titanium concentration measured by ICP-AES (points) and calibrated from XRF scan results (curve), C:N atomic ratio,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  of bulk organic matter from the last 2500 years of the sediment archive of lake Igaliku.



**Fig. 6.5** (a) Cross-plot of  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ . The isotopic ratios are negatively correlated ( $r = -0.73$ ) except for the period 1030 – 1230 AD (grey diamonds) where the correlation is positive ( $r = 0.78$ ). (b) Cross-plot of C:N ratio and  $\delta^{13}\text{C}$ . The filled triangles represent the outliers from 1997 to 2007 AD.

the shifts to higher Ti concentrations in the sediment points to enhanced physical weathering of aluminosilicates in the watershed that can be climatic or due to land use (Kylander *et al.*, 2011). Bulk sediment C:N ratios are widely used in palaeolimnology for assessing the abundance of terrestrial and aquatic components of organic matter (eg. Kaushal and Binford, 1999). For Igaliku, C:N ratios between 11.5 and 16 indicate a mixture of lacustrine and terrestrial contribution to the organic matter pool (lacustrine plants  $\sim 6$ -9, land plants  $\geq 20$  ; (Meyers and Ishiwatari, 1993). Values above 14 during the period 1010 – 1335 AD and after  $\sim 1960$  indicate increases in terrestrial OM input and suggest soil erosion. The consistency of Ti and C:N demonstrate that they constitute two robust proxy of soil erosion and strengthen the significance of the two detritic events described above. It appears that the geochemical parameters provide a very high resolution,

but relative, view of soil erosion, whereas the  $\text{MAR}_{\text{min}}$  give an absolute, but smoothed estimate.

Changes in organic matter supplies are also mirrored in the isotopic composition of carbon and nitrogen. The  $\delta^{13}\text{C}$  of organic carbon produced photosynthetically is enriched with increases in primary production and is used as a proxy for lacustrine productivity (Schelske and Hodell, 1995). However, for the Igaliku core, the strong negative correlation between  $\delta^{13}\text{C}$  and C:N ratio indicates that the isotopic composition of bulk organic carbon is principally influenced by changes in terrestrial organic matter supplies. Although N utilization associated with productivity variations have been considered the most common cause of changes in sediment  $\delta^{15}\text{N}$  (e.g. Jinglu *et al.*, 2007), N isotopes are affected to a greater extent by food chain dynamics than are C isotopes (Hodell and Schelske, 1998) and external N inputs from sewage, fertilizers or soil erosion can also contribute to it (Teranes and Bernasconi, 2000; Talbot, 2002; Lu *et al.*, 2010). Thus,  $\delta^{15}\text{N}$  values are likely controlled both by in-lake mechanisms and allochthonous sources. That may explain its different pattern from that of  $\delta^{13}\text{C}$ .

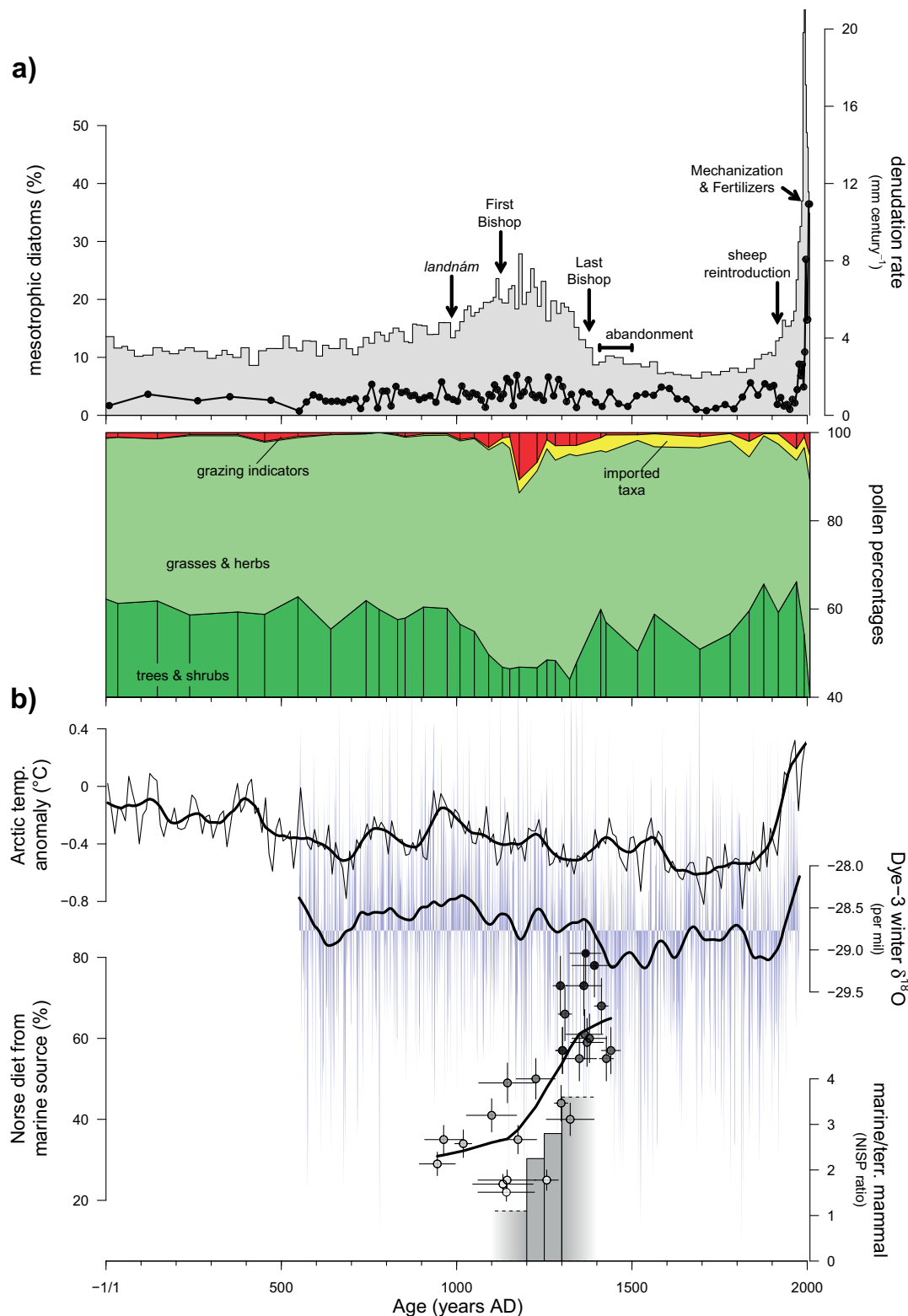
## 6.5 | Discussion

### 6.5.1 Natural variability of soil erosion before the Norse arrival (500 BC – 986 AD)

The lake Igaliku sediment record documents large fluctuations in mass accumulation rates and geochemical parameters that are consistent with meaningful changes in soil erosion regime. These results can be linked to climate variations and to human activities for the last 2500 years.

The DR is stable for the period 500 BC – 986 AD and ranges between 2.5 and 5  $\text{mm century}^{-1}$  (figure 6a). The main feature of the Igaliku profiles for this period is the large oscillation in Ti, C:N ratio and Si:Ti ratio between 100 and 600 AD which indicate changes in the balance between detritic inputs and in-lake productivity (figure 4). The high detritic inputs and low productivity around 250 AD suggests a cooling which corresponds to relatively low temperatures in the Arctic between 165 – 345 AD (Kaufman *et al.*, 2009). The low C:N and Ti values at  $\sim 400$  AD indicate low erosion and/or high algal productivity which could be linked to a warm climate. This period is indeed coeval with almost the warmer time interval (375 – 415 AD) recorded in the Arctic for the last 2000 years (Kaufman *et al.*, 2009). The most detritic period in at 470 – 550 AD roughly corresponds to a major cooling in the North Atlantic





**Fig. 6.6** (a) Reconstruction of past soil erosion rates (grey barplot), lake trophic status (points) and vegetation change for the Igaliku lake system with historical cultural events (black marks). (b) The Dye-3 Winter  $\delta^{18}\text{O}$  (Vinther *et al.*, 2010) and Arctic temperature anomaly (Kaufman *et al.*, 2009) time series, shown against the estimation of Norse diet (points) from  $\delta^{13}\text{C}$  of Norse skeletons (Arneborg *et al.*, 1999) and the relative proportion of marine and terrestrial mammal bones from the Norse farm Ø29a (McGovern and Pálsdóttir, 2006). This figure was inspired by the work of Dugmore *et al.* (2009).

(Bond, 1997) and in the Igaliku Fjord waters (Jensen *et al.*, 2004; Lassen *et al.*, 2004) at ~ 550 – 650 AD. On the winter  $\delta^{18}\text{O}$  curve of the Dye-3 ice core (Vinther *et al.*, 2010), which is the closest available glacial record (figure 1a), this cold period culminates around 650 AD. The slight discrepancy between the records could be explained by the littoral position of Lake Igaliku which is more influenced by oceanic surface currents than the Dye-3 location (Andresen *et al.*, 2004).

### 6.5.2 Impacts of medieval farming (ca. 1010 – 1335 AD)

The Norse arrived during the relatively warm temperatures of the Medieval Climate Anomaly (figure 6b), temperatures that are comparable to those of the 1920's (Vinther *et al.*, 2010). Warm temperatures in the early 11<sup>th</sup> century results in a reduction of seasonal ice cover in the Igaliku Fjord (Roncaglia and Kuijpers, 2004) indicating an extension of the growing season which was favourable to Norse farming. Thus, compared with the relatively stable soil erosion rate before the Norse *landnám*, its increase during the period 1010 – 1335 AD is interpreted as a consequence of agricultural activities in the lake catchment. Soon after the Norse arrival, the land clearance (indicated in pollen data by a decrease in woody taxa) and the introduction of sheep led to a rapid increase in soil erosion to a maximum of 8 mm century<sup>-1</sup> around 1180 AD, twice the background level (figure 6a). The positive phase of correlation between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  between 1030 and 1230 AD as well as maximum values in C:N ratio and Ti suggest a stronger impact of Norse farming during this period (figure 5a). Maximum erosion appears a few decades after the appointment of the first bishop when *Garðar* was probably close to its maximum development and activity (figure 6a). First land-use erosion around Lake Igaliku also precedes by 100 years the formation of an anthropogenic soil horizon at *Garðar* between ~1110 – 1370 AD (Buckland *et al.*, 2009) and constitute the older evidence of human impact on the area.

Soil erosion is perfectly synchronized with the grazing pressure recorded by the amount of coprophilous fungal spores (grazing indicators, figure 6a) which are typically found on animal dung (Gauthier *et al.*, 2010). The grazing pressure and associated soil erosion still remain high until 1335 AD with high levels and large amplitude fluctuations of the C:N ratio indicating a destabilisation of soils in the watershed (figure 4). Surface horizons of *Garðar*'s soils are high in organic matter (~25%) because of the short growing and decomposition periods (Rutherford, 1995). Thus, erosion of surface horizons

could result in a rapid increase in soil organic matter input that could explain the simultaneous increase of OM accumulation rates and high sediment organic contents (figure 3) as well as the marked changes in elemental and isotopic composition of OM (figure 4 and 5). Indeed, although allochthonous input does not seem to have caused substantial changes in trophic status of the lake, indicated by a relatively stable abundance in mesotrophic diatoms (Perren *et al.*, 2012; figure 6a), a reversed slope in linear relationship between C and N isotopes has already been observed in Lake Ontario and interpreted as a change in phosphorus loading to the basin (Hodell and Schelske, 1998). At Igaliku, high inflows of soil organic matter made the sediment composition remain relatively stable during erosion phases. Other sedimentary sequences, close to the archaeological remains, may have recorded a more localized and intense erosion which was able to cause noteworthy change in the sediment composition (Sandgren and Fredskild, 1991; Edwards *et al.*, 2008; Schofield *et al.*, 2008; Buckland *et al.*, 2009; Schofield *et al.*, 2010).

After 1335 AD, the grazing pressure decreased as indicated by a return of coprophilous fungal spores to pre-*landnám* background values (Gauthier *et al.*, 2010). At the same time the dwarf-shrub community recovered and soil erosion level decreased to reach pre-anthropogenic values (figure 6a). Our data indicate a substantial decline of agro-pastoral practices around the lake of Igaliku well before the end of the Norse Eastern Settlement. This decline occurred a few decades before the death of the last bishop known to have lived at *Garðar* (figure 6a) suggesting that the activity was already reduced before this historical evidence of decline.

### 6.5.3 Adaptation versus destruction

Land degradation and mass erosion leading to a serious decline in agricultural yield is supported by many authors (e.g. Gad, 1970; Jacobsen and Jakobsen, 1986; Jacobsen, 1987; Fredskild, 1988; McGovern *et al.*, 1988; Jakobsen, 1991; Fredskild, 1992; Diamond, 2005; Edwards *et al.*, 2008; Schofield and Edwards, 2011). Coupled with worsening climate conditions of the 'Little Ice Age' and the refusal to drastically change their sedentary lifestyle, what Barlow (1997) called 'cultural intransigence', the overexploitation of the environment would have been a major cause of the collapse of the medieval Norse society in Greenland. Archaeology nonetheless provides evidence that might oppose this theory. The Norse were only partly

dependent upon agriculture (Krogh, 1967) and studies of the archaeofauna from several Norse farms have demonstrated a change of the dietary habits giving more and more importance to hunting, especially sealing (McGovern and Bigelow, 1984; McGovern *et al.*, 1996; Enghoff, 2003). This is illustrated in figure 6b by the increasing relative proportion of marine mammal bones during the different phases of activity at a major farm of *Brattahilð* (Ø29a, figure 1a) (McGovern and Pálsson, 2006) and by human isotopic data showing an increasing proportion of diet from marine source over the five centuries of the Greenland settlement (Arneborg *et al.*, 1999).

The modern farming developments (section 2.2) demonstrate that cold years in such a marginal area as southern Greenland can have dramatic consequences for livestock. Soon after 1000 AD, a regime of more extreme climatic fluctuations was inferred from the outer Igaliku Fjord core with, since ~1245 AD, stronger advections of the cold East Greenland Current, more sea ice and lower summer temperatures (Jensen *et al.*, 2004). A succession of harsh winters is also noted in the Dye-3 winter  $\delta^{18}\text{O}$  record toward the end of the 12<sup>th</sup> century (figure 6b). It suggests that climate deterioration was likely the main driver of the evolution of the Norse subsistence pattern (Dugmore *et al.*, 2009). This may have led to a decrease of sheep herds and related grazing pressure early before fully entering the 'Little Ice Age' indicated, in the early 15<sup>th</sup> century, by a negative shift in the Dye-3 winter  $\delta^{18}\text{O}$  record (Vinther *et al.*, 2010; figure 6b) and by the culmination of a cooling in the Igaliku fjord at ~1405 AD (Lassen *et al.*, 2004).

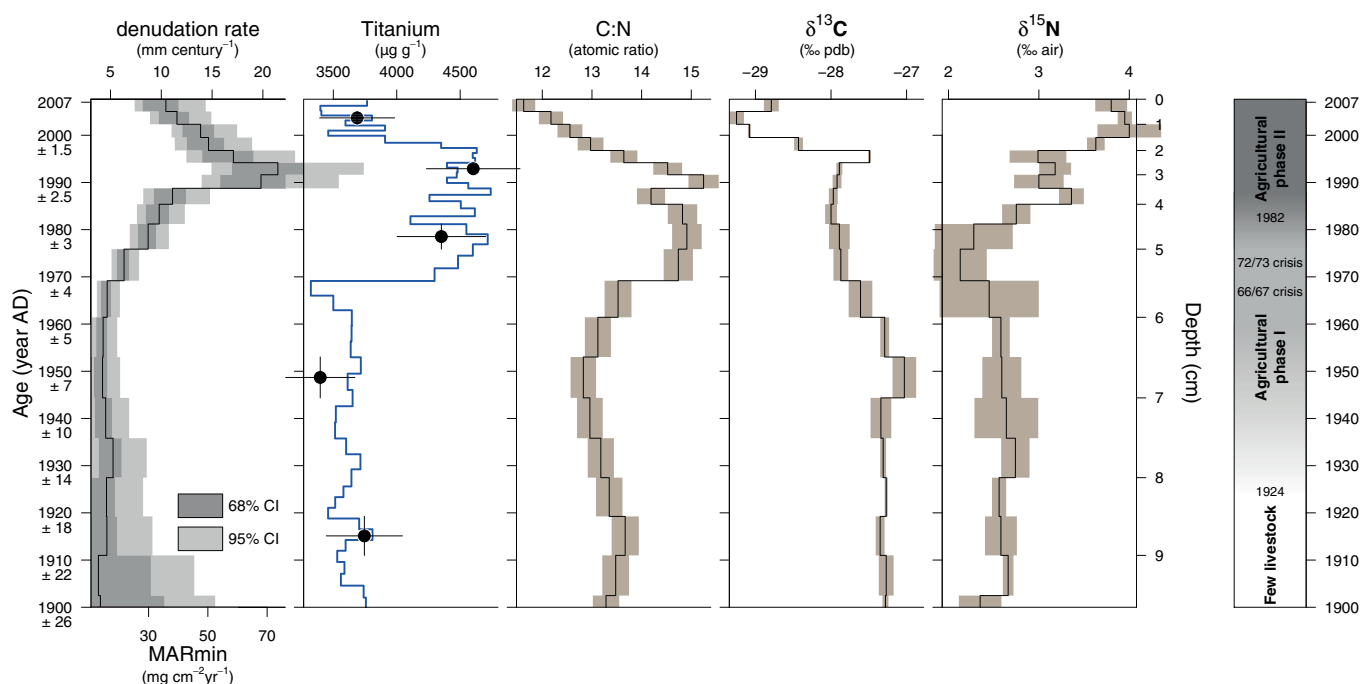
While Sandgren and Fredskild (1991) argue that the most severe erosion seems to have taken place at the end of the Norse era, our observations bring strong evidence of reduced agro-pastoral pressure a least one century before the abandonment, perhaps since 1230 AD as indicated by the isotopic ratios of N and C, in accordance to the climate deterioration and the changes in Norse diet. An early decrease in grazing intensity was also demonstrated close to a large Norse farm complex (Ø39, figure 1a) of the Eastern Settlement (Schofield and Edwards, 2011). The Igaliku record showed no continuous increase of soil erosion until the end of the Eastern Settlement, which contradicts the idea of catastrophic erosion due to overgrazing as the ultimate cause of the collapse of the Greenland Norse society. Moreover, the highest level of Norse soil erosion recorded at Igaliku, 8 mm century<sup>-1</sup> (2 sigma range of 6-12 mm century<sup>-1</sup>) could even be considered as characteristic of conservation agriculture (12.4 ± 2.2 mm century<sup>-1</sup>) (Montgomery, 2007).

#### 6.5.4 Incomplete recovery of the Igaliku lake system (ca 1450 – 1915 AD)

Pollen assemblages indicate that the vegetation did not completely recover from Norse impacts (Gauthier *et al.*, 2010). As for other studied sites (Fredskild, 1973; 1978) the most obvious footprint of Norse farming on vegetation at Igaliku is the persistence of Norse apophytes like *Rumex acetosa* and *Ranunculus acris* type which are widespread today around ruins of medieval farms (figure 6a). C:N ratio and  $\delta^{13}\text{C}$  to natural values and indicate a cessation of soil erosion associated with agriculture. Higher concentrations of titanium after the abandonment could be interpreted as a legacy of more than four centuries of Norse farming which could have altered the physicochemical properties of soils for a long time. However, a well-documented change in climatic conditions occurred at the onset of the Little Ice Age. Initiated close to the end of the Norse Eastern Settlement ca. 1425 AD (Dugmore *et al.*, 2007), this period was characterized by cold and dry air masses above the North Atlantic with increased wind speed and storm frequency which caused an enhanced deposition of eolian material (O'Brien *et al.*, 1995; Christiansen, 1998; Willemse *et al.*, 2003; Jackson *et al.*, 2005). This is also apparent in the rise of sea salt spray in a peat bog deposit from Qinnua Kangilleq (figure 1a) located 50 km north from Igaliku (Schofield and Edwards, 2011). A shift to dry and windy conditions may have brought more aeolian dust to the Igaliku Lake basin and, with a possible persistent modification of soils properties due to Norse farming, it could contribute to higher Ti concentrations.

#### 6.5.5 Impacts of modern agriculture (since 1915 AD)

From the beginning of the 20<sup>th</sup> century to ~1960 (± 5 yr) no sedimentary parameter reveals any significant increase of erosion around the lake of Igaliku (figure 7a) suggesting that sheep grazing around the lake was minimal before that date. Since ~1960 the grazing pressure, once again revealed by a decline in woody taxa and a rise in coprophilous fungi (figure 6a) caused a progressive increase in soil erosion which started gently as indicated by subtle changes in all parameters except Ti. Soil erosion accelerated in 1969 (± 4 yr), with a sharp increase in Ti and C:N ratio, to reach ~11 mm century<sup>-1</sup> in 1988 (± 2.5 yr), slightly more than the medieval period (figure 7a). The year 1969 also marks the beginning of a steady increase in  $\delta^{15}\text{N}$  for the remainder part of the profile. It may partly reflect an increase in



**Fig. 6.7** Mass accumulation rate of minerogenic matter ( $MAR_{min}$ ), soil denudation rate, titanium concentration measured by ICP-AES (points) and calibrated from XRF scan results (curve), C:N atomic ratio,  $\delta^{13}C$  and  $\delta^{15}N$  of bulk organic matter from the recent sediment archive of lake Igaliku (1900 – 2007 AD). The left diagram represents the recent agricultural phases in South Greenland.

primary productivity due to enhanced nutrient loading and also external contribution from enriched sources like animal dung (Teranes and Bernasconi, 2000). Around 1988, major earthworks and digging of drainage ditches were carried out in both hayfields (figure 1b). At the same time, soil erosion increased dramatically, up to  $21 \text{ mm century}^{-1}$ . After 1997 ( $\pm 2 \text{ yr}$ ), the erosion rate decreased continuously and may mark the stabilization of the material remobilized by the drainage works. This phase also corresponds to the four outliers in the organic matter geochemical composition (figure 5ab). Despite the high level of soil erosion, the C:N ratio continuously decreased due to the highest N concentrations of the core ( $> 0.6\%$ ). The  $+1\text{‰}$  offset in  $\delta^{15}N$  could be attributed to the loss of  $^{14}N$  stimulated by greater primary production and deposition of nitrogen-rich organic matter (algal) due to the input of N fertilisers and barn effluents into the lake. This is supported by the sharp increase in the relative abundance of the mesotrophic diatom, *Fragilaria tenera*, from 10% to 36% after 1997 (figure 6a). However, early diagenesis effects on isotopical and elemental composition (Meyers and Ishiwatari, 1993; Lehmann *et al.*, 2002), such as the preferential degradation of lake derived organic matter (Gälman *et al.*, 2008), cannot be ruled out. These two periods of soil erosion, 1960 – 1988 and 1988 – 2007, are consistent with the two modern

agricultural phases of south Greenland (figure 7b) discussed in section 2.2. The former corresponds to the first phase of free-ranging sheep whereas the later is the expression of intensified practices and hay-field management that followed the agrarian reform of 1982. Consequently, the Igaliku lake system is undergoing the most important environmental changes of the last 2500 years, with soil erosion is 3-fold the Norse level. Even if soil loss inferior to  $10 \text{ mm century}^{-1}$  could be tolerable (Montgomery, 2007), the mean denudation rate refers to the whole catchment area of lake Igaliku (355 ha) and erosion on the plowed 30 ha hay-fields must be much higher.

## 6.6 | Synthesis and Conclusion

This study is the first quantification of soil erosion from a lake deposit of South Greenland. The results demonstrate that the Igaliku lake system is very sensitive to the human land use and permits a high resolution reconstruction of the history of agricultural impacts on the landscape. The estimation of sediment yield from an accurate core chronology as well as the use of geochemical parameters (C:N, Ti,  $\delta^{15}N$ ,  $\delta^{13}C$ ) turned out to be two valuable and independent methods to investigate past soil erosion in subarctic lake systems.

Although other studies of lake sedimentary archives are needed before generalizing about the fate of the Greenland Norse settlements, our findings question the veracity of the catastrophic scenario of overgrazing and land degradation considered to have been one of the major factors responsible for their demise. The mutations of subsistence practices toward hunting and fishing have probably contributed to the reduction of grazing pressure and associated soil erosion which is recorded in the sediments of Lake Igaliku long before the end of the Eastern Settlement and therefore is unlikely to have been the prominent cause of its abandonment.

Due to technological evolution, the medieval and modern farmers have followed diametrically opposed pathways in adaptation strategies to climate changes. Thus medieval and modern agricultures are not true analogues. In response to the succession of harsh winters, modern farmers have mechanically and chemically intensified their fodder production on the sparse arable

lands to protect their livestock from other agricultural disasters. This caused unprecedented soil erosion that could have consequences for the future of Greenland agriculture which is expected to benefit from warming future climate.

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## Chapitre 7

### Conclusion et perspectives





## Chapitre 7

### Conclusion et perspectives

#### 7.1 | Apports et limites de la thèse

Les résultats obtenus sur la séquence d'Igaliku confirment son potentiel exceptionnel pour retracer les impacts des pratiques agricoles médiévales et modernes, mais aussi pour la reconstitution de l'histoire paléoenvironnementale du sud du Groenland au cours des dix derniers millénaires.

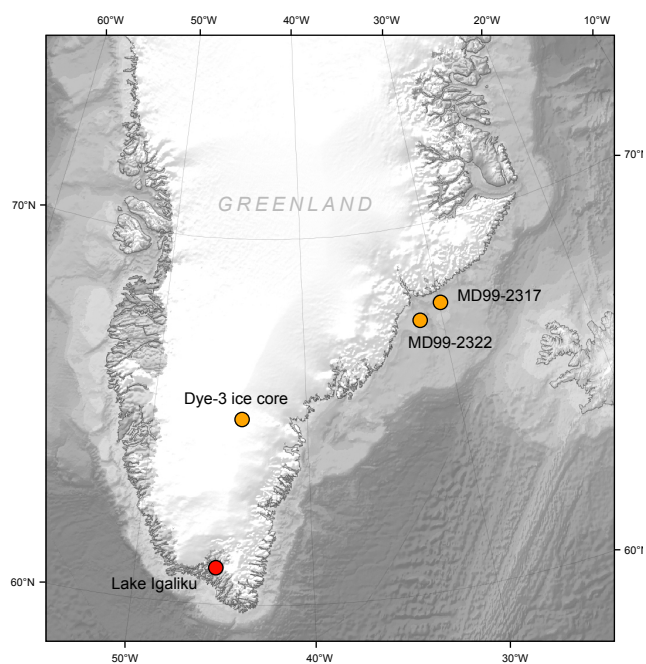
##### 7.1.1 Contribution à l'histoire climatique de la région subarctique groenlandaise

Le paramètre majeur contrôlant l'évolution du climat de l'Hémisphère Nord au cours de l'Holocène est le déclin progressif de l'insolation estivale en relation avec la précession des équinoxes (Berger et Loutre, 1991). Ainsi, les conditions d'accroissement des températures au cours de la première moitié de l'Holocène, cèdent la place à un refroidissement au cours de la seconde moitié, que l'on qualifie de néoglaciale. Le corpus croissant de données paléoclimatiques montre qu'à ce forçage orbital se surimpose une multitude de perturbations, de types périodiques ou événementiels, induites par d'autres paramètres forçants, tels que l'activité solaire, les éruptions volcaniques ou les variations de la circulation thermohaline (Mayewski *et al.*, 2004 ; Wanner *et al.*, 2008 ; Debret *et al.*, 2009). Divers forçages et rétroactions de nature régionale complexifient encore l'évolution spatio-temporelle du climat de notre interglaciaire. Par exemple, la présence de la calotte glaciaire Laurentide ou la proximité des courants océaniques de l'Atlantique Nord sont connues pour avoir grandement influencé la magnitude et la temporalité du maximum thermique holocène (HTM) dans la région Nord Atlantique (Kaufman *et al.*, 2004 ; Kaplan et Wolfe, 2006). Dans le contexte actuel de réchauffement rapide de l'Arctique, l'amélioration de la résolution spatiale et temporelle de la connaissance des changements climatiques holocènes est nécessaire pour une meilleure compréhension des mécanismes de forçage et de rétroactions.

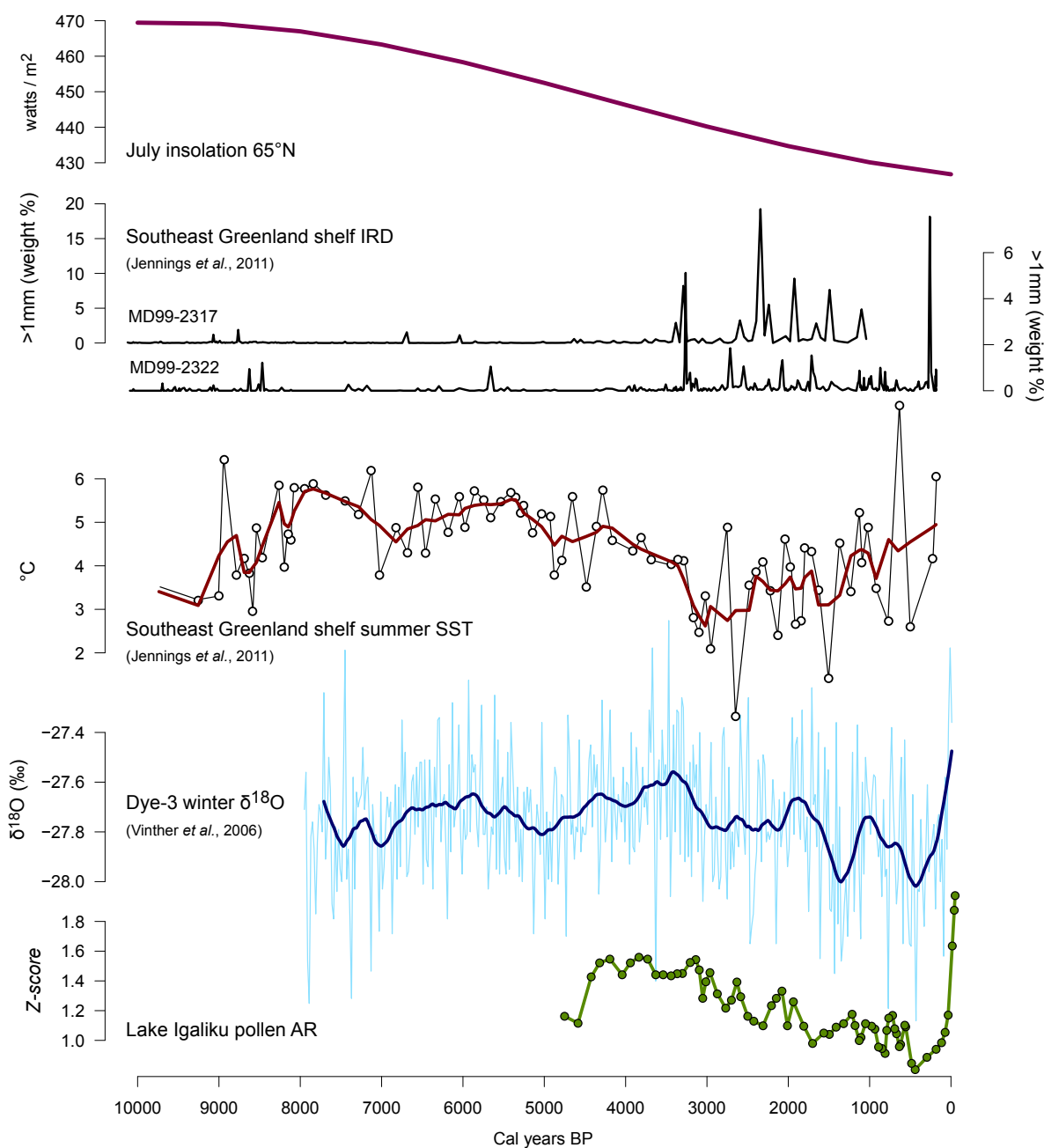
Sur ce thème, la principale contribution de cette thèse porte sur l'amélioration des connaissances sur la transition HTM-Néoglaciale au sud du Groenland, qui permet d'affiner spatialement et temporellement notre compréhension de la nature et de l'expression des changements climatiques holocènes. La séquence

sédimentaire du lac Igaliku témoigne de la totalité de l'évolution du lac et de son bassin versant à la suite du retrait glaciaire. Les conditions climatiques chaudes et relativement sèches de la première moitié de l'Holocène évoluent vers des conditions plus humides et peut-être plus froides à partir d'environ 4800 cal BP (**chapitre 3**). Cette évolution est contemporaine de modifications majeures des conditions climatiques dans d'autres régions du Groenland (McGowan *et al.*, 2003 ; Andresen *et al.*, 2004 ; Masson-Delmotte *et al.*, 2005 ; Aebly et Fritz, 2009 ; Nørgaard-Pedersen et Mikkelsen, 2009 ; Jennings *et al.*, 2011) et suggère une évolution du climat à large échelle. Fréchette et de Vernal (2009) propose d'interpréter cette transition mi-Holocène à l'échelle de la circulation atmosphérique synoptique par une transition vers un mode négatif dominant de l'oscillation Nord-Atlantique, impliquant notamment une augmentation de la nébulosité et des précipitations au sud du Groenland.

À partir de 3000 cal BP une tendance au refroidissement est clairement enregistrée à Dye-3 (Vinther *et al.*, 2010) et Igaliku (**chapitre 3**) en réponse à la baisse de l'insolation (fig. 7.2 a et b). Dans le même temps, l'augmentation des IRD sur la plate-forme continentale du Sud-Est du Groenland (Jennings *et al.*, 2011) (fig. 7.1) indique clairement l'expansion néoglaciale de l'inlandsis (fig. 7.2c). La reconstruction des températures océaniques de surface indique que ce refroidissement s'est amorcé dans le Déroit du Danemark il y a environ



**Fig. 7.1** Situation géographique des référentiels présentés dans la figure 7.2



**Fig. 7.2** Comparaison du flux de pollen arboréen reconstruit à partir de la séquence sédimentaire du lac d'Igaliku avec (a) le  $\delta^{18}\text{O}$  de la carotte de glace Dye-3, (b) les IRD et (c) les SST au niveau de la plateforme continentale du SE du Groenland (figure présentée à la conférence IPY 2012)

4000 ans (Jennings *et al.*, 2011) (fig. 7.2 d). Cette forte tendance néoglaciale enregistrée le long de la côte sud-est du Groenland ainsi que la convergence entre les enregistrements continentaux et marins suggèrent régionalement un étroit couplage océan-atmosphère. Le forçage océanique, notamment les influx d'eau polaire du Courant Est Groenlandais et d'eau chaude dérivant du Courant Nord Atlantique, semble ainsi jouer un rôle prépondérant en tant que modulateur du changement climatique (Kaufman *et al.*, 2004).

### 7.1.2. Contribution historique

#### *Quantification de l'impact des pratiques agropastorales*

L'étude des sédiments lacustres, en particulier sur le site d'Igaliku, offre l'opportunité de revisiter à haute résolution temporelle l'histoire et les conséquences environnementales de la colonisation médiévale. Si les résultats obtenus au cours de cette thèse confirment la

chronologie de l'occupation viking déjà définie par les textes historiques et l'archéologie (**chapitre 5 et 6**), ils conduisent, en tous cas à Igaliku, à contredire la vision catastrophiste d'un abandon lié à la surexploitation du milieu défendue par certains auteurs (e.g. Gad, 1970 ; Jacobsen et Jakobsen, 1986 ; Jacobsen, 1987 ; Fredskild, 1988 ; McGovern *et al.*, 1988 ; Jakobsen, 1991 ; Fredskild, 1992 ; Diamond, 2005 ; Edwards *et al.*, 2008 ; Schofield et Edwards, 2011). Les taux d'érosion des sols calculés pour l'époque médiévale sont modestes (~8 mm/siècle au paroxysme de l'activité agraire médiévale), voire même compatibles avec des pratiques agricoles que l'on qualifie aujourd'hui de « durables » (Montgomery, 2007). Ils sont sans commune mesure avec les incidences érosives de l'agriculture moderne pratiquée depuis les années 1980 dans le bassin versant du lac d'Igaliku (jusqu'à 21 mm/siècle). L'analyse sédimentaire traduit également un écosystème lacustre dont les changements apparaissent sous le contrôle dominant des activités anthropiques lors des phases d'occupation agricole du bassin versant. L'agropastoralisme médiéval a marqué l'environnement d'une empreinte lisible et partiellement résiliente, sans pour autant avoir engendré une mutation écosystémique profonde. Au contraire, les activités agricoles contemporaines, appelées à se développer dans le contexte du réchauffement climatique en cours, produisent déjà, et produiront sans doute davantage demain, des impacts environnementaux beaucoup plus spectaculaires. Stimulé par les apports de nutriments naturels ou chimiques de l'agriculture, le lac oligotrophe d'Igaliku subit, à l'instar de la plupart des lacs des régions tempérées anthropisées, une évolution rapide vers l'eutrophisation.

#### *Adaptations médiévales et modernes aux changements climatiques : conséquences sur l'environnement*

La dégradation des conditions climatiques dans une région agricole aussi marginale que le sud du Groenland peut avoir des conséquences dramatiques pour le bétail et les hommes qui en vivent. Face aux rigueurs du climat, il apparaît que les agriculteurs médiévaux et leurs homologues modernes ont suivi des stratégies d'adaptation diamétralement opposées. Face au refroidissement du climat, la composition du cheptel des colons médiévaux a évolué en faveur des moutons et des chèvres, plus robustes et moins consommateurs en fourrage que les bovins, et l'utilisation des ressources cynégétiques a augmenté (Arneborg *et al.*, 1999 ; Enghoff, 2003 ; Dugmore *et al.*, 2009). Ces mutations des pratiques de subsistance ont

probablement contribué à la réduction de la pression pastorale et des impacts associés, enregistrés dans les sédiments du lac d'Igaliku pour le dernier siècle de colonisation (1320 – ca. 1450 AD). À l'opposé, en réponse aux mortalités catastrophiques des troupeaux de moutons à la suite des hivers rigoureux des années 1960/1970, les agriculteurs contemporains, soutenus par les politiques publiques, ont intensifié la production de fourrage et construit des étables pour la stabulation hivernale afin de se mettre à l'abri des catastrophes agricoles (**chapitre 5 et 6**). Bien sûr, les technologies ont fortement progressé depuis le Moyen-Âge, et au cours des temps les mêmes intentions n'ont pas forcément les mêmes conséquences. La production de foin à l'époque médiévale consistait à fertiliser et irriguer les sols mais surtout à maintenir les animaux en dehors des prairies de fauche, les protégeant de l'érosion (Albrethsen, 1991). Au contraire, la production intensive de fourrage à partir des années 1980 a provoqué une accélération de l'érosion des sols et une modification de l'écologie du lac sans précédent sur les 9500 dernières années (**chapitre 3**).

Comme au Moyen-Âge, la production d'une quantité suffisante de fourrage pour passer l'hiver est devenue une préoccupation majeure pour Mikki Egede, actuel agriculteur au lac d'Igaliku. Avec les moyens modernes, il parvient à produire 450 à 500 balles de foin par an sur environ 28 hectares pour nourrir ses 650 moutons. Cela reste néanmoins insuffisant certaines années et l'importation de fourrage complémentaire en provenance du Danemark est encore nécessaire (Miki Egede, communication personnelle, 2011). Afin d'élever ses quatre vaches acquises en 2010, et d'accroître son cheptel bovin dans les années futures, le fermier d'Igaliku a d'ailleurs prévu d'étendre ses surfaces de culture sur le littoral nord du lac d'Igaliku.

#### *Vers une nouvelle perception des conséquences environnementales de l'agro-pastoralisme médiéval*

Les articles publiés au cours de cette thèse sont les premiers à avoir constaté les effets relativement limités des pratiques agricoles médiévales, dans le temps comme dans la magnitude de ses expressions. À la suite de nos travaux, notamment l'article d'Émilie Gauthier *et al.* (2010), Schofield et Edwards (2011) ont présenté des résultats similaires à ceux de la séquence d'Igaliku, provenant du secteur nord de l'Établissement Oriental, avec notamment une déprise agro-pastorale précoce et un impact très limité sur le couvert de bouleau, allant même jusqu'à suggérer une « gestion durable » des ressources végétales par les colons

scandinaves. Les travaux en cours dans le secteur du *Vatnahverfi* soutiennent aussi les résultats obtenus à Igaliku : l'étude palynologique de six séquences tourbeuses à proximité de vestiges archéologiques montre que les fermes sont toutes abandonnées dès 1280-1340 AD (Paul Ledger, données non publiées, 2012). L'analyse de profils pédologiques dans le même secteur suggère une première phase d'emprise agropastorale caractérisée par des pratiques de fertilisation marquées, suivie d'une diminution de l'empreinte anthropique dès ca. 1200 AD et d'un abandon des sites vers la moitié du XIVe siècle (Ian Simpson, données non publiées, 2012). L'observation sur différents sites d'une évolution similaire des conséquences environnementales de l'agriculture médiévale souligne la forte représentativité du site d'Igaliku à l'échelle de l'Établissement Oriental.

### 7.1.3. Apports et limites méthodologiques

L'innovation de la présente thèse ne réside pas dans le développement de nouveaux marqueurs paléoenvironnementaux, mais dans l'application d'une étude multiparamètre des sédiments lacustres pour faire progresser une problématique déjà largement abordée par d'autres auteurs. La partie suivante aborde brièvement les principaux apports méthodologiques de cette thèse et identifie ses lacunes majeures.

#### *Le potentiel de l'étude des sédiments lacustres au cœur de l'implantation médiévale*

Depuis les travaux de Bent Fredskild (Fredskild, 1973 ; Fredskild, 1978 ; 1988 ; Sandgren et Fredskild, 1991 ; Fredskild, 1992), personne ne s'était intéressé aux sédiments des lacs de l'Établissement Oriental. Les chercheurs s'intéressant aux variations climatiques évitent cette zone sous l'influence notable de l'agriculture et préfèrent l'étude de sites isolés des colonies (Kaplan et Wolfe, 2006 ; Fréchette et de Vernal, 2009) voire insulaires (Andresen *et al.*, 2004). Pour autant, dans le **chapitre 3**, nous avons montré la validité de la séquence d'Igaliku en tant qu'enregistrement des conditions climatiques à l'échelle des dix derniers millénaires, l'impact de l'Homme concernant finalement qu'une part réduite de la séquence. Certains marqueurs, comme les flux de grains de pollen (fig. 7.2), semblent même très faiblement affectés par les activités agricoles et pourraient parfaitement être utilisés comme indicateurs directs des paramètres climatiques.

Les autres chercheurs travaillant sur les conséquences environnementales de la colonisation médiévale (cf. **chapitre 2**) se sont surtout focalisés sur des dépôts

tourbeux, pourtant souvent affectés par d'importants hiatus (Edwards *et al.*, 2008 ; Schofield *et al.*, 2008 ; Buckland *et al.*, 2009 ; Schofield *et al.*, 2010 ; Schofield et Edwards, 2011). Les recherches en cours, par les mêmes auteurs, dans le secteur du *Vatnahverfi* ou du « Middle Settlement » (cf. **chapitre 2**) concernent encore exclusivement des dépôts tourbeux (Kevin Edwards., communication personnelle, 2012). Ce désintérêt pour les séquences lacustres trouve probablement son origine dans les travaux de Fredskild, où seules quelques dates radiométriques sur sédiment total ont pu être réalisées à l'époque, faute de macrorestes d'origine terrestre suffisants pour être datés. En effet dans ces contextes, la rareté des restes végétaux terrestres est souvent un problème de taille pour établir la chronologie des sédiments lacustres (Wolfe *et al.*, 2004 ; Edwards *et al.*, 2011), et il est bien souvent nécessaire de combiner les datations des rares macrofossiles disponibles avec des dates sur sédiment total ou sur bryophytes aquatiques (*e.g.* Perren *et al.*, 2012). Pourtant, malgré les progrès des méthodes de datation permettant l'analyse d'échantillons de faible masse, certains auteurs impliqués considèrent encore les sédiments lacustres comme trop incertains pour établir des chronologies fiables (Kevin Edwards, communication personnelle, 2007).

Lors de la rédaction du **chapitre 2** le modèle âge-profondeur encore imprécis de la carotte d'Igaliku pouvait laisser supposer d'une emprise agropastorale antérieure à l'arrivée d'Eric le Rouge en 986 AD (Gauthier *et al.*, 2010). Cette possibilité, qui est maintenant écartée en raison d'une chronologie robuste élaborée avec de nombreuses dates (cf. **chapitre 6**), n'était pas sans fondements. Bien que controversés sur leur datation, il existe en effet des indices paléoenvironnementaux d'occupations humaines précoces (VIe-VIIe siècle) dans les îles Féroé et en Islande, attribuées à la présence de moines irlandais précurseurs de la colonisation européenne en Atlantique Nord (Jóhansen, 1971 ; 1979 ; 1989 ; Hansom et Briggs, 1990 ; Hannon *et al.*, 1998 ; Hannon et Bradshaw, 2000 ; Hannon *et al.*, 2005).

Même si la construction d'un modèle d'âge fiable nécessita un effort considérable dans la recherche de matériel datable (cf. **chapitre 3, 4 et 6**), la séquence d'Igaliku est à ce jour une des séquences lacustres groenlandaises les mieux datées, permettant une interprétation fiable et détaillée du signal sédimentaire. Cette thèse démontre donc, si besoin en est, le potentiel extrêmement prometteur des enregistrements sédimentaires lacustres pour l'étude des changements environnementaux engendrés par les changements

climatiques et les pratiques agricoles médiévales et modernes au sein des colonies viking du Groenland.

### *La silice biogénique*

La teneur des sédiments du lac d'Igaliku en silice authigène (opale) n'a pas été directement mesurée mais estimée à partir des concentrations en valves de diatomées du rapport Si/Ti issu du scanner XRF. Cette méthode indirecte est imparfaite et induit sans doute une marge d'erreur dans le calcul des flux détritiques présentés dans les **chapitres 3** et **6** qui peuvent être partiellement surestimés par la non-prise en compte de la contribution de la silice authigène. D'autant que dans certains lacs groenlandais, ce composant représente jusqu'à 35% de la matière minérale du sédiment et peut expliquer plus de 40% de sa variance (Willemse, 2002). Le silicium ne pouvant pas être mesuré après une attaque à l'acide fluorhydrique (car il se volatilise), il a donc été impossible d'estimer la concentration en silice biogénique à partir des données géochimiques quantitatives obtenues pour Igaliku (ICP-AES, **chapitre 6**) (e.g. Peinerud *et al.*, 2001 ; Giguët-Covex *et al.*, 2010). En outre, il s'avère hasardeux d'estimer la teneur en opale à partir des concentrations de valves de diatomées car la relation entre les deux paramètres dépend de nombreux facteurs (composition des assemblages, taille des frustules, degré de silicification, dissolution partielle) qui peuvent varier considérablement d'un lac à l'autre comme au sein d'une même séquence sédimentaire (Conley, 1988). Par exemple, sur la côte Est du Groenland, le rapport entre la teneur en opale et la concentration en valves de diatomées peut varier d'un facteur 1 à 20 au cours de l'évolution d'une même séquence (Cremer *et al.*, 2001b), et d'un facteur moyen de 1 à 5 d'un lac à l'autre (Wagner *et al.*, 2000 ; Cremer *et al.*, 2001a). Le calcul des biovolumes de diatomées (e.g. Conley, 1988 ; Wolfe, 2003) aurait été un meilleur estimateur de la teneur en opale mais l'exercice, nécessitant une morphométrie poussée, est très fastidieux. Il nous semble donc impératif que les prochaines études menées sur les séquences lacustres, dans la perspective de mieux quantifier les flux détritiques, comportent prioritairement un dosage de la silice authigène dans le panel analytique.

### *Évolution holocène des sols du bassin versant*

Dans le **chapitre 3**, l'approche multiparamètres associant grains de pollen, diatomées et paramètres sédimentologiques, a permis d'aborder les processus d'interactions entre le climat, l'écologie du lac d'Igaliku et l'évolution des sols de son bassin versant. Ce sujet a été jusqu'alors très peu abordé pour le Sud du

Groenland. Les études pluridisciplinaires permettant une telle approche restent même assez rares à l'échelle du Groenland (Wagner *et al.*, 2008 ; Presthus Heggen *et al.*, 2010). Assez logiquement, les données obtenues à Igaliku suggèrent une évolution continue des propriétés des sols du bassin versant au cours de leur évolution postglaciaire. Néanmoins, l'absence de marqueur permettant de suivre directement les processus pédologiques n'a pas permis d'approfondir cette hypothèse. Dans son investigation analytique des sols de l'établissement Oriental, Rutherford (1995) souligne la présence de minéraux argileux d'origine probablement pédogénétique (smectite, vermiculite interstratifiée et illite). La détermination du cortège argileux sédimentaire des sédiments du lac d'Igaliku par diffraction X a donc été entreprise dans la perspective d'évaluer l'évolution qualitative des sols (e.g. Manalt *et al.*, 2001). Ces travaux n'ont pas abouti en raison d'une trop faible concentration en argiles dans les échantillons traités (n = 110). De plus, un artefact de mesure par diagraphie XRF<sup>1</sup> ne nous a pas permis de pallier la carence des teneurs en argiles et d'explorer la question des sols par le biais de la géochimie des éléments majeurs. Couplées à la signature géochimique des sols actuels ces mesures auraient apporté une meilleure compréhension de la dynamique du bassin versant (e.g. Mourier *et al.*, 2010 ; Giguët-Covex *et al.*, 2011). Dans la même perspective, la caractérisation géochimique des sources potentielles de matières organiques s'avère pertinente (Thevenon *et al.*, 2012). Ainsi, ce type d'analyses (C, N, S,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) a été entrepris sur des échantillons de sols et de plantes aquatiques et terrestres (mission Ultimagri 2009) et prolongé sur la totalité de la séquence d'Igaliku.

## **7.2 | Perspectives pour les recherches à venir**

Une quantité substantielle de données a été générée au cours de cette thèse de doctorat, non seulement à partir de la séquence d'Igaliku mais aussi à partir des nombreuses carottes rapportées des missions de terrain (**chapitre 1**). En outre, de nombreux questionnements

1 Lors des diagraphies XRF, probablement à cause d'un dysfonctionnement du capteur et de la source de rayon-X, les profils des éléments légers (Al, Si, Ti, Ca, Na, K) présentent des variations incohérentes avec le reste du jeu de données en dessous de 130 cm. Le problème a été résolu en septembre 2011 par une nouvelle diagraphie XRF réalisée avec le scanner Avaatech de l'université de Bordeaux 1.



découlent des études précédentes. Cette dernière partie du manuscrit traite donc des publications en préparation sur les différentes séquences et donne des pistes à suivre quant à la poursuite des recherches.

### 7.2.1 Les variations climatiques au cœur des colonies médiévales

#### *La recherche d'un référentiel climatique pour l'Établissement Oriental*

De nombreux chercheurs ont tenté de replacer l'histoire des colonies groenlandaises dans leur contexte climatique (e.g. Barlow *et al.*, 1997 ; Dugmore *et al.*, 2007 ; Patterson *et al.*, 2010 ; Ribeiro *et al.*, 2012). Les études paléoclimatiques du Groenland prenant en compte la période du *landnám* sont principalement fondées sur l'utilisation de proxies issus des carottages glaciaires GISP2 (Buckland *et al.*, 1996 ; Dugmore *et al.*, 2012), Dye-3 ou Crete (Adderley et Simpson, 2006), car contrairement à l'Islande, il y a très peu, voire aucune, source écrite couvrant cette période (Ogilvie, 1991 ; Ogilvie *et al.*, 2000). Ces archives glaciaires sont très éloignées des colonies, entre 475 et 1320 km, limitant leur représentativité à l'échelle du Groenland. De la zone côtière à l'inlandsis, les variations climatiques ne sont pas forcément en phase sur la période médiévale, et leur amplitude diffère probablement à cause du forçage océanique (Andresen *et al.*, 2004 ; Kaufman *et al.*, 2004). Plus proches des colonies, les travaux en domaine lacustre n'ont produit que des données à basse résolution (Kaplan *et al.*, 2002 ; Andresen *et al.*, 2004 ; Fréchette et de Vernal, 2009) ne permettant que de cerner les variations séculaires du climat. Le même défaut caractérise les études des sédiments du fjord d'Igaliku qui, jusqu'à présent, sont les seuls travaux paléoclimatiques menés au cœur d'une colonie médiévale (Jensen *et al.*, 2004 ; Lassen *et al.*, 2004 ; Roncaglia et Kuijpers, 2004). Afin de mieux cerner l'incidence des variations climatiques sur l'histoire des colons scandinaves, il est nécessaire d'étudier des archives paléoclimatiques situées au cœur des colonies. L'étude de la séquence d'Igaliku démontre le fort potentiel des séquences lacustres pour enregistrer à très haute résolution les changements des conditions environnementales (environ 5 à 4 ans par millimètre sur les deux derniers millénaires). Mais comment éviter dans ce cas les effets du forçage anthropique sur les marqueurs environnementaux ? L'exploration des lacs d'altitudes, loin des prairies à foin et des pâtures est une piste d'étude potentielle mais complexe à mettre en œuvre du fait des gradients climatiques altitudinaux

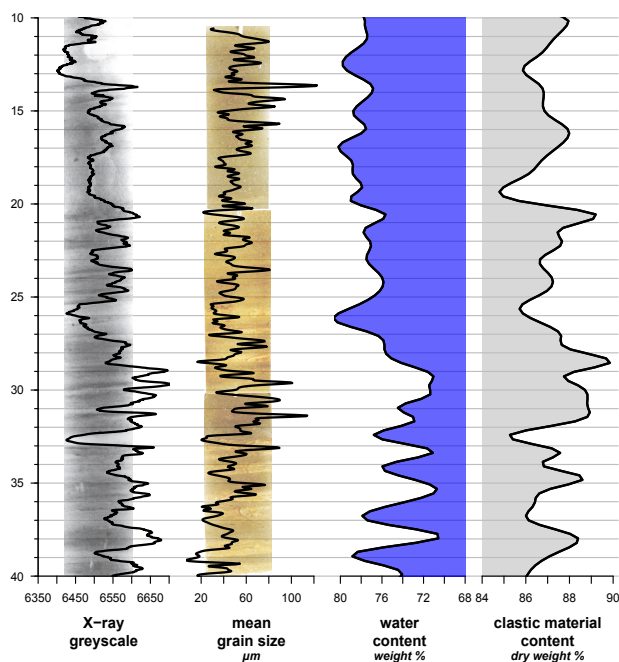
et de l'accumulation sédimentaire souvent très faible dans ces zones le plus souvent dépourvues de sol. Poursuivre les investigations sur la séquence d'Igaliku demeure une piste viable. La faible conséquence des pratiques agricoles médiévales sur l'écologie du lac (**chapitre 4**) offre la possibilité d'appréhender le climat par le biais de paramètres biotiques aquatiques. Associée au calcul des flux de grains de pollen, l'étude des assemblages de capsules céphaliques des chironomidés devrait apporter plus d'informations sur le climat d'Igaliku. Les premières études engagées dans ce sens sont très encourageantes (Laurent Millet, données non publiées). La séquence d'Igaliku offre peut-être l'occasion d'étudier conjointement les changements du climat et les mutations environnementales engendrés par les pratiques agricoles, et ainsi de revisiter à haute résolution temporelle l'histoire des interactions entre le climat et l'Homme au sud du Groenland.

#### *La question de l'activité éolienne*

L'anthropisation rapide du Sud-Ouest du Groenland par les colons scandinaves, très contrainte géographiquement et chronologiquement, facilite grandement la caractérisation de ses répercussions environnementales. Pour autant, la question de l'érosion liée aux développements agricoles et la réponse sédimentaire détritique induite dans les sédiments lacustres doit être envisagée sans négliger le rôle de forçage climatique. Dans le contexte groenlandais, où sécheresses saisonnières, vents catabatiques et disponibilité en matériel sédimentaire fin hérité de l'érosion glaciaire sont des paramètres récurrents, la question de la part des flux éoliens dans la dynamique de surface est une question qui doit être approfondie. Il a été suggéré que les horizons sableux observés dans les séquences lacustres et les profils de sol du secteur d'Igaliku Kujalleq, à quelques kilomètres au Sud-Est d'Igaliku (Sondre Igaliku, chapitre 1, fig. 1.1) sont la conséquence de l'érosion des sols liée aux activités agropastorales médiévales (Fredskild, 1978 ; Jakobsen, 1991 ; Sandgren et Fredskild, 1991). Néanmoins, les sites étudiés sont situés à proximité d'un vaste sandur qui prolonge deux glaciers s'écoulant de l'inlandsis (Kuijpers et Mikkelsen, 2009). Un tel contexte géomorphologique produit une grande quantité de sédiments éoliens et se montre très sensible aux variations de la vitesse du vent et la sécheresse. Aussi, les dépôts de sable observés sont également interprétés comme le résultat de l'activité accrue des tempêtes enregistrées pour le sud du Groenland à la transition entre l'Optimum climatique Médiéval et le

Petit Âge Glaciaire (Mikkelsen *et al.*, 2001 ; Andresen *et al.*, 2004 ; Lassen *et al.*, 2004 ; Kuijpers et Mikkelsen, 2009).

Concernant le lac d'Igaliku, même si celui-ci ne se trouve pas dans le couloir d'une vallée glaciaire et que les larges variations de l'activité éolienne qui caractérisent le climat de l'Atlantique Nord (e.g. Bond, 1997 ; Lassen *et al.*, 2004 ; Jackson *et al.*, 2005) ne semblent pas avoir eu d'influence notable sur la sédimentation après 4800 cal BP (**chapitre 3**), le transport éolien pourrait avoir joué un rôle dans l'augmentation des apports détritiques enregistrés durant la colonisation médiévale. Une meilleure détermination du rôle joué par les facteurs climatiques (précipitations, vent) sur les flux détritiques à l'échelle des temps historiques est donc une piste d'étude pour la poursuite des recherches. La longue période de gel hivernal du lac favorise le dépôt saisonnier de clastes détritiques sur la glace et leur dépôt ultérieur dans les sédiments lors de la fonte printanière (Andresen *et al.*, 2006). La recherche systématique de ce type d'apports dans la séquence, après induration du sédiment et lecture sur lame mince, constitue un axe méthodologique possible.



**Fig. 7.3** Détail des laminations de la séquence d'Igaliku (10 à 40 cm). (a) radiographie de la carotte, (b) diamètre moyen des clastes (quartz et feldspath) mesuré à partir de l'analyse d'image de sections indurées en lumière polarisée analysée, (c) teneur en eau, (d) teneur en matière minérale. (figure présentée au congrès de l'AGU, 2010)

## 7.2.2 Le lac d'Igaliku, pour aller plus loin

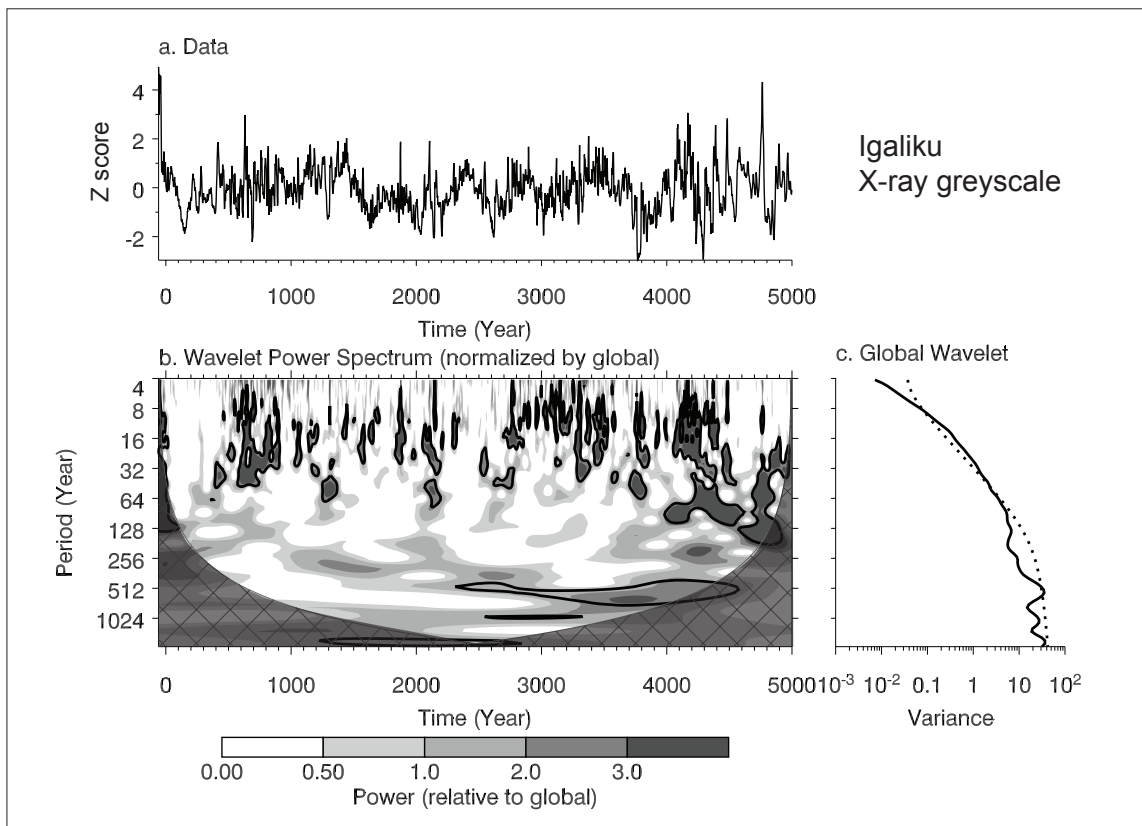
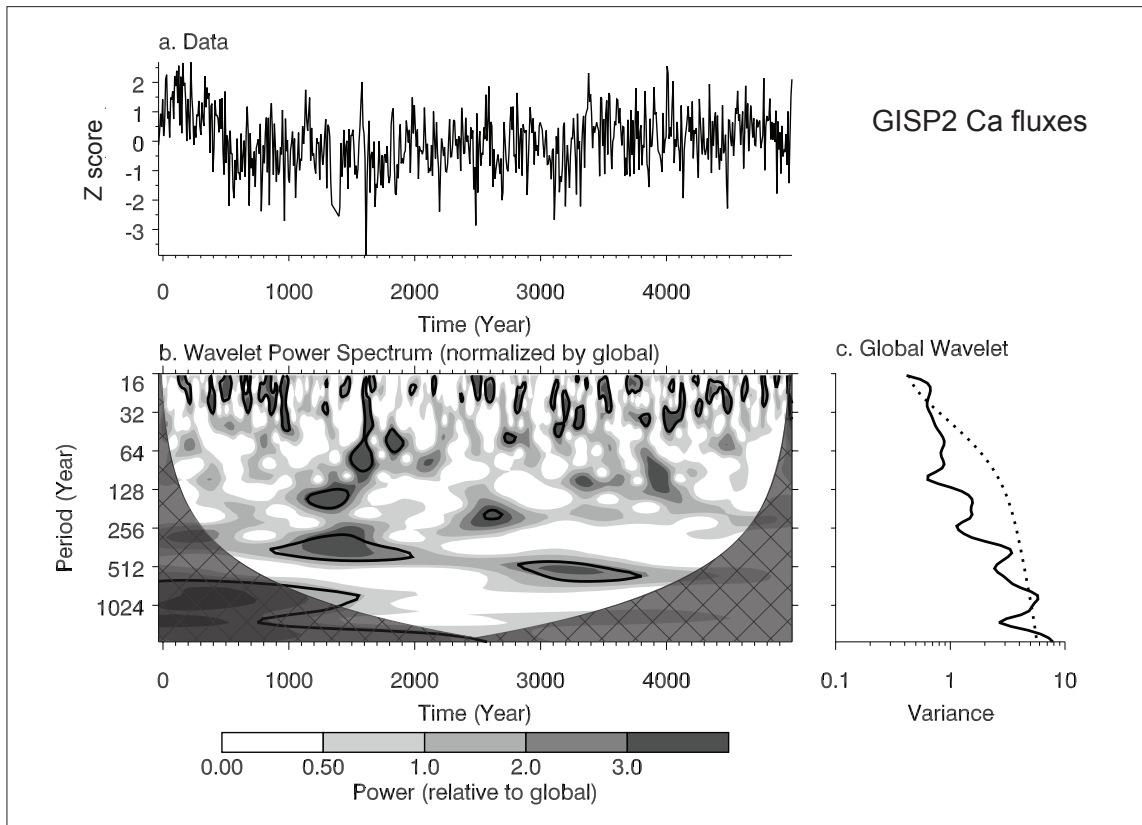
### Analyse spectrale des variations sédimentaires

Ces dernières années beaucoup d'efforts ont été consacrés à la recherche de séquences sédimentaires lacustres laminés<sup>2</sup> le long de la côte Sud-Ouest du Groenland, dans l'espoir d'y découvrir des séries varvées et d'établir des chronologies annuellement résolues (Anderson et Bennike, 1997 ; Anderson *et al.*, 1999). Malheureusement les lamines observées ne correspondent pas à une cyclicité annuelle et les facteurs environnementaux contrôlant leur formation sont encore mal connus (Anderson et Leng, 2004). Depuis ces tentatives, aucune étude n'a révélé l'existence de régimes cycliques de sédimentation dans les lacs groenlandais. Pourtant, certaines carottes de sédiment prélevées dans le cadre de cette thèse présentent des fluctuations remarquables, qui contrairement aux laminations citées précédemment sont invisibles à l'œil nu. Il s'agit de variations de la porosité aux rayons-X, d'échelles pluriséculaires à pluriannuelles, visibles dans les séquences d'Igaliku, de Qunguliussaq et de Normu. Ces variations sont dues à des fluctuations de la taille des grains et de la teneur en matière minérale (fig. 7.3) suggérant un lien avec des variations de l'énergie mise en jeu lors du transport du sédiment. Le traitement de ces signaux est envisagé à l'aide de transformées en ondelettes continues (fig. 7.4) afin d'étudier les modes de variabilité de ces séquences et leurs évolutions au cours du temps (Torrence et Compo, 1998). L'analyse conjointe d'enregistrements paléoclimatiques de références, par exemple par le biais d'analyses de cohérence par ondelettes croisées (Grinsted *et al.*, 2004), devrait permettre de mieux comprendre les forçages climatiques en jeu dans les variabilités observées, et ce à différentes échelles de temps.

### Paléopollution au plomb

Au cours de la présente étude, les concentrations et la composition en isotopes stables du plomb ont été mesurées dans les sédiments du lac d'Igaliku afin d'évaluer à long terme l'histoire de la pollution par le plomb au Sud du Groenland. Ces résultats sont en cours de traitement en intégrant d'autres données déjà publiées provenant de la tourbière de Tasiusaq (Shotyk *et al.* 2003) située à 16 kilomètres au Nord-

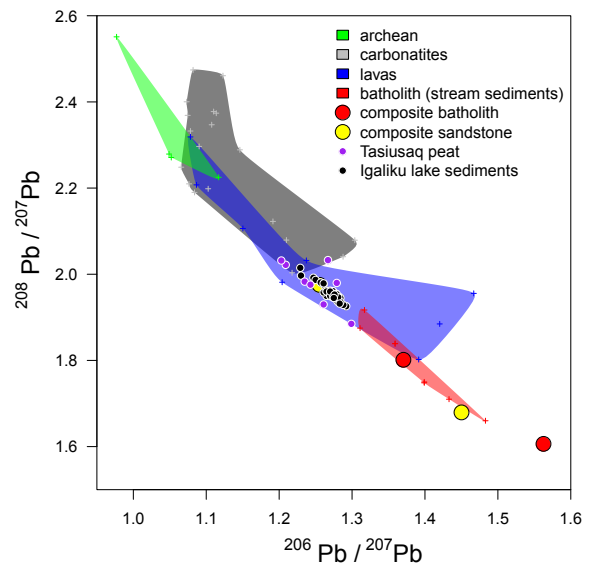
2 C'est-à-dire composées d'une succession de couches millimétriques à infra-millimétriques.



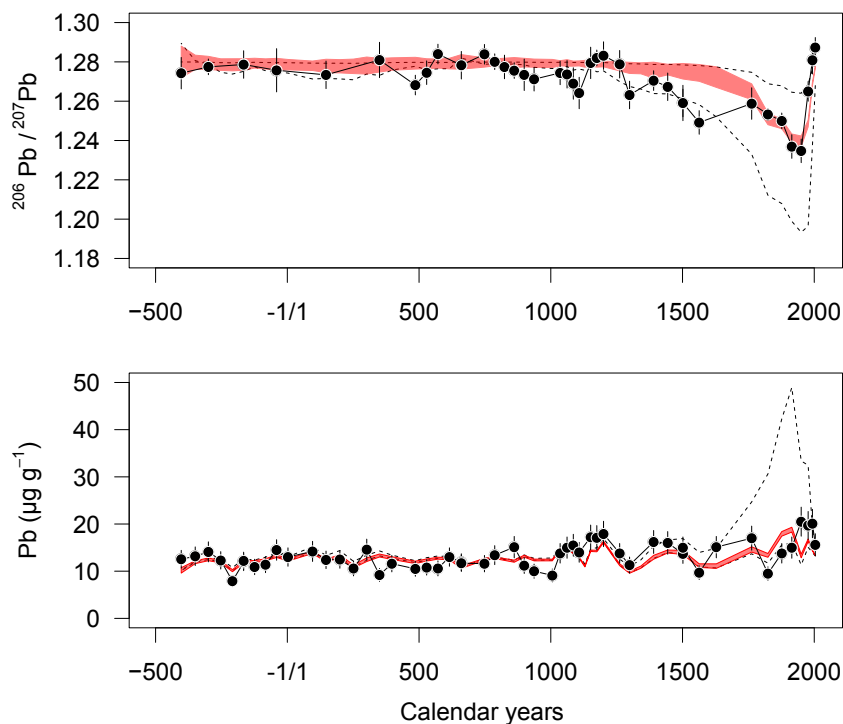
**Fig. 7.4** Analyse en ondelettes continues du niveau de gris de la radiographie de la séquence d'Igaliku et du flux de calcium de GISP2 (séries détendancées sur les cinq derniers millénaires). On peut voir que les deux spectres présentent une bande significative dans les variations pluriséculaires, avec la transition d'une période de 695 ans à une période de 375 vers 2500 cal an BP.

Ouest d'Igaliku. Comme le fond géochimique est apparu, dans les deux cas, très défavorable pour calculer l'évolution temporelle des flux de plomb anthropogéniques (rapport  $^{206}\text{Pb}/^{207}\text{Pb}$  variable (fig. 7.5), concentrations élevées autour de  $13 \mu\text{g/g}$ ), une méthode de modélisation inverse a été appliquée aux deux archives (fig. 7.6). Cette approche alternative consiste à simuler les flux anthropiques passés à partir d'un enregistrement de référence<sup>3</sup>, et à examiner pour quelle intensité de ce flux, les concentrations et les compositions isotopiques calculées correspondent le mieux aux valeurs observées. Une telle approche a déjà démontré son efficacité, du moins pour la pollution au plomb et au  $^{137}\text{Cs}$ , dans le cas des 42 parcelles expérimentales de sols étudiées par l'INRA à Versailles (Semlali *et al.*, 2004 ; Monna *et al.*, 2009). Dans l'état de nos connaissances, l'application de cette méthode aux séquences paléoenvironnementales d'Igaliku et de Tasiusaq constitue une démarche novatrice. Un article est en préparation et devrait être soumis dans le courant de l'été à la revue *Atmospheric Environment*.

3 Le choix s'est porté sur la séquence de la tourbière de l'étang de la Guère (Jura, Suisse) (Shotyk *et al.*, 1998).



**Fig. 7.5** Diagramme  $^{206}\text{Pb}/^{207}\text{Pb}$  versus  $^{208}\text{Pb}/^{207}\text{Pb}$  des sources de plomb naturelles du sud du Groenland (complexe de Qassiarsuk (Andersen, 1997), batholithe de Julianehåb (Kalsbeek et Taylor, 1985) et sédiments fluviaux de la région (Colville *et al.*, 2011)). Les échantillons de la séquence lacustre d'Igaliku et de la tourbière de Tasiusaq (Shotyk *et al.*, 2003) ont une composition isotopique qui moyenne celle des roches de leur bassin versant. L'extrême dispersion des valeurs reflète la grande hétérogénéité des roches locales et explique l'instabilité du fond géochimique.



**Fig. 7.6** Simulation de l'évolution de la concentration et de la composition isotopique du plomb au cours des deux derniers millénaires dans les sédiments du lac d'Igaliku, pour un paramètre de flux  $a$  variant entre 0.002 et 0.016 (courbes noires) ; et pour  $a = 0.008$  pour lequel l'erreur quadratique de prédiction est minimisée (enveloppe rouge). L'enveloppe représente la propagation de l'erreur des paramètres d'entrée du modèle et correspond à un intervalle de confiance à 95%. Les valeurs mesurées sont représentées en points avec des barres d'erreur correspondantes à un intervalle de confiance à 95%.

### 7.2.3 Potentiel des autres séquences lacustres

#### *Étendre l'étude des effets de l'agriculture médiévale à d'autres sites*

L'étude des sédiments du lac d'Igaliku a permis de préciser la chronologie et les modalités de l'expansion, durant 200 ans, de la colonie viking du sud du Groenland, puis son repli sur près de deux siècles. Afin de préciser l'amplitude et la chronologie des effets de la colonisation, il convient maintenant d'étendre les observations réalisées à Igaliku à l'ensemble des secteurs de l'occupation médiévale à partir des séquences collectées lors des différentes missions.

Dans l'Établissement Occidental, la séquence « Little Kapi » (64°N, cf. **chapitre 1**, fig. 1.1), qui contient des feuilles de bouleaux nains parfaitement conservées, idéales pour la datation au radiocarbone, semble prometteuse. Les premières dates obtenues sur cette séquence indiquent un taux de sédimentation similaire à celui du lac d'Igaliku. Concernant l'Établissement Oriental, un effort de datation sur la séquence d'une tourbière proche du lac 548, permettra d'interpréter le diagramme pollinique réalisé par Émilie Gauthier (données non publiées) et qui documente l'impact de l'agriculture médiévale sur la végétation du secteur de Qassiarsuk/*Brathahild*. Dans le même secteur, la séquence de Qunguliussaq a un intérêt double : (i) les 4,5 mètres de sédiment présentent de grandes similitudes avec la séquence d'Igaliku pour les événements climatiques holocènes (8200 BP, 5000 BP, Néoglaciation) ; (ii) ses versants fortement pentés, sableux et instables, développés sur les grès rouges de la formation d'Eriksford, en font un site sensible à l'érosion causée par la pression pastorale. Aussi, avec les ruines d'une ferme viking installée à quelques mètres seulement du rivage, le site 547 semble être l'objet d'étude idéal pour caractériser l'impact de l'agriculture médiévale sur des petits systèmes lacustres.

Sur le plan méthodologique, si la faible quantité de matière organique figurée disponible empêche l'établissement de chronologies très précises (cf. **chapitre 1**) et donc l'estimation fiable des flux de matière, l'analyse des paramètres géochimiques révèle avec une grande lisibilité l'évolution de l'érosion des sols due aux phases d'emprise et de déprise agropastorales (**chapitre 6**). Aussi, l'étude des paramètres, biogéochimiques et isotopiques, sensibles aux activités agricoles (dispersion d'effluents d'élevage liée au pâturage et à l'amendement des sols dans le bassin versant du lac), sont des axes analytiques

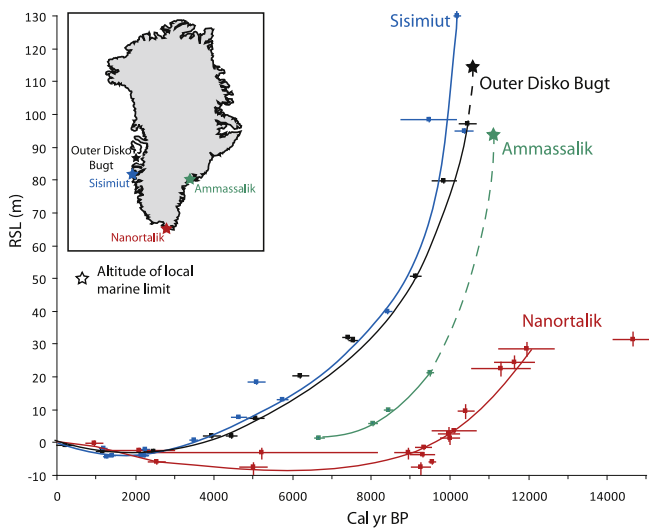
à privilégier pour une lisibilité accrue des pratiques agricoles médiévales.

#### *Normu Saqqaata Tasia : un lac sous influence éolienne*

Bien que des projets aient été menés dans le fjord d'Igaliku (Lassen *et al.*, 2004), aucune étude n'a encore été conduite en milieu continental pour évaluer directement, et à haute résolution, l'importance et la variabilité de l'activité éolienne au Sud du Groenland. Le lac de *Normu Saqqaata Tasia* (cf. **chapitre 1**, fig. 1.2), situé dans le secteur du *Vatnahverfi* ne semble pas être adapté à l'étude de l'impact des activités humaines. Sa situation géomorphologique, dans l'axe d'une plaine alluviale glaciaire balayée parallèlement par des vents dominant ouest/sud-ouest (Cappelen *et al.*, 2001), place le lac sous un flux détritique éolien intense qui *a priori* devrait masquer tout impact de l'activité humaine sur la sédimentation. L'étude de cette séquence doit être envisagée sous l'angle paléoclimatique. L'objectif serait de caractériser l'activité éolienne holocène dont la contribution dans les flux détritiques régionaux est encore mal comprise. L'étude portera principalement sur la caractérisation granulométrique à haute résolution de l'intégralité de la séquence accompagnée par l'étude d'un profil pédologique du bassin versant. Les résultats déjà obtenus indiquent une forte variabilité de la granulométrie le long de la séquence en lien avec des fluctuations d'ordre séculaire à pluri-décennal. Le caractère hautement multimodal de la distribution granulométrique (des argiles aux sables) permet aisément sa décomposition en sous-populations granulométriques (*e.g.* Sun *et al.*, 2002 ; Prins *et al.*, 2007) qui peuvent être directement liées aux processus de transport et de dépôt (hydraulique, éolien, énergies mises en jeu). Les résultats obtenus pourront être comparés aux aérosols de la carotte de glace de GISP2 (O'Brien *et al.*, 1995) et interprétés dans le contexte de la circulation atmosphérique de l'Atlantique Nord.

#### *Les séquences d'émersion (Igaliku/Normu/Paamiut)*

Une datation radiocarbone effectuée sur la séquence de Paamiut (62°N) (site Paamiut Nord, cf. **chapitre 1**, fig. 1.2) révèle un taux de sédimentation beaucoup trop faible (10000 ans pour 57 cm) pour que plus de temps et de moyens y soient consacrés. L'idée que cette séquence puisse être exploitée en tant que référentiel non anthropisé (**chapitre 1**) est donc abandonnée. Cette séquence possède néanmoins une



**Fig. 7.7** Amplitude du rebond isostatique depuis 15 000 ans BP évalué à partir des séquences lacustres et littorales du sud du Groenland. Synthèse publiée par Long *et al.* (2011).

caractéristique intéressante commune avec celles des lacs d'Igaliku et de Normu : une transition rapide d'une sédimentation en milieu marin vers une sédimentation en milieu lacustre (**chapitre 3**). Cette transition a lieu assez tôt dans l'histoire sédimentaire des trois lacs, respectivement à  $9500 \pm 200$ ,  $9800 \pm 300$  et  $10060 \pm 150$  ans cal. BP pour Igaliku, Normu et Paamiut. La datation des transitions marin/lacustre permet de reconstruire l'évolution du niveau marin relatif qui est principalement lié à l'ajustement glacio-isostatique (Long *et al.*, 2011). La détermination de la limite stratigraphique marin/lacustre est établie sur la base de l'étude des diatomées et des paramètres sédimentologiques. Un intérêt particulier sera porté au rapport carbone/souffre qui s'avère être un marqueur particulièrement efficace de l'émersion des bassins (**chapitre 3**). Cette étude contribuera au volume croissant de données de bassin d'émersion du Groenland (Long *et al.*, 1999 ; Weidick *et al.*, 2004 ; Sparrenbom *et al.*, 2006a ; Sparrenbom *et al.*, 2006b ; Long *et al.*, 2009 ; Bennike *et al.*, 2011 ; Long *et al.*, 2011 ; Long *et al.*, 2012) qui fournit maintenant des contraintes locales et régionales sur le comportement holocène du niveau relatif de la mer et donc de l'histoire de la calotte polaire. Ces données sont essentielles pour l'interprétation des changements actuels et futurs de la calotte glaciaire groenlandaise. Un article compilant les données des trois séquences précitées est en préparation.

Les lacs du Sud du Groenland, par leur histoire née du dernier retrait glaciaire, par leur sensibilité à enregistrer les variations climatiques, par leur capacité à délivrer

l'histoire des populations qui ont occupé leurs rives, permettent une rétro-observation pertinente des mutations environnementales survenues au cours des derniers milliers d'années. Ils constituent aussi un formidable observatoire des mutations à venir induites par le réchauffement climatique spectaculaire de la région arctique.

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*Au Moyen Age, lorsque les Vikings ont découvert le Groenland, il y avait encore moins de glace qu'aujourd'hui. C'est pour cela qu'ils l'ont appelé le « pays vert » \**





**Annexes**





## Annexe 1

### Listes des publications et communications relatives aux programmes ULTIMAGRI & ANR Green Greenland (UMR CNRS 6249 - juin 2012)

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#### Articles dans des revues internationales à comité de lecture

##### Articles publiés

GAUTHIER E., BICHET V., **MASSA C.**, PETIT C., VANNIERE B., RICHARD H. (2010) – Pollen and Non Pollen Palynomorph evidence of medieval farming activities in South Western Greenland. *Vegetation History and Archaeobotany*, 19:427–438. DOI 10.1007/s00334-010-0251-5.

**MASSA C.**, BICHET V., GAUTHIER E., PERREN B., MATHIEU O., PETIT C., MONNA F., GIRAUDEAU J., LOSNO R., RICHARD H. (2012) - A 2500 year record of natural and anthropogenic soil erosion in South Greenland. *Quaternary Science Review*, 32, p.119-130. doi:10.1016/j.quascirev.2011.11.014.

PERREN B., **MASSA C.**, BICHET V., GAUTHIER E., MATHIEU O., PETIT C., RICHARD H. (2012) - A paleoecological perspective on 1450 years of human impacts from a lake in South Greenland. *The Holocene*. DOI: 10.1177/0959683612437865

**MASSA C.**, PERREN B., GAUTHIER E., BICHET V., PETIT C., RICHARD H. (2012) - A 10 ka record of environmental change from Lake Igaliku, South Greenland. *Journal of Palaeolimnology*. DOI 10.1007/s10933-012-9594-5.

##### Article sous presse

BICHET V., GAUTHIER E., **MASSA C.**, PERREN B., PETIT C., MATHIEU O., RICHARD H. (2012) - History and impacts of South Greenland farming activities: an insight from lake deposits. *Polar Record*.

##### Article soumis (en révision)

MASSON-DELMOTTE V., SWINGEDOUW D., LANDAIS A., SEIDENKRANTZ M.S., GAUTHIER E., BICHET V., **MASSA C.**, PERREN B., JOMELLI V., ADALGEIRSDOTTIR G., HESSELBJERG CHRISTENSEN J., ARNEBORG J., BHATT U., WALKER D.A., ELBERLING B., GILLET-CHAULET F., RITZ C., GALLÉE H., VAN DEN BROEKE M., FETTWEIS X., DE VERNAL A., VINTHER B. - Greenland climate change: from the past to the future. Soumis à *Climate Change*.

#### Articles dans des revues nationales à comité de lecture

##### Publications en ligne

**MASSA C.** (2010) - L'implantation médiévale scandinave de la côte sud-ouest du Groenland comme la limite du modèle agro-pastoral importé d'Europe du nord : Implications paléoenvironnementales. Sciences Humaines Combinées, 2010, 5, Limite/Limites. *Revue en ligne des écoles doctorales LISIT-LETS* (<http://revuesshs.u-bourgogne.fr/lisit491/document.php?id=627>)

#### Chapitres d'ouvrages

**MASSA C.**, BICHET V., GAUTHIER E., PETIT C., RICHARD H. (2011) - Vers l'Amérique : l'implantation médiévale scandinave de la côte sud-ouest du Groenland. Approches historiques et premiers résultats des études paléoenvironnementales. In *Peuplements et préhistoire en Amériques*, sous la direction de D. VIALOU, Editions du CTHS, Paris, pp. 181-191.

BICHET V., GAUTHIER E., **MASSA C.**, PETIT C., RICHARD H. (2012) - Aux limites de l'agriculture : les archives sédimentaires de la colonisation médiévale au Groenland. In *Des Climats et des Hommes*, sous la direction de J.F. BERGER, Ed. La découverte, Paris, pp. 307-325.

GAUTHIER E., RICHARD H., **MASSA C.**, PERREN B., BICHET V., MILLET L. (2012) L'agriculture médiévale et contemporaine au Groenland : retro-observation des pratiques et conséquences sur l'environnement. In *Etudier les interactions hommes-milieux Questions et réflexions autour des pratiques de la recherche scientifique en environnement*. Eds Quae – Collections Indisciplines. Soumis.

#### Communications – colloques internationaux

BICHET V., PETIT C., GAUTHIER E., VANNIERE B., RICHARD H., **MASSA C.** - Towards America: environmental consequences of the Viking occupation in Greenland. 133e congrès CTHS, Migrations, transferts et échanges de part et d'autre de l'Atlantique, Québec, Canada. Juin 2008 – Communication orale.

GAUTHIER E., BICHET V., RICHARD H., VANNIERE B., **MASSA C.**, PETIT C. - Environmental consequences of the Norse occupation in south Greenland: first results of pollen and NPP's data from a peat bog (Qassiarsuk). 3rd International Workshop on Quaternary Non-Pollen Palynomorphs, Padova, Italia, June 25-28, 2008 – Poster.



GAUTHIER E., **MASSA C.**, BICHET V., PETIT C., GRISEY H., VANNIÈRE B., RICHARD H. - The impact of Norse occupation in south Greenland : pollen, NPP's and sedimentological analyses from lakes and peat deposit. XIIth International Palynology Congress, Bonn, Germany, August 30 – September 5, 2008 – Poster.

PERREN B., MILLET L., **MASSA C.**, GAUTHIER E., BICHET V., PETIT C., VANNIERE B., RICHARD H. Sizing up the effects of the Norse in Greenland: diatoms, pollen, NPPs, chironomids and sedimentological analyses from Lake Igaliku, south Greenland. 8th European Palaeobotany and Palynology Conference - Symposium Pollen Plus! Multidisciplinary records of environmental change over the last 1000 years. Budapest, Hungary. Juillet 2010. Communication orale.

**MASSA C.**, BICHET V., GIRAUDEAU J., PETIT C., VANNIERE B., MONNA F., GAUTHIER E., RICHARD H. - Contribution to the Holocene North Atlantic wind activity reconstruction from Lake Igaliku, South Greenland. Abstract PP11F-02, 2010 Fall Meeting, AGU, San Francisco, USA. 13-17 December 2010. Communication orale.

BICHET V., **MASSA C.**, GAUTHIER E., PERREN B., PETIT C., RICHARD H., VANNIERE B. - History and impacts of South Greenland farming activities: a new insight from lake deposits. International Conference Polar Worlds - Environmental and Social Sciences to Understand Observed Changes. Paris, France, 26-28 January 2011. Communication orale.

**MASSA C.**, BICHET V., GIRAUDEAU J., PERREN B., PETIT C., GAUTHIER E., RICHARD H. - Contribution to North Atlantic climate history from Lake Igaliku, South Greenland. International Conference Polar Worlds - Environmental and Social Sciences to Understand Observed Changes. Paris, France, 26-28 January 2011. Communication orale.

GAUTHIER E., **MASSA C.**, BICHET V., PERREN B., PETIT C., RICHARD H. - From first Caribou to Norse sheep: impact of grazing in south Greenland. AGU Chapman Conference on Climates, Past Landscapes, and Civilizations. Santa Fe, New Mexico, USA. 21-25 March, 2011. Poster.

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**MASSA C.**, BICHET V., GAUTHIER E., PETIT C., MILLET L., PERREN B., VANNIERE B., RICHARD H. - Identification des indices environnementaux d'anthropisation dans la séquence sédimentaire historique du lac d'Igaliku (Groenland). Colloque Q7 : Bio-

géosystèmes continentaux quaternaires : variabilité climatique et anthropisation / AFEQ - Besançon, février 2010. Communication orale.

BICHET V., GAUTHIER E. – Aux limites de l'agriculture : la colonisation médiévale du Groenland. Les archives sédimentaires lacustres. Colloque international INRAP, Cité des Sciences, Météo-France Des Climats et des Hommes, glaciologie, climatologie, archéologie, histoire. 19 – 21 novembre 2010, Paris. Communication orale.

GAUTHIER E., PERREN B., **MASSA C.**, BICHET V., PETIT C., RICHARD H. - L'impact des herbivores sur la végétation en zone subarctique : l'étude multi-proxy de la séquence lacustre d'Igaliku (sud Groenland). Symposium APLF-APPLE « Palynologie et diversités : marqueurs, milieux, méthodes, modèles, applications ». Meudon, 21-23 septembre 2011. Communication orale.

**MASSA C.**, BICHET V., GAUTHIER E., PERREN B., PETIT C., RICHARD H. – Evolution holocène du système lacustre d'Igaliku (Groenland). 13<sup>e</sup> colloque de l'Association des Sédimentologues Français, Dijon, Novembre 2011. Communication orale.

**MASSA C.**, BICHET V., GAUTHIER E., PERREN B., MATHIEU O., PETIT C., MONNA F., RICHARD H. – Quantification des taux d'érosion naturelle et anthropique depuis 2500 ans à partir de l'analyse des sédiments lacustres du sud du Groenland. 13<sup>e</sup> colloque de l'Association des Sédimentologues Français, Dijon, Novembre 2011. Communication orale. Poster.



## **Annexe 2**

### **Données analytiques de la séquence holocène du lac d'Igaliku**

Chronologie, CNS, taux d'accumulation, granulométrie

support de la publication Massa et al., JOPL 2012 / chapitre 3

Les données complètes (pollen, diatomées), sont téléchargeables à l'adresse  
<http://www.ncdc.noaa.gov/paleo/pubs/jopl2012arctic/jopl2012arctic.html>

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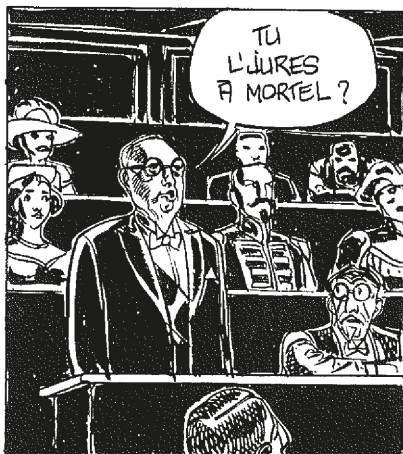
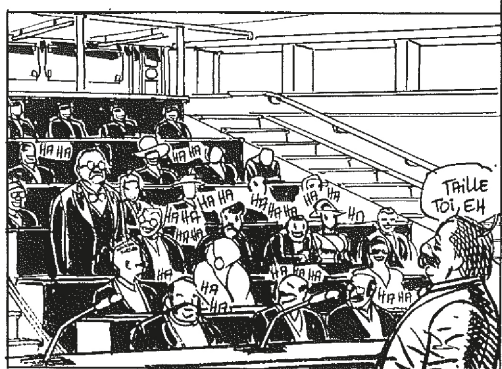
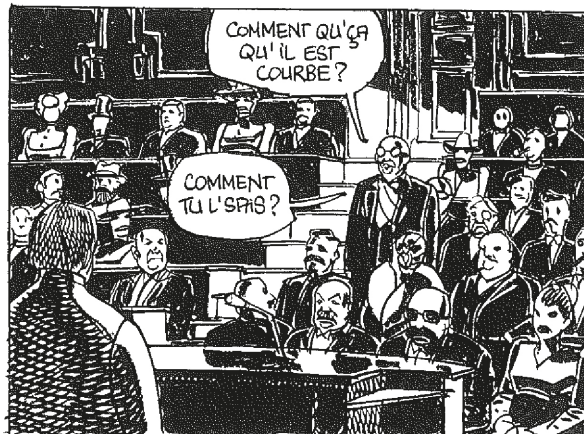






top cm	bottom cm	middle cm	agetop cal a BP	agebot cal a BP	agemid cal a BP	water %	C %	N %	S %	MARmin mg.cm <sup>-2</sup> .yr <sup>-1</sup>	MARorg mg.cm <sup>-2</sup> .yr <sup>-1</sup>	Median µm	sup200 % vol	sup255 % vol
313,2	314,2	313,70	9681,3	9685,4	9683,4	31,3	0,675	0,091	0,614	349,36	5,51			
314,2	315,2	314,70	9685,4	9689,6	9687,5	30,6	0,616	0,084	0,575	328,67	4,72			
315,2	316,2	315,70	9689,6	9693,7	9691,7	32,3	0,645	0,089	0,659	328,25	4,94			
316,2	317,2	316,70	9693,7	9697,9	9695,8	33,0	0,667	0,084	0,735	323,57	5,04			
317,2	318,2	317,70	9697,9	9702	9700	31,7	0,607	0,081	0,625	333,74	4,73			
318,2	319,2	318,70	9702	9706,2	9704,1	30,2	0,595	0,078	0,630	328,57	4,56			
319,2	320,2	319,70	9706,2	9710,4	9708,3	27,4	0,480	0,064	0,556	376,41	4,20			
320,2	321,2	320,70	9710,4	9714,5	9712,4	27,4	0,491	0,062	0,549	391,05	4,47			
321,2	322,2	321,70	9714,5	9718,7	9716,6	26,7	0,432	0,057	0,475	370,97	3,72			
322,2	323,2	322,70	9718,7	9722,8	9720,7	28,9	0,529	0,074	0,573	363,25	4,47			
323,2	324,2	323,70	9722,8	9727	9724,9	29,5	0,568	0,078	0,598	363,14	4,81			
324,2	325,2	324,70	9727	9731,1	9729	29,4	0,583	0,075	0,623	354,00	4,81			
325,2	326,2	325,70	9731,1	9735,3	9733,2	29,8	0,542	0,073	0,564	362,63	4,58			
326,2	327,2	326,70	9735,3	9739,4	9737,4	29,2	0,559	0,073	0,630	360,18	4,69			
327,2	328,2	327,70	9739,4	9743,6	9741,5	29,1	0,514	0,070	0,625	372,29	4,45			
328,2	329,2	328,70	9743,6	9747,7	9745,7	27,4	0,472	0,066	0,518	387,22	4,25			
329,2	330,2	329,70	9747,7	9751,9	9749,8	27,8	0,528	0,066	0,499	380,55	4,68			
330,2	331,2	330,70	9751,9	9756	9754	25,8	0,450	0,058	0,422	387,01	4,05			
331,2	332,2	331,70	9756	9760,2	9758,1	25,1	0,402	0,056	0,461	378,96	3,54	5,2	0,00	0,00
332,2	334,2	333,20	9760,2	9768,5	9764,4	29,5	0,571	0,075	0,520	343,49	4,57			
334,2	336,2	335,20	9768,5	9776,8	9772,7	30,5	0,609	0,080	0,549	337,26	4,79			
336,2	338,2	337,20	9776,8	9785,1	9781	33,2	0,718	0,092	0,718	315,11	5,29			
338,2	340,2	339,20	9785,1	9793,4	9789,3	33,6	0,697	0,091	0,597	320,22	5,22			
340,2	342,2	341,20	9793,4	9801,7	9797,6	32,3	0,665	0,087	0,658	330,73	5,14			
342,2	344,2	343,20	9801,7	9810	9805,9	32,8	0,657	0,086	0,673	325,84	5,00			
344,2	346,2	345,20	9810	9818,3	9814,2	33,2	0,650	0,084	0,579	322,53	4,90			
346,2	348,2	347,20	9818,3	9826,7	9822,5	27,5	0,505	0,065	0,467	387,85	4,56			
348,2	350,2	349,20	9826,7	9835	9830,8	33,2	0,697	0,088	0,611	342,01	5,57			
350,2	351,2	350,70	9835	9839,1	9837	28,8	0,539	0,072	0,346	361,81	4,54			
351,2	352,2	351,70	9839,1	9843,3	9841,2	26,0	0,455	0,063	0,425	413,74	4,38	5,2	0,00	0,00
352,2	354,2	353,20	9843,3	9851,6	9847,4	31,9	0,592	0,077	0,436	392,40	5,42			
354,2	356,2	355,20	9851,6	9859,9	9855,7	30,6	0,608	0,079	0,483	349,70	4,96			
356,2	358,2	357,20	9859,9	9868,2	9864	30,0	0,587	0,076	0,525	361,76	4,95			
358,2	360,2	359,20	9868,2	9876,5	9872,3	26,6	0,462	0,061	0,379	367,96	3,95			
360,2	362,2	361,20	9876,5	9884,8	9880,7	27,9	0,487	0,063	0,496	366,34	4,15			
362,2	364,2	363,20	9884,8	9893,1	9889	29,0	0,515	0,069	0,508	356,70	4,28			
364,2	366,2	365,20	9893,1	9901,4	9897,3	27,5	0,502	0,064	0,546	361,13	4,22			
366,2	368,2	367,20	9901,4	9909,7	9905,6	29,2	0,524	0,069	0,527	334,35	4,08			
368,2	370,2	369,20	9909,7	9918	9913,9	29,2	0,579	0,070	0,532	348,03	4,70			
370,2	371,2	370,70	9918	9922,2	9920,1	31,5	0,568	0,076	0,429	334,81	4,43			
371,2	372,2	371,70	9922,2	9926,3	9924,3	30,0	0,513	0,071	0,582	336,99	4,02	6,3	0,00	0,00
372,2	374,2	373,20	9926,3	9934,7	9930,5	30,1	0,531	0,071	0,469	343,89	4,25			
374,2	376,2	375,20	9934,7	9943	9938,8	28,4	0,507	0,067	0,590	360,83	4,26			
376,2	378,2	377,20	9943	9951,3	9947,1	27,7	0,452	0,059	0,446	365,64	3,84			
378,2	380,2	379,20	9951,3	9959,6	9955,4	25,2	0,453	0,057	0,433	376,12	3,96			
380,2	382,2	381,20	9959,6	9967,9	9963,7	29,1	0,461	0,064	0,468	356,08	3,82			
382,2	384,2	383,20	9967,9	9976,2	9972	27,7	0,487	0,067	0,510	368,10	4,17			
384,2	386,2	385,20	9976,2	9984,5	9980,3	26,3	0,411	0,056	0,465	376,40	3,59			
386,2	388,2	387,20	9984,5	9992,8	9988,7	27,9	0,426	0,058	0,471	365,54	3,62			
388,2	390,2	389,20	9992,8	10001	9997	25,5	0,357	0,046	0,465	395,03	3,27			
390,2	391,2	390,70	10001	10005	10003	20,9	0,254	0,033	0,246	472,08	2,77			
391,2	392,2	391,70	10005	10009	10007	21,5	0,246	0,038	0,295	442,43	2,52	7,2	0,00	0,00
392,2	394,2	393,20	10009	10018	10014	24,0	0,276	0,039	0,343	412,59	2,64			
394,2	396,2	395,20	10018	10026	10022	24,2	0,275	0,040	0,363	474,44	3,02			
396,2	398,2	397,20	10026	10034	10030	25,0	0,283	0,041	0,369	389,86	2,55			
398,2	400,2	399,20	10034	10043	10039	25,1	0,274	0,040	0,360	397,72	2,52			





Daniel Goossens

Extrait de «La vie d'Einstein, tome 2 : Le révolté »

