Morpho-tectono-magmatic evolution and reactivation of ultra-distal magma-poor rifted margins : the fossil Err-Platta Ocean-Continent-Transition (SE Switzerland) and comparison to present-day analogues

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Soutenue le **30 novembre 2017**

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Discipline : Géologie

Spécialité : Tectonique

Evolution morpho-tectonique et magmatique polyphasée des marges ultra-distales pauvres en magma: la transition océan-continent fossile de l'Err et de la Platta (SE Suisse) et comparaison avec des analogues actuels.

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Piz Platta

été 2015

L'imagination est plus importante que la connaissance. La connaissance est limitée alors que l'imagination englobe le monde entier, stimule le progrès, suscite l'évolution. Albert Einstein

…à tous les dyslexiques, à tous ceux qui ne peuvent, ou n'ont pu faire d'études…

Avant-Propos

Les travaux présentés dans ce manuscrit de thèse font partie intégrante de la recherche développée à l'Université de Strasbourg depuis plusieurs années sur la compréhension des transitions océan-continent. Ces travaux se placent dans la suite de plusieurs projets de recherche sur la compréhension des marges peu-magmatiques fossiles (Téthys Alpine) et actuelles (Ibérie-Terre Neuve). Au cours des dernières années la recherche sur les marges s'est de plus en plus focalisée sur les parties distales. Cette étude traite de l'architecture des marges ultra-distales peu-magmatiques et de leur transition vers le domaine océanique. Cette thèse a été encadrée par Gianreto Manatschal de l'Université de Strasbourg et par Marc Lescanne de Total à Pau.

Au début, mon sujet de thèse était axé sur la transition des marges distales vers l'accrétion océanique et la formation du domaine appelé « outer highs », avec une étude des marges Ibérie-Terre Neuve et sur des analogues actuels et fossiles. Les campagnes de terrain réalisées dans les Grisons (Alpes Suisse) se sont révélées beaucoup plus prometteuses qu'envisagé au départ, ce qui a réorienté la thèse en focalisant sur les nouvelles observations de terrain. Je présente dans cette thèse mes résultats obtenus après ces campagnes de terrain (Chapitre 2 à 4, Partie II). L'aspect de comparaison avec les systèmes actuels est abordé dans la discussion (Partie III) pour remettre mes observations de terrain à l'échelle des marges, mais n'est pas présenté comme un travail à part entière.

Le soutien financier de ce contrat doctoral a été apporté par Total et géré par le CNRS. Sans ce soutien financier, qui a permis de financer plusieurs longues missions de terrain (33 jours l'été 2015 et 23 jours l'été 2016), ainsi que de nombreuses excursions sur d'autres chantiers, workshops et conférences, cette recherche n'aurait pas pu être menée à bien.

CONTENTS

Résumé étendu

L'évolution de la théorie de la dérive des continents vers celle de la tectonique des plaques est intimement liée au développement de nouvelles méthodes et au progrès de la géophysique marine. Ces nouvelles techniques permettent d'imager les domaines océaniques, d'augmenter l'échelle d'observation et ainsi de mieux comprendre les processus de rifting et d'expansion océanique. Cela a permis de décrire et de modéliser les processus qui expliquent les limites de plaques actives comme les dorsales océaniques et les zones de subduction. Durant le développement de ces découvertes en domaine océanique, l'intérêt pour l'étude des chaines de montagne et des marges a été momentanément diminué. Alors que les chaines de montagne restent le terrain d'étude privilégié des géologues de terrain, les marges deviennent le lieu d'exploration et d'étude principal des compagnies pétrolières. La difficulté d'accès et les coûts d'exploration des domaines distaux des marges ont retardé et complexifié l'étude de ces domaines. Cependant, trois découvertes majeures ont réactivé l'intérêt des études des marges distales : 1) les forages profonds sur la marge Ibérique et la découverte inattendue de manteau exhumé (*Boillot et al.*, 1980), 2) la découverte de réservoirs d'hydrocarbure dans les parties profondes des marges, 3) le développement de nouvelles méthodes haute définition permettant d'imager les marges à grande échelle, jusqu'à la croûte. L'imagerie et les forages des parties distales des marges ont révélé des résultats imprévus et non compatibles avec la vision «classique» des limites de plaques et de la tectonique des plaques. De nouvelles questions fondamentales ont été posées grâce à ces nouveaux résultats de l'exploration des marges distales. Actuellement, par manque de données de forages dans la « Transition Océan Continent » (TOC), la communauté scientifique manque d'observations pour comprendre et expliquer certains mécanismes complexes, lesquels sont : l'extension de la croûte et de la lithosphère ainsi que les premiers stades de l'océanisation. En effet, la formation de nouveaux océans, la structure des domaines liés et les processus associés sont encore mal compris. Bien que les progrès récents de l'imagerie sismique fournissent des images de haute résolution et que la modélisation dynamique permette de proposer des modèles évolutifs, le manque d'observations directes et d'échantillons rend difficile l'étalonnage et la mise à l'épreuve de ces différents modèles. Les analogues fossiles des marges distales, préservés dans les orogènes de collision comme les Alpes, sont donc d'une importance majeure. Ces analogues fossiles ont été décrits par les pionniers de la géologie alpine qui ont proposé les premiers concepts associés aux ophiolites des marges fossiles dans les orogènes (*Steinmann*, 1925). La reconstruction des transitions océan-continent dans les Alpes et la comparaison avec les marges actuelles forées et imagées de l'Ibérie ne permettent pas seulement de mieux comprendre les étapes finales du rifting, mais elles mettent également en évidence l'importance de l'héritage des structures de rifts lors de leur réactivation dans la formation des orogènes. Ces premiers résultats, basés sur des exemples de marges distales sur terre et en mer, montrent que ces domaines sont vraiment différents des parties plus proximales des marges. L'identification de ces domaines, caractérisés par de la croûte continentale extrêmement amincie et du manteau exhumé, conduit à de nouveaux champs de recherche incluant : la compréhension des interactions entre la déformation, le magmatisme, les circulations de fluides et la sédimentation durant l'amincissement crustal, l'exhumation mantellique ou encore la rupture lithosphérique.

A partir de ces constats, l'objectif de cette thèse est de compléter et d'améliorer la compréhension de la formation des marges distales par une approche axée sur les observations d'un analogue de terrain. Ces observations seront comparées aux données de marges distales actuelles. Cette étude est centrée sur l'analyse de reliques de domaine de croûte hyper-étirée et de manteau exhumé de la Téthys Alpine exposées dans la nappe de l'Err et de la Platta au Sud-Est de la Suisse. A travers une étude classique de terrain, le caractère polyphasé des processus tectoniques, magmatiques et l'évolution des fluides associés de ces domaines seront décrits et comparés à des systèmes actuels. Les questions posées dans cette étude se répartissent en trois axes principaux.

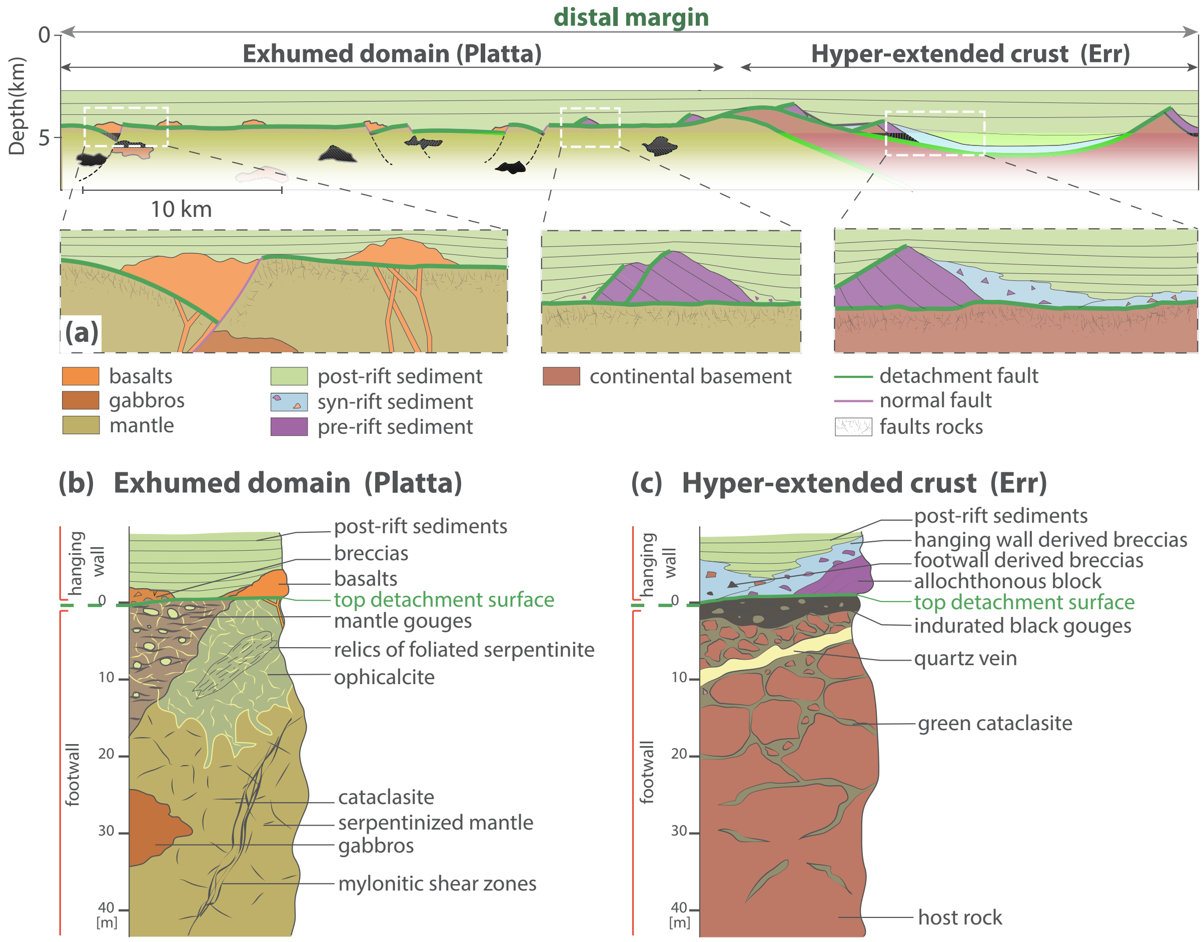
- Comment, quand et dans quelles conditions se produisent les dernières phases de l'amincissement crustal ? Comment la rupture lithosphérique se met-elle en place ? Est-ce que les failles de détachement sont à l'origine de l'amincissment de la croûte et de l'exhumation du manteau ? Et si oui, comment ? Où s'enracinent ces structures en profondeur ? Comment ces structures accommodent-elles la déformation et comment se développent-elles dans le temps et dans l'espace ?
- Quelle est l'architecture d'un domaine de manteau exhumé, comment les processus magmatiques et tectoniques interagissent-ils durant sa formation et quel est le rôle des fluides durant l'exhumation ?
- Quel est le rôle de l'héritage durant l'extension et la reprise en compression des marges distales ?

L'accès à un analogue de terrain bien exposé et de taille importante peut fournir des informations décisives et peut permettre de trouver des réponses aux questions difficiles à résoudre pour les marges actuelles, en raison du manque de données disponibles. La comparaison avec les systèmes actuels remet en contexte, à l'échelle de la sismique, les observations obtenues.

En complément d'une partie introductive et d'une partie de discussion, le manuscrit de thèse est composé de 3 chapitres principaux comprenant chacun un article scientifique précédé et suivi d'une introduction, d'un résumé des résultats principaux et des questions engendrées par cette étude. Des données supplémentaires et des photos complémentaires aux études de terrain présentées dans les articles scientifiques sont disponibles dans les annexes (Annexes 1). La première partie de la thèse comporte la présentation de la zone d'étude, les nappes de l'Err et de la Platta, et inclut une approche méthodologique qui permet de cartographier la zone et d'en extraire les relations de terrain liées à l'architecture du rift par rapport aux structures dues à la compression Alpine. Une technique conceptuelle de restauration permettra de proposer une restauration des nappes de l'Err et de la Platta au Jurassique, et de discuter les relations entre les structures héritées du rift et leur réactivation lors de la collision. La deuxième partie de la thèse comporte une description de terrain du système de failles de détachement observable dans la nappe de l'Err. Ce système de failles de détachement constitue la partie distale de la marge Adriatique et permet de discuter la géométrie, l'évolution et le rôle des failles de détachement dans la formation des domaines hyper-amincis des marges pauvres en magma. La troisième partie de la thèse comporte une étude de la nappe de Platta qui correspond à un domaine de manteau exhumé. Cette étude a permis de décrire l'évolution polyphasée d'un domaine de manteau exhumé en mettant en évidence les relations entre les processus tectoniques et magmatiques et de souligner une complexe histoire des fluides. Les résultats principaux de ma thèse, peuvent être résumés comme suit.

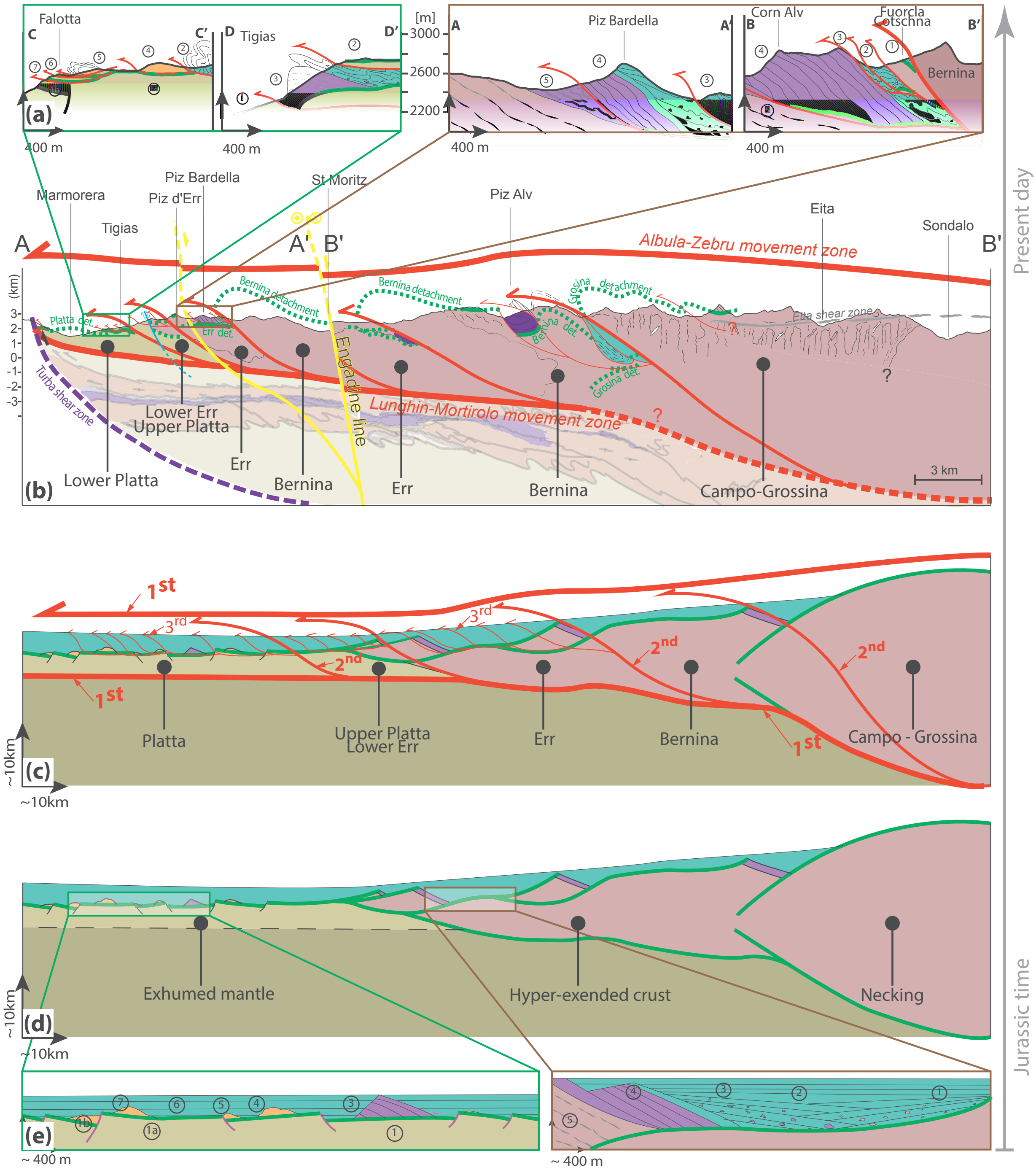
1) Définir l'héritage du rift et décrire son rôle durant la réactivation en compression.

Il est communément accepté que les orogènes de collision proviennent de la réactivation de marges. L'identification de l'héritage du rift et la façon dont ce dernier contrôle l'architecture de l'orogène reste un point débattu. J'ai analysé l'importance de l'héritage du rift lors de sa réactivation, avec des couches non homogènes et linéaires (non « layer-cake ») des domaines de l'Err et de la Platta (Sud-Est de la Suisse). Ces nappes représentent les anciennes parties distales et ultra-distales pauvres en magma de la marge Adriatique de la Téthys alpine. J'ai redéfini des critères d'identification généraux (Fig. 1) pour déterminer les structures de rift préservées dans les orogènes qui incluent : 1) des roches de faille caractéristiques avec une signature chimique mantellique, 2) des brèches tecto-sédimentaires remaniant des roches de socle exhumé et évoluant graduellement vers des dépôts syn- à post-rift.



Résumé étendu - Fig. 1: **(a)** *Coupe schématique de la marge distale Adriatique montrant l'architecture 1er ordre avant la réactivation Alpine et zooms sur différents sites illustrant la stratigraphie et les différentes relations structurales. Logs conceptuels représentant les marqueurs clé d'une faille de détachement dans le domaine du manteau exhumé* **(b)***, et le domaine de croûte hyper-étirée* **(c)**.

A partir de l'étude de ces marqueurs, je propose une méthode qui permet de : 1) cartographier les failles de détachement liées au rift, 2) analyser leur rôle durant la réactivation et la formation d'écailles, et 3) définir des chevauchements de 1er, 2nd et 3ème ordre. Dans cette étude il a été possible de montrer que les chevauchements réactivaient souvent les failles de détachement dans le domaine de manteau exhumé (nappe de Platta), alors que dans la croûte hyper-étirée (nappe de l'Err) les réactivations sont plus complexes et partielles. En effet les systèmes de détachement sont mieux préservés dans la nappe de l'Err que dans celle de la Platta. L'histoire de la déformation alpine et préalpine des nappes de l'Err et de la Platta est ainsi mieux contrainte. Cette étude, à double incidence, permet de proposer une restauration de ces domaines, mais également de mieux comprendre l'importance de l'héritage sur la réactivation alpine (Fig. 2). D'un point de vue plus général, cela peut aider à mieux identifier les reliques des marges distales dans les orogènes. En effet, cette étude montre comment identifier et utiliser les critères de l'héritage de structures de marge distales pour analyser l'architecture complexe des



Cover	Basement	Alpine structures	Jurassic rift structures
basalt syn- and post-rift sediments pre-rift sediments	continental crust serpentinised mantle mantle	D1 first and second order thrusts D1 third order thrust	Extensional fault Normal fault

Résumé étendu - Fig. 2: *Coupe schématique de l'empilement actuel des nappes et des domaines de marges associés montrant l'importance des structures héritées lors de la réactivation.* **(a)** *Coupe actuelle à travers les zones de Bardella-Fuorcla Cotschna et Falotta-Tigias.* **(b)** *Coupe actuelle à travers les nappes Pénninique supérieure et Austroalpine (modifié d'après Mohn et al., 2011).* **(c)** *Architecture simplifiée de la marge Adriatique basée sur la restauration des nappes Austroalpines, avec la localisation des futurs chevauchements alpins de 1er, 2nd, et 3ème ordre.* **(d)** *Architecture de la marge Adriatique avec les différents domaines de la marge.* **(e)** *Restauration des coupes présentées en (a).*

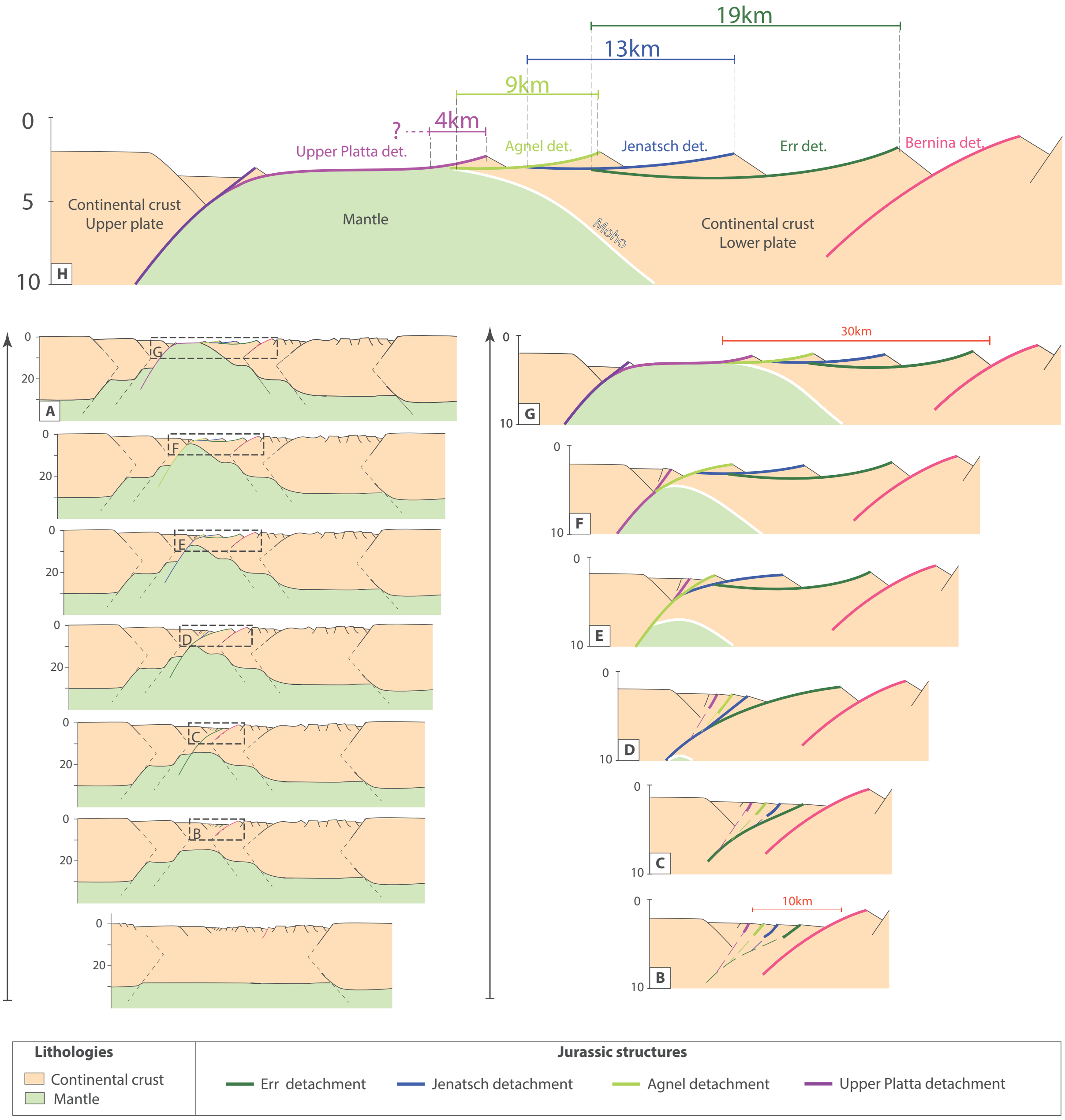
chevauchements observés dans de nombreuses parties internes des chaines de montagnes. Cette partie sera détaillée dans le papier 1 du chapitre 2 de la Partie II de la thèse.

2) L'architecture d'un système de faille de détachement dans une croute hyper-étirée et son rôle sur l'amincissement crustal.

Tandis que les systèmes de détachement liés à l'extension post-orogénique ou aux dorsales ultra-lentes ont déjà été largement décrits, les exemples liés à l'hyper-extension et la formation de marges pauvres en magma sont plus rares. Ici je décris l'un des exemples de système de détachements en domaine continental, en contexte d'amincissement extrême le mieux exposé et décrit au monde, observable sur plus de 200km² dans la nappe de l'Err au Sud-Est de la Suisse. En m'appuyant sur les nombreuses études précédemment menées sur la zone, ainsi que sur mes nouvelles observations, j'ai réalisé une carte détaillée permettant de discuter l'architecture 3D d'un système de détachement, ainsi que son rôle lors de l'amincissement crustal et l'évolution du domaine en hyper-extension. J'ai montré que le système de détachement présenté dans la zone pouvait être décrit comme étant composé de plusieurs failles de détachements qui se développent en séquence (Err, Jenatsch, Agnel, Platta supérieure ; Fig. 3). L'évolution séquentielle de ces failles permet d'interpréter les failles de détachement grâce au modèle de « rolling hinge ». Toutefois, la présence d'un bassin Permien, ainsi que d'évaporites dans la série pré-rift Triasique peuvent contrôler fortement la géométrie locale d'une faille de détachement. A partir des observations préexistantes, la façon dont les failles de détachement sont liées les unes aux autres reste très peu claire. Les observations globales réalisées dans la nappe de l'Err permettent de décrire comment un système de détachement fonctionne dans la partie la plus distale d'une marge. Cette partie sera détaillée dans le papier 2 du chapitre 3 de la Partie II de la thèse.

3) L'évolution polyphasée de la tectonique, du magmatisme et des circulations de fluides liés à l'exhumation mantellique dans les parties ultra-distales des marges pauvres en magma.

En dépit du fait que beaucoup d'études s'intéressent au manteau exhumé sur les dorsales ultra-lentes et les marges pauvres en magma, il existe encore de nombreuses questions concernant l'architecture 3D, l'évolution du magma, des fluides et de la thermicité de ces domaines. En effet, les observations de la sismique réflexion de ces domaines montrent que le socle est très structuré avec une évolution spatiale complexe. Leur évolution morpho-tectonique et magmatique reste inconnue. Cette étude décrit l'architecture 3D d'un domaine de manteau exhumé préservé dans la nappe de la Platta au Sud-Est de la Suisse, et définit les étapes, le



Résumé étendu - Fig. 3: *Coupe schématique montrant le développement des différentes failles de détachement selon le modèle du « rolling hinge » conduisant à la rupture lithosphérique continentale et à l'exhumation du manteau.*

déroulement et les processus contrôlant son évolution. Une cartographie détaillée de la nappe de la Platta m'a permis de documenter la morphologie et la nature du toit du socle d'un domaine de manteau exhumé. Ces nouvelles observations ont permis de caractériser l'organisation des structures liées au rift et à l'océanisation notamment avec l'arrivée du magma et des fluides. Mes observations montrent une histoire polyphasée importante (Fig. 4) avec : 1) une histoire de la déformation associée avec l'exhumation du manteau le long de failles de détachement recoupées par des failles normales plus tardives, 2) une morphologie complexe du manteau exhumé recouvert par des roches volcaniques et/ou sédimentaires, 3) une évolution tectonique et magmatique intégrant l'exhumation de gabbros mis en place à des niveaux plus profonds et recouverts par du magmatisme extrusif. L'étude de l'influence des circulations de fluides reliés à la serpentinisation du manteau, la calcification (ophicalcites) tardive, la rodingitisation et la spilitisation ainsi que l'hydrothermalisme, qui affectent le manteau exhumé et le magma associé a été menée en parallèle par des travaux associés (Thèse M. Amann). Les résultats et travaux en cours soulignent l'importance du rôle des fluides, profonds ou océaniques dans les mécanismes de structuration des domaines de l'Err et Platta.

Toutes ces observations fournissent des informations importantes sur l'évolution temporelle et spatiale des systèmes tectoniques, magmatiques et semblent corrélées avec une évolution complexe des fluides associés qui contrôlent la formation des marges ultra-distales pauvres en magma ainsi que des processus qui contrôlent la rupture lithosphérique. L'objectif final étant de comparer les observations de terrain aux transitions océan-continent pauvres en magma actuelles ainsi qu'aux domaines de dorsales ultra-lentes et d'essayer d'améliorer les connaissances sur les processus de rupture lithosphérique.

Les résultats principaux de ma thèse, basée sur une approche de terrain, permettent d'améliorer la connaissance des marges distales dans les TOC pauvres en magma et de mieux comprendre les dernières étapes de formation d'un rift.

Dans un premier temps, j'ai montré l'importance des structures héritées de la transition océan continent dans la localisation de la déformation lors de la réactivation en compression. J'ai proposé une nouvelle cartographie de la zone d'étude (nappe de l'Err et de la Platta) en essayant d'identifier toutes les structures héritées du rift et de restaurer leur géométrie complexe. En raison de leur complexité, certains de ces domaines avaient été cartographiés comme des zones de mélange. La méthode développée et décrite dans cette étude a pour objectif de pouvoir être appliquée à d'autres analogues fossiles de marge distale.

Dans un second temps, j'ai décrit un exemple d'évolution de faille de détachement en séquence formant un domaine hyper-étiré (nappe de l'Err). Ces failles sont responsables d'un amincissement crustal conduisant à la rupture continentale et à l'exhumation de manteau sous-continental. Ces observations devraient permettre d'enrichir et/ou de calibrer des modèles numériques ou analytiques. Cela pourrait aussi permettre, avec des études complémentaires, de proposer un modèle capable de quantifier les contraintes et l'évolution thermique des marges distales.

Dans un troisième temps, j'ai décrit un analogue fossile de manteau exhumé en position de transition océan continent. Ce domaine montre une évolution de la tectonique et du magmatisme complexe et polyphasé. L'influence des circulations de fluides associés semble déterminante dans les étapes de cette évolution et des travaux complémentaires devraient préciser son importance. Les observations réalisées sur le terrain permettent de lier l'histoire de la déformation avec celle de l'emplacement et de l'évolution du magma, au cours de l'histoire du rift.

Ces nouvelles observations permettent de discuter des processus liés à la rupture lithosphérique et à la transition d'un domaine de manteau exhumé à une croûte océanique sensu stricto, stable, ou à une dorsale ultra-lente. Ces observations clés doivent être intégrées dans l'interprétation des données de sismiques et de géophysique sur les marges distales pauvres en magma, comme par exemple dans les travaux de Péron-Pinvidic et al. (2007), Ranoro et Pérez-Guissinyé (2010), Gillard et al. (2015).

Extended Abstract

The evolution from the continental drifting to the plate tectonic theory is intimately linked to the development of new methods and the progress of marine geophysics. The advent of these new technics enabled to image oceanic domains, to increase the observational scale and to develop a better understanding of the rifting and seafloor spreading processes. This enabled to describe and model the processes that explain active plate boundaries such as mid ocean ridges and subduction zones while the studies of mountain belts and rifted margins faded transitorily into the background. While mountains remained the favourite playground of field geologists, the study of rifted margins became one of the main domains of oil companies. The difficul access, the expensive aspect and rare drill holes from distal rifted margins delayed and complicated particularly the research in these domains. However, three major developments tore the research of rifted margins from its sleep: 1) the drilling of the deep Iberia margin and the unexpected discovery of exhumed mantle rocks (*Boillot et al.*, 1980); 2) the discovery of giant hydrocarbon reservoirs at deep water rifted margins, and 3) the development of new high resolution seismic imaging methods that enabled to image rifted margins at a crustal scale. The imaging and drilling of distal, deep water rifted margins resulted in discoveries that were unpredicted by the classical plate tectonic concepts and resulted in a change in paradigm that is still ongoing. Major new questions that were either ignored or previously not considered to be important emerged trough the new exploration results at distal rifted margins. At present, and due to the lack of drill hole data at Ocean-Continent-Transitions (OCT), the science community lacks observations to understand and explain how continental crust and lithosphere extends and how new oceans form. Indeed, little is known about how oceans are formed and how these domains are structured and what are the processes that controlled their formation. Although the recent progress in seismic imaging provides high-resolution images, and although dynamic models enable to propose evolutionary models for these domains, the lack of direct observations and samples make it difficult to calibrate and test the new ideas and models. Therefore, fossil analogues of distal rifted margins preserved in collisional orogens like the Alps are of key importance. These analogues have been described since the early days of field geology resulting in the precursor concepts of ophiolites and rifted margins in the Alps and other orogens (*Steinmann*, 1925). In particular the reconstructions of remnants of OCT in the Alps and their comparison with their present-day analogues drilled and seismically imaged of Iberia not only enabled to better understand the final stages of rifting, but also to recognize the importance of rift inheritance in the formation of collisional orogens. A key result of the observations made at on- and offshore examples of distal and ultra-distal domains, i.e. at hyperextended continental crust and exhume mantle domains, is that these domains are very different from the more proximal parts at rifted margins. As a consequence, we have to admit that we are only at the beginning of a new research phase and that distal and ultra-distal rifted margins can be considered at present as one of the least investigated tectonic systems. The very punctual geological and geophysical data sets makes the understanding of the processes difficult and makes that our understanding of how the interaction between deformation, magmatism, fluid and sedimentary systems during crustal thinning, mantle exhumation and lithospheric breakup is still in its infancy.

Based on these considerations, the aim of this study is to develop an observation driven approach using field analogues to scrutinize, test and improve our geological understanding of distal margins that will be combined with the study of present-day distal rifted margins. The study focus on the investigation of exposed remnants of hyperextended and exhumed mantle domains of the former Tethyan margins today exposed in the Err and Platta nappes in the Alps of SE Switzerland. Based on classical field work, the polyphase tectonic, magmatic and fluid evolution of these domains are described and compared with present-day analogues imaged in seismic images. Key questions that are addressed in this study are around 3 principal axes.

- How, when and under what conditions does extreme crustal thinning and lithospheric breakup occur? How did the lithospheric break-up occur? Where did the faults root at depth? How did these structures accommodate the deformation and how did this evolve in time and space?
- How do detachment faults thin the crust and eventually exhume mantle, where do these structures root at depth, how do they accommodate strain and how do they develop in time and space?
- What is the architecture of an exhumed mantle domain, how do tectonic and magmatic processes interact during their formation and what is the role of fluids during exhumation?

The access to a well-exposed field analogue can provide important insights and enable to find answers to questions difficult to answer at present-day margins due to the lack of drill hole data. In addition, the use of a kilometer scale field analogue can help to up-scale and to interpret extensional detachment systems at present-day margins.

The thesis manuscript consists, in addition of an introduction and discussion part, of three main parts, each one corresponding to a precise, well-defined theme corresponding to a scientific article that is preceded and followed by an introduction, a resume and remaining questions. Additional data, observations and interpretations that have been used but not included in the articles are added in the annex (Annex 1). The first part of the thesis deals with the description of the study area (Err-Platta nappes) and includes a methodological approach to map and extract rift-related information from Alpine nappes, a conceptual restoration technique that enables to restore the pre-collisional situation, and discusses the relation between rift inherited structures and collisional reactivation. A second part contains a field description of an exposed detachment system within the Err nappe that belongs to the former distal margin and discusses the geometry and kinematics of this detachment system and its role in structuring the former hyper-extended rifted margin. The third part contains a study of the Platta nappe, which corresponds to the exhumed mantle domain and describes the polyphase evolution and link between tectonic, magmatic and fluid systems and the related processed forming the ultra-distal rifted margin. The main results of my PhD can be summarized as follow.

1) Defining rift inheritance and describing its role during reactivation

It is commonly accepted that collisional orogens involve the reactivation of former rifted margins. How rift inheritance can be identified and how it controls the architecture of orogens remains, however, debated. In my PhD I analysed the importance of rift-inheritance during reactivation of complex, non-layer cake rift structures within the well-exposed Err and Platta nappes (SE Switzerland). These nappes represent the former distal Adriatic margin of the Alpine Tethys. I defined general diagnostic criteria to describe rift inheritance which include: (1) typical fault rocks with a mantle derived fluid signature, and (2) tectono-sedimentary breccias made of reworked exhumed basement and grading upwards into late syn- and post-rift sediments. Based on the study of these ‘‘recognizable’’ features, I proposed a methodology, which enables to (1) map rift related detachment faults, (2) analyse their role during reactivation and formation of a thrust stack, and 3) define first, second and third order thrust systems. The results of the study show that thrust faults commonly reactivate former extensional detachment faults in the exhumed mantle domain (Platta nappe), while in the hyperextended domain (Err nappe) reactivation of rift-inherited structures is more complex and often incomplete. The results of this study enabled to better define the Alpine and pre-Alpine deformation history of the Err and Platta nappes and may help, in a more general way, to better identify remnants of former distal margins in orogenic systems. Indeed, this study exemplifies how rift inheritance may be recognized and used to define and analyses the complex stacking patterns observed in many internal parts of Alpine type collisional orogens.

2) Architecture of detachment systems in hyperextended crust and their role in continental thinning

While extensional detachment systems linked to post-orogenic or oceanic settings have been described from many places, examples linked to hyper-extension and formation of magma-poor margins remain rare. Here I describe one of the best-exposed examples of a detachment system worldwide that is exposed over 200 km^2 in the Err nappe in SE Switzerland. Based on preexisting work I realized a detailed mapping which allowing to discuss the 3D structure of the detachment system and its role in thinning the crust and controlling the architecture and structural evolution of the hyperextended crust. I show that the currently described detachment system can be defined by different detachment faults that developed in-sequence. The sequential evolution of these faults allows to interprete the detachment system by the rolling hinge model. However, the occurrence of Permian basins resulting in a strong pre-structuration of the upper crust, and, the occurrence of evaporates in the Triassic pre-rift sequence strongly controlled the local geometry of the detachment system. From the existing observations it remains unclear how and where the detachment fault rooted at depth. The overall observations made in the Err nappe allowed to describe how extensional detachment systems can explain the final rift evolution preceding mantle exhumation and how it shapes the hyper-extended continental wedge at distal margins.

3) Polyphase tectonic, magmatic and fluid processes related to mantle exhumation in ultra-distal rifted margins

Despite the fact that many studies have investigated mantle exhumation at ultraslow spreading ridges and magma-poor rifted margins, there are still numerous questions concerning the 3D architecture, magmatic, fluid and thermal evolution of these domains that remain unexplained. Indeed, it has been observed in seismic data from ultra-distal magma-poor rifted margins that the top basement is heavily structured and complex, however, the processes controlling the morpho-tectonic and magmatic evolution of these domains remain unknown. The aim of this study was to describe the 3D top basement morphology of an exhumed mantle domain, exposed over 200 km^2 in the fossil Platta domain in SE Switzerland, and to define the timing and processes controlling its evolution. Detailed mapping of parts of the Platta nappe enabled us to document the top basement architecture of an exhumed mantle domain and to investigate its link to later, rift/oceanic structures, magmatic additions and hydrothermal fluid systems. Our observations show a polyphase and/or complex: 1) deformation history associated with mantle exhumation along low-angle exhumation faults overprinted by later high-angle normal faults, 2) top basement morphology capped by magmatic and/or sedimentary rocks, 3) tectono-magmatic evolution that includes gabbros, emplaced at deeper levels and subsequently exhumed and overlain by younger extrusive magmatic additions. The circulation of fluids during exhumation controls serpentinization of mantle rocks and calcificationof the latter (ophicalcites), and the rondingitization and spilitization of mafic rocks. The study of these processes was carried out in parallel in the PhD thesis of Méderic Amann.

The overall observations provide important information on the temporal and spatial evolution of the tectonic, magmatic and fluid systems controlling the formation of ultra-distal magma-poor rifted margins as well as the processes controlling lithospheric breakup. In this context, our field observations helped us to better understand the tectono-magmatic processes associated to these, not yet drilled domains. We compare our field observations to present-day Ocean-Continent Transition in magma-poor systems and try to enhance the knowledge of the lithospheric breakup processes.

The main results of my PhD, which are mainly based on a field approach, enable to improve the knowledge of distal rifted margins and OCT's in particular, and to better understand the processes controlling their formation. **Firstly** I showed the importance of rift inherited structures at the location of the deformation during a subsequent collisional reactivation of an OCT. I used new mapping methods in the field to try to identify inherited rift structures and restore their complex geometries, previously referred to by some geologists as "zone de mélange". The method developed and described in this study can also be applied to other fossil analogues. **Secondly** I described a field example of an in-sequence evolution of a detachment fault systems that formed and structured a former hyperextended domain. These observations provided direct access to a tectonic system that is responsible for extreme crustal thinning and mantle exhumation. This new geological observations may enable to improve and calibrate numerical and analoge models and eventually to propose models that can quantify the strain evolution of detachment systems. **Thirdly** I have highlighted a well preserved on-shore example of an exhumed mantle domain that show a complex polyphase tectono-magmatic and fluid evolution. The direct observations made on a fossil mantle detachment system enabled to link the deformation history with the magmatic and fluid systems.

These new observations enable to discuss the processes associated to the lithospheric breakup and the transition from an exhumed mantle domain to a steady state oceanic crust or ultra-slow spreading ridge, and provide key observations that need to be integrated in the interpretation of seismic and other geophysical data sets.

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PALÜ BIER

Introduction

The work presented in this thesis is an integral part of the research developed over the last years on the understanding of Ocean Continent Transitions at magma-poor rifted margins at the University of Strasbourg. To improve the knowledge of the distal domains and the associated processes, I focused on the description of fossil distal margins present in the Alps. Thanks to the description of these fossil analogues preserving remnants of hyper-extended and exhumed mantle domains in the Err and Platta nappes in the Central Alps in SE Switzerland, I discussed the processes controlling final rifting, continental break up, exhumation of the mantle, formation of a new plate boundary and the compressional reactivation of the rift structures at this fossil distal margin. This study is focused around 3 major aspects of distal magma-poor rifted margins: 1) the reactivation of a distal margin and how it is preserved in the present-day Alpine system, 2) the architecture and evolution of a hyper-extended margin, and 3) the architecture and evolution of an exhumed mantle domain within an Ocean Continent Transition.

Part I: Formation and reactivation of rifted margins: an introduction

Part I consists of four chapters that provide an historical perspective and general introduction to the subject investigated in the PhD project (Chapter 1), a short presentation of the sites studied (Chapter 2), an overview of the approach and methods used in the project (Chapter 3), and the aim, main scientific questions and general organisation of the PhD thesis (Chapter 4).

CHAPTER 1: FROM MOUNTAINS TO OCEANS, FROM OBSERVATIONS TO MODELS: AN HISTORICAL PERSPECTIVE

Over the last two centuries, observations enabled to propose models that can explain the major processes at the origin of the formation of mountain belts and oceans. Observations were made in mountain belts and present-day oceans thanks to the development of new methods. Spectacular advances in the last decades and the development of new analytical and geophysical methods enabled to trace and date geological materials, and image deep seated crustal and mantle structures. Despite these spectacular advances, there are still open questions that remain and that need to be answered. Some of these questions are related to the formation and reactivation of ultra-distal rifted margins and adjacent oceanic domains and the processes that are at the origin of the formation of plate boundaries at convergent and divergent margins. The lack of knowledge that hinders us to answer to these questions is mainly due to the inaccessibility of these domains that are at present buried underneath kilometres of sediments and are at several thousands of meters of water depth. This chapter summarizes, in an concise way, the evolution of our knowledge, from the first historical discoveries associated with the study of ophiolites to the study of present day rifting systems leading to the current understanding of processes and concepts.

1. Pioneers and development of first concepts describing distal margins

In its early days, geology started by the observation and description of outcrops in mountain belts or exposed terrains. In the 18th century a systematic exploration of the Alps began. However, at this early stage, the understanding of the kinematic and dynamic evolution was not yet linked and integrated into an observational approach.

One of the first theories trying to explain the link between oceans and continents prior to plate tectonics was the geosyncline theory. This theory, firstly developed in the United States by Hall (1859) and Dana (1873), was applied to the Alpine system by Suess (1875). He already interpreted the occurrence of "pelagic" facies and its importance for the interpretation of marine domains (for a more extensive description see *Trümpy*, 2003). Haug (1900) interprets the geosyncline as made of deep marine furrows. In parallel, Steinman (1905) compared Alpine red and green radiolarian cherts to recent radiolarian oozes and suggested that they were deposited in water depth of around 5km. He also demonstrated the frequent association of these starved deep-water sediments with ophiolites. Steinman thought that ophiolites characterised the deepest parts of a Mesozoic Alpine ocean. The "Steinman Trinity" (illustrated in Fig. 1-1), defined as a lithological sequence made of cherts, diabase and serpentinites (for more details see *Bernoulli et al.*, 2003), described the succession observed along the Alpine arc, which preceded the definition of the ophiolite sequence, consisting of gabbros, sheeted dykes and pillow basalts overlain by deep water sediments (e.g. Penrose conference, 1969). Argand (1916) and Staub (1916) followed and further developed the idea of the geosyncline and the geanticlines developed by Haug (1900) and proposed paleogeographical restorations for the Alpine system (e.g. "Tectonique embrionaire"; *Argand*, 1916, Fig. 1-1). For Staub (1924) it appeared evident that the Alpine geosyncline had an oceanic nature (Fig. 1-1). In his 1934 paper, Argand proposed that the geosyncline was formed by a polyphase evolution including extension and compression and mentioned "…if extension continue... the geosyncline makes place to an ocean".

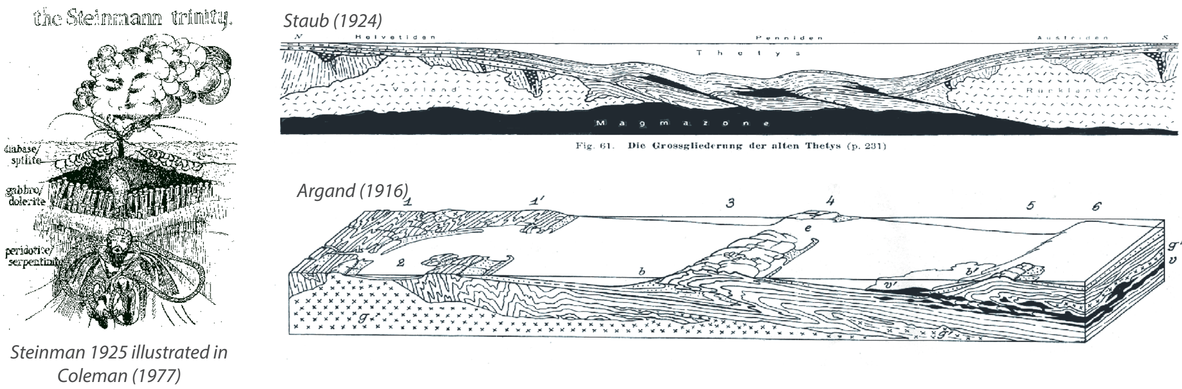


Fig. 1-1: *Representation of two concepts that have been developed by Alpine pioneers based on field observations: the "Steinmann trinity" (Steinmann, 1925; image from Coleman, 1977)) and the "tectonique embryonnaire" (schematic representation of the geosyncline theory of Staub (1924) and Argand (1916)).*

Thus, long before the plate tectonic theory has been established, pioneers described, based on field observations made in the Alps, the occurrence of continental and oceanic domains (*Trümpy*, 1912; 1975; 1976; 2003). However, only with the onset of the continental drift theory by Wegner (1912) and later by the plate tectonic theory, the understanding of the genetic relationship between mountain belts and oceans and the kinematic and dynamic processes that links the two have been integrated and understood.

2. Plate Tectonic revolution

The theory of Plate Tectonics has developed from the early ideas of the continental drift theory proposed by Wegner (1912). The foundation of this theory was based on the idea that the present continents were connected, before they drifted apart, like "icebergs". It was only with the development of geophysical methods, such as paleo-magnetism, potential field methods, seismology, but also dating methods and isotopic geochemistry that the ideas of Wegner could finally be confirmed by direct observations and hard data.

The Plate Tectonic theory provided a kinematic and dynamic framework explaining the motion of the tectonic plates. With this theory it became possible to explain that plates either converge or diverge forming respectively orogens or oceans (Fig. 1-2A). Wilson (1966) showed, using the example of the North Atlantic, that the opening of the North Atlantic ocean used an older fossil plate boundary. This observation led to the suggestion that Plate Tectonic processes go through cycles referred to as the “Wilson cycle”. Morgan (1968) proposed a model of the Earth surface made of 12 rigid plates that moved relative to each other. Only two month after the publication of Morgan’s paper, Le Pichon (1968) published a model of 6 major plates and the relative motion among them. These publications marked the acceptance of the Plate Tectonics theory by the scientific community. The new ideas enabled to define and quantify the physical processes controlling plate motions. McKenzie (1967) showed, using the example of the Pacific, that plates can translate and rotate on the surface of the globe. Based on the location of strong earthquakes, it became possible to define active plate boundaries (Fig. 1-2A). Although in the late 60^{ties} and 70^{ties} the kinematic framework had been unravelled, the dynamic processes responsible of the formation of plate boundaries remained unclear. Research in the last decades focused mainly on active plate boundaries, i.e. on Mid Ocean Ridges (MOR), subduction zones and transform faults. In contrast, the processes related to the formation of new plate boundaries in convergent and divergent systems remained little understood.

In this study, I will focus on the processes associated to the formation of a convergent plate boundary, i.e. on the processes that control the rift to drift transition preserved in an ultra-distal rifted margin. The aim is to investigate how these domains form and how they are reactivated leading to the initiation of a subduction zone and the formation of a mountain belt.

3. Formation and reactivation of present-day and fossil plate boundaries

The structures and processes associated with present-day active plate boundaries exposed at Mid Ocean Ridges, subduction zones and within orogens are relatively well investigated (Fig. 1-2A). In contrast, the initial formation of new plate boundaries is much less understood and remains one of the major outstanding problems that needs to be solved in Plate Tectonics. The formation of an “embryonic” plate boundary is intimately linked to the study of present-day and fossil distal margins and the adjacent first oceanic crust in compressional and extensional systems.

3.1 Convergent plate boundaries: subduction zone and collisional orogens

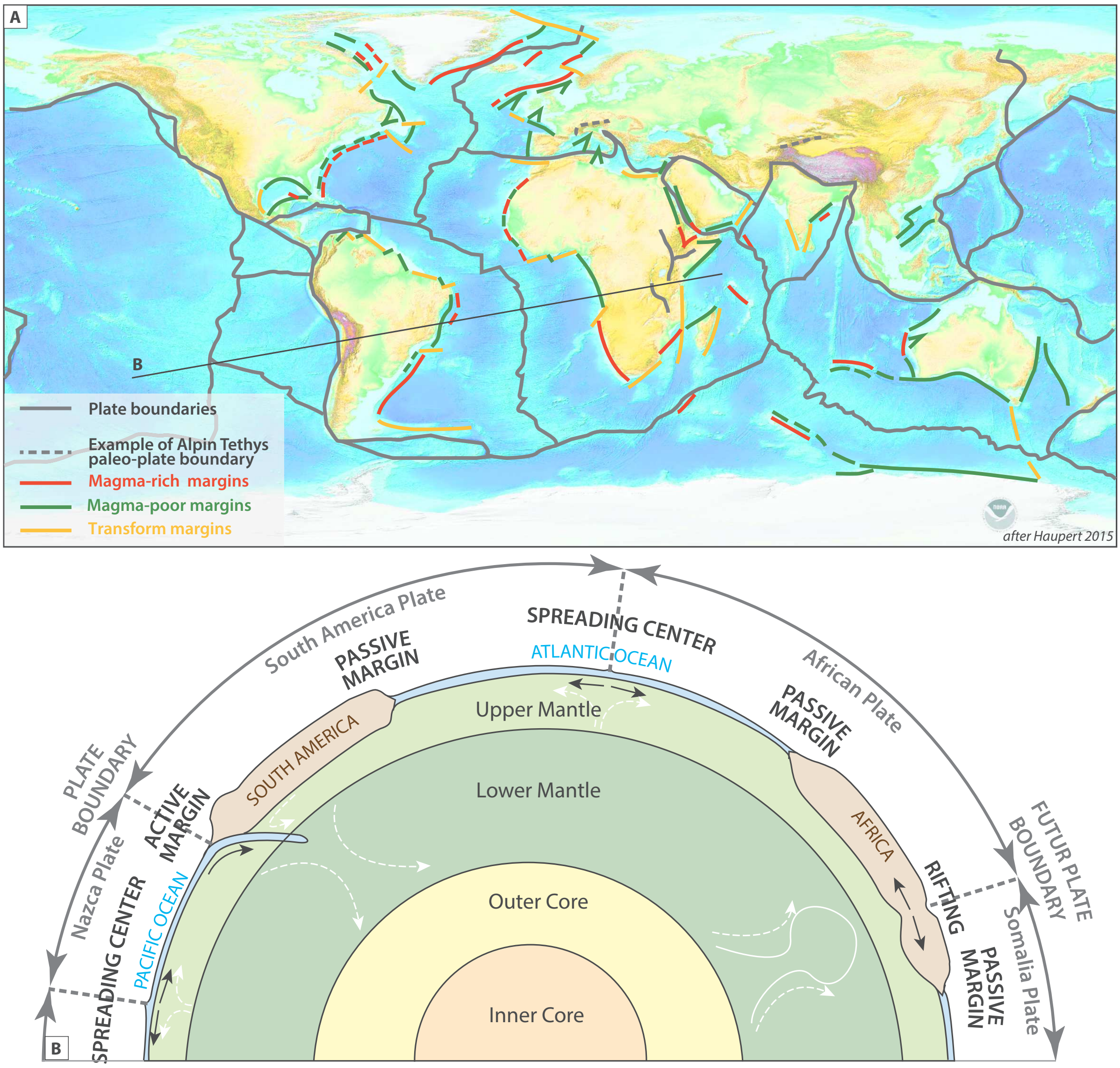


Fig. 1-2: **A** *Bathymetric map of the world showing the repartition of different types of rifted margins (modified after Haupert 2015 and using data from the National Geophysical Data Centre).* **B** *Schematic section of the first order structure of the Earth showing the major plate tectonic settings and the first order structure of the globe (thickness of crust, lithosphere and asthenosphere are not scaled).*

3.1.1 Subduction

A subduction zone is the location where plate convergence is accommodated and where one tectonic plate moves underneath another one (Fig. 1-2B). Initiation of subduction is at present little understood (*Nikolaeva et al.*, 2010). In contrast, much more is known about subduction processes. This is due to the fact that while onset of subduction occurs only sporadically and is therefore rare, subduction zones as such are continuously active and can therefore be directly investigated. Although subductions are generally supposed to initiate within or at the limits of oceanic crust/lithosphere it cannot be excluded that it can also initiate within an intracontinental setting (e.g. Tien Shan tectonic, *Poupinet et al.*, 2002).

Subduction initiation can occur spontaneously or by forcing. In the first case, subduction can be triggered in oceanic crust if the underlying oceanic lithosphere is dense, i.e. old and cold. In that event the lithosphere is gravitationally instable and can plunge. This mode of initiation can apply to oceanic lithosphere but not to continental lithosphere that is lighter. In the second case, first order plate reorganizations resulting in changes of plate kinematics can force the creation/destruction of microplates and/or oceans. This process is generally initiated in OCTs as shown in the example of the Bay of Biscay. However, in most examples, onset of subduction is masked by the collisional process. As a consequence, timing and location of initiation, size of the involved oceanic domain and the processes that control onset of subduction are difficult to investigate. This is the case of the Alps, were key questions regarding the reactivation of the margins remain unanswered, such as: how important is rift inheritance, in particular in the most distal parts of the rifted margin, and does it control reactivation. Peron-Pinvidic et al. (2008)

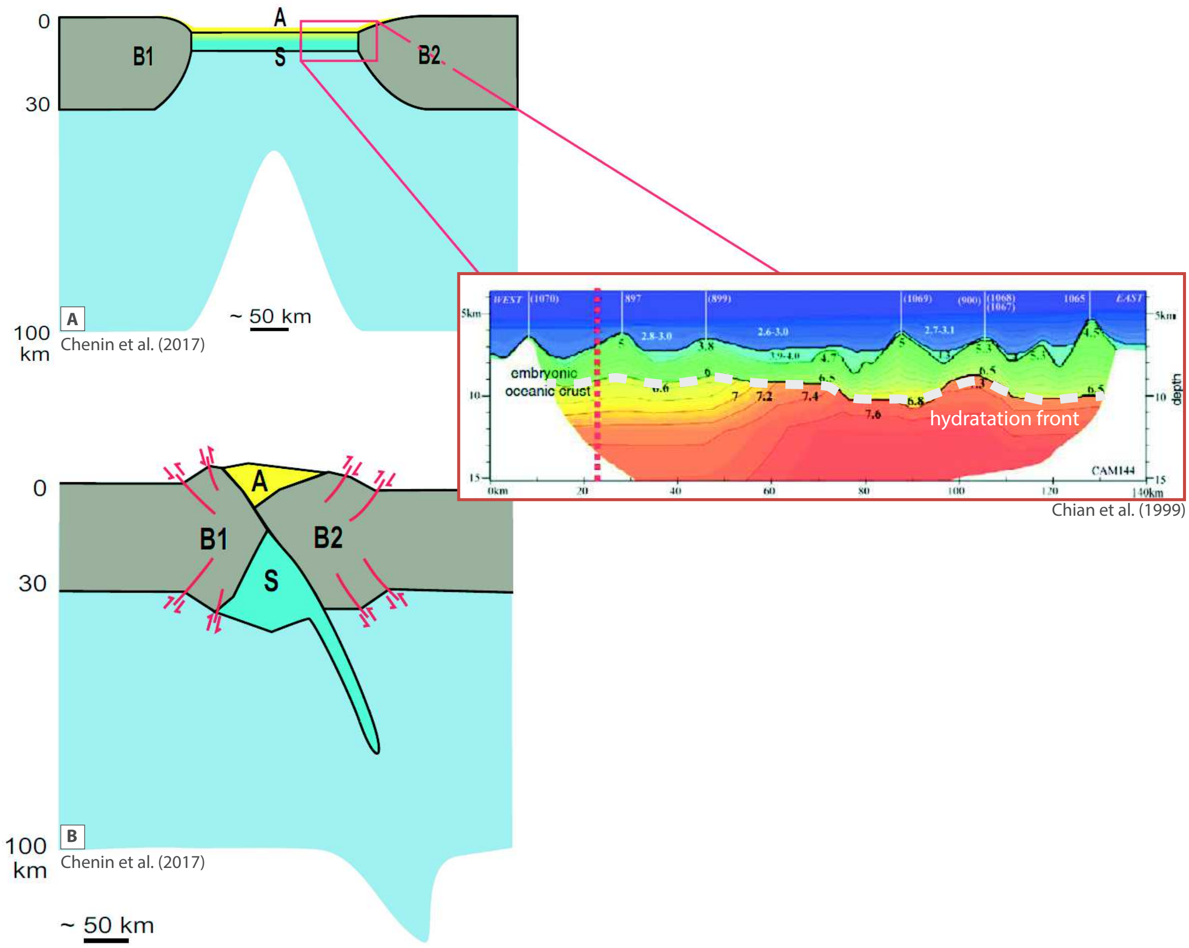


Fig. 1-3: *Role of serpentinization in controlling the reactivation of margins:* **A** *The decoupling level between the subducted (S) and accreted materiel (A) during subduction may correspond to the hydratation front (Chenin et al., 2017) that corresponds to a well-defined zone in OCTs of magma-poor rifted margins. For an example see refraction section CAM 144 from the distal western Iberia margin (Chian et al., 1999 and Beltrando et al., 2014).* **B** *Simplified first order architecture of an Alpine type collisional orogen: note the importance of necking zones (B1 and B2) acting as buttresses during the collisional process (for more details see Chenin et al., 2017).*

and Chenin et al. (2017) investigated the reactivation of ultra-distal margins. Their studies suggest that the exhumed mantle domains are a likely place to initiate subduction (Fig. 1-3).

In this study, we investigate the reactivation of the distal Adriatic margin during Late Cretaceous convergence (e.g. Chapter 6). The fact that the studied area shows relatively well preserved rift structures that have only been weakly overprinted by the subsequent collision makes it one of the best places to study the role of rift inheritance during onset of subduction.

3.1.2 Collision

Subduction of oceanic lithosphere that commonly leads to the formation of island arcs is followed by the collision of the converging margins or the arc with a margin, leading to the formation of a mountain belt. Chenin et al. (2017) discussed the evolution of wide vs. narrow oceanic domains and the role of the width of oceans in forming collisional orogens. They showed that the width of the oceanic domain as well as the nature of the subducting mantle may have a first order control on the fate of the orogenic system, i.e. the magmatic budget during subduction and the P-T conditions of the orogenic root during the subsequent collision. Following this study, the Alpine system studied here, could correspond to the closure of a narrow and immature oceanic domain. However, size and nature of the Alpine Tethys oceanic domain remains debated.

In this study, I focus on the reactivation and stacking of the most distal Adriatic rift domains during Late Cretaceous thrusting. Indeed, the studied Err and Platta nappes were stacked in a fold and thrust belt during the subduction and subsequent collision of the eastern Adriatic margin (e.g. eo-Alpine event) that predated the onset of subduction in the Alpine Tethys realm leading to the Alpine collision. Thus, subduction and associated collision stepped from the east (Meliata/Vardar domain) to the west (Alpine Tethys domain) resulting in a stacking of two orogenic domains (Fig. 1-4). As a consequence, the accreted nappe stack including units of former distal Adriatic domain became part of the hanging wall of the subduction of the Alpine Tethys ocean (e.g. *Schmid et al.*, 2017). Collision with the former European rifted margin occurred only much later, during Eocean time. The complex orogenic evolution may be controlled by the paleogeographic framework that includes the existence of several hyperextended and partly oceanized domains that limit micro continents such as Adria.

The reconstruction of the pre-collisional history of the Alps has been undertaken by identifying ophiolite-bearing suture zones (e.g. *Dietrich*, 1972) and by documenting facies changes in deformed and metamorphosed Mesozoic sedimentary sequences forming the cover

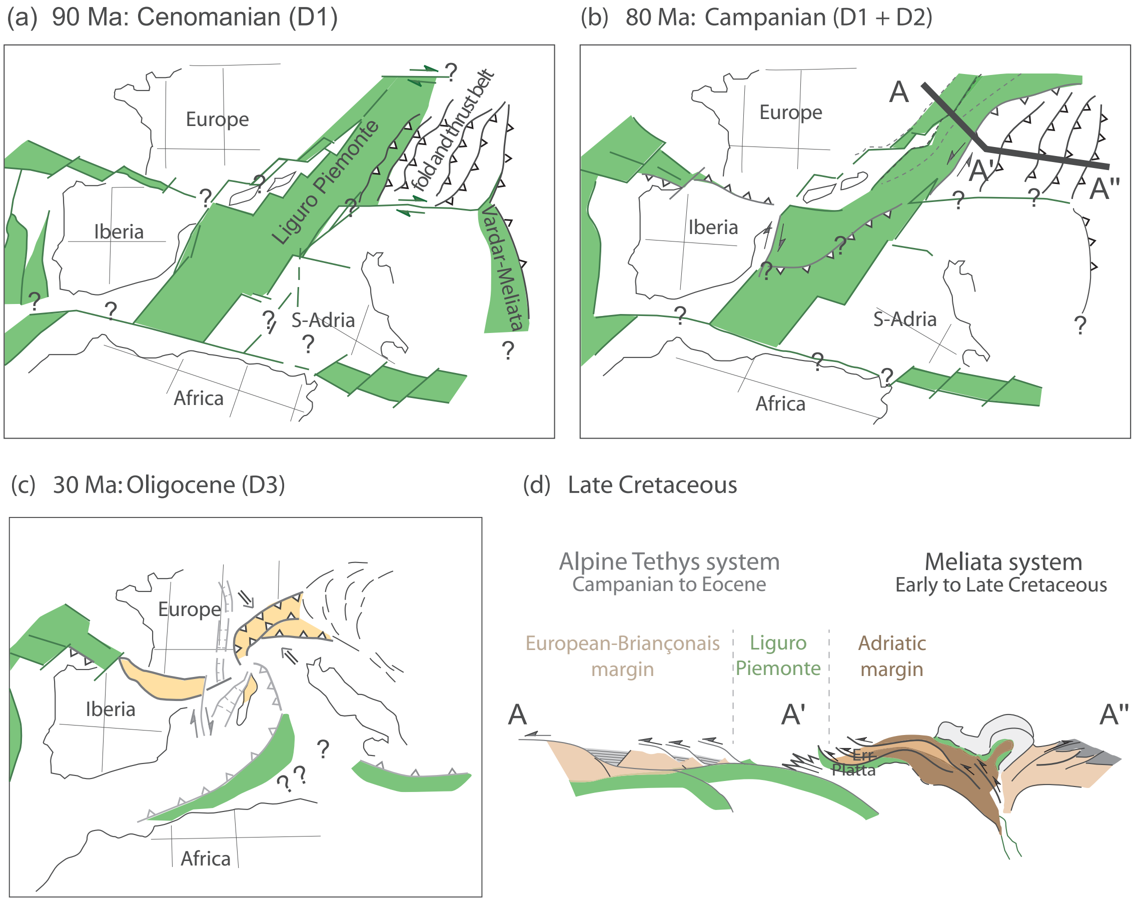


Fig. 1-4: Paleogeographic maps of the Alpine realm for: a Cenomanian, b Campanian to Maastrichtian, and c Oligocene. d Section shows the Adriatic-European margins during the Late Cretaceous convergence. During this event, the distal part of the Adriatic margin was stacked in a fold and thrust belt. Note that the western part of the distal northern Adriatic margin was stacked in a fault and thrust belt already before the onset of subduction in the Liguria-Piemonte Ocean. Figure modified after Manatschal and Müntener, 2009.

of allochthonous basement slices (e.g. *Stampfli et al.*, 1991). The numerous models and the lively debates among Alpine geologists show that the Alpine system is complex and polyphase and, despite more than a century of research, still not yet fully understood. However, the fact that evidence for the formation of arcs and long lasting subductions are missing, may lead to the suggestion that one part of the complexity may not be explained by the subduction and collisional processes alone, but may be partly due to the complex inherited history. Froitzheim and Eberli (1990), Marroni et al. (1998), Beltrando et al. (2014) and many others showed evidence of rift-related hyper-extension in the fossil Western Tethys domain. The importance of rift inheritance in structuring the Alpine belt remains, however, debated. While reactivation of the former proximal margins may be only of moderate and local importance and related to the reactivation of former fault bounded basins, reactivation of former distal margins, in particular of rift-related detachment systems and hydration fronts (Fig. 1-3), may be very important. Beltrando et al. (2014), and Mohn et al. (2014) suggested that large parts of the internal zones corresponded to former hyper-extended domains belonging to the distal Adriatic and European rifted margins, whereas the external zones derived from the little deformed proximal domains (Fig. 1-5). It remains therefore questionable, if the limit between internal and external Alpine units corresponds to a reactivated necking zone inherited from the previous rift event, or if it is controlled purely by the compressional system (Fig. 1-4). The internal zone of the Alps is bounded by two major structures, the Penninic front and the Insubric Line. How far these structures are correspond to inherited and reactivated former rift structures remains debated (for discussion see *Mohn et al.*, 2014 and *Decarlis et al.*, 2018). The strong Alpine overprint in the internal part of the Alps, affected by subduction processes as testified by high pressure metamorphism (eclogite), makes it difficult to restore the former rift structures and to evaluate their role during convergence with confidence.

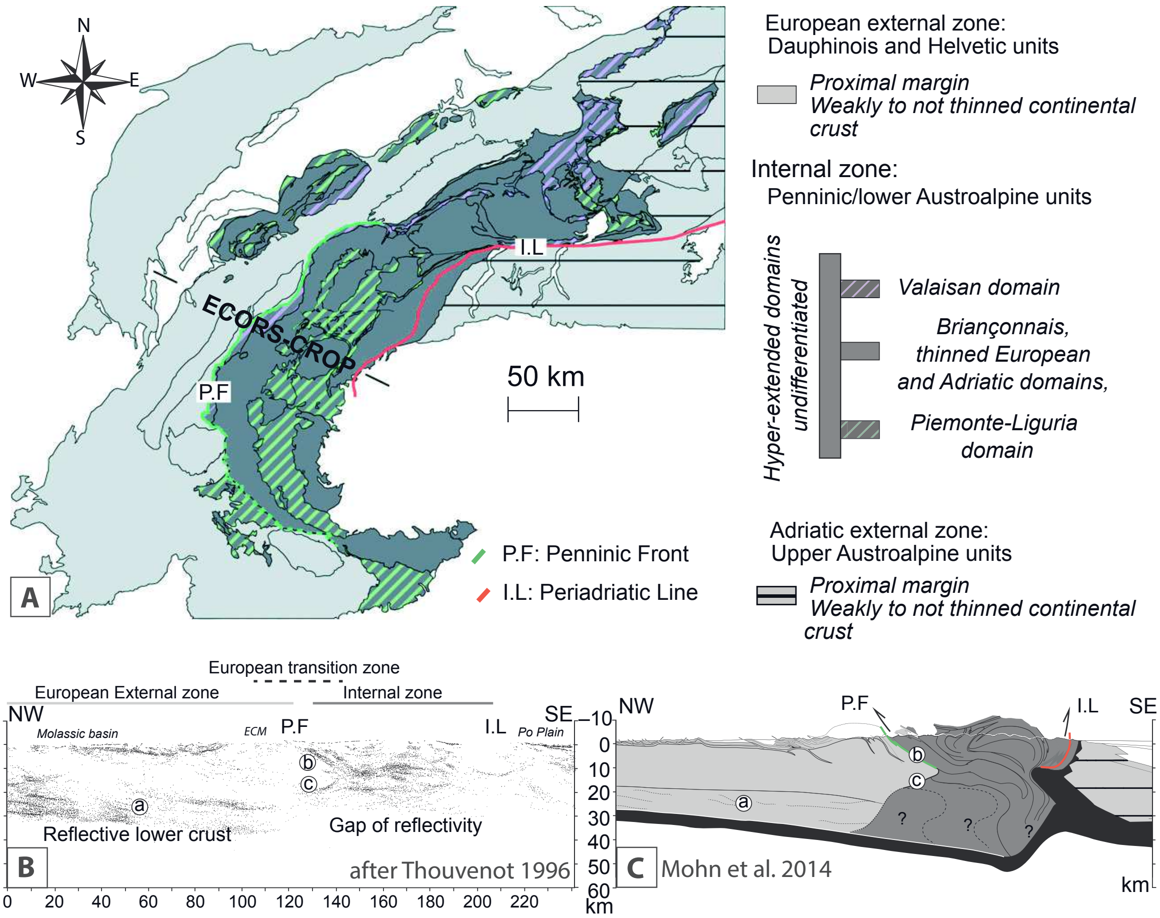


Fig. 1-5: ***A*** *Simplified tectonic map of the Alps showing Alpine domains and their interpreted paleogeographic origin.* ***B*** *Depth migrated ECORS-CROP profile across the Western Alps (after Thouvenot, 1996).* ***C*** *Interpretation of the ECORS-CROP profile assuming that the former necking zone of the European margin acted as a buttress (from Mohn et al., 2014).*

In this study, I focus therefore on the less metamorphosed and deformed internal parts of the orogen, which are exposed in south-eastern Switzerland and are part of the Cretaceous top to the west nappe stack that remained in the hanging wall of the Tertiary Alpine subduction (e.g. orogenic lid of *Laubscher*, 1983, or "Stockwerk Tektonik" of *Liniger and Nievergelt*, 1990). The mild Alpine tectonic overprint makes the study area an interesting place to study the compressional reactivation of a distal rifted margin. In Chapter 6 and Chapter 11, I describe and discuss the rift architecture and major structures of the most distal rifted margin exposed in the Err and Platta nappes and discuss their role during reactivation. Particular attention is given to the question of how rift inheritance of the distal rifted margin may have controlled the reactivation and the final architecture of the collisional orogen exposed in the study area (see Chapter 6 and Chapter 11).

3.2 Divergent plate boundaries: rifting and spreading

3.2.1 Rifting

Continental rifting is an extension driven process associated to lithospheric thinning that is commonly linked to magmatic activity. Rift systems either fail (e.g. Rhine Graben), or, if successful, lead to the formation of an oceanic domain with a stable, steady state spreading centre (Mid Ocean Ridge). Thus, rift systems, in their more developed stage, result in the formation of a "new" plate boundary that will be fossilized at the transition between the rifted margin and the first oceanic crust, also referred to as the Ocean Continent Boundary (OCB) or Ocean Continent Transition (OCT). Sengör and Burke (1978) showed that two kinds of rift systems existed, active and passive rift systems. Active rift systems are controlled by mantle convection, i.e. mantle plumes (Fig. 1-2B), whereas passive rifting is controlled by external forces. Extensional forces can be generated by gravitational forces or convective movements at the base of the lithosphere. The processes driving onset of rifting remain, however, little understood. In this study I will focus on a rift system that was able to separate crustal domains (Europe from Adria). I will mainly investigate the final stages of this process that is associated with the thinning of the crust and lithosphere, the exhumation of mantle and the onset of a magmatic system leading to seafloor spreading and the formation of an OCT, i.e. the formation of a passive margin.

The study of deep-water present-day passive margins initiated in the 70's and 80's is intimately linked to the development of marine geophysics and the development of the Plate Tectonic theory. Several models have been developed to explain the formation of rifted margins.

McKenzie (1978) proposed a depth uniform pure shear model to explain the thinning of the crust and lithosphere during rifting. In this model, rifting; i.e. mechanical extension/thinning, are instantaneous, symmetric and thinning of the crust and the mantle lithosphere are coupled. As a consequence, horizontal extension is inverse proportional to crustal/lithospheric thinning. Because in this model the base of the lithosphere is defined as an isotherm, mechanical thinning of the lithosphere is directly linked to a change in the thermal state. Therefore this model is a thermo-mechanical model (Fig. 1-6). This model can explain the key observations made at rift systems, i.e. extension is associated with uplift of the lithosphere, resulting in higher geothermal gradients and magmatic activity and is followed by thermal cooling and subsidence. However, this model cannot explain mantle exhumation and migration of deformation as observed in the studied area.

Wernicke (1981; 1985) proposed, based on observations in the Basin and Rang, a simple shear model, in which the lithosphere is transected by a lithospheric scale low angle detachment fault (Fig. 1-6). In this case the rift has a strong asymmetry enabling to distinguish between an upper plate and a lower plate. The thermal and isostatic evolution associated with extension is strongly asymmetric. Lister et al. (1989) proposed a model combining the pure and simple shear models in which detachment faults were decoupled along ductile weak decollement horizons separating the upper and the lower crusts as well as the crust and the mantle (Fig. 1-6). Following the establishment of these 3 types of rifting, several models have been developed. However, numerous questions remain, in particular associated to how these models can explain the final stage of rifting and the formation of first oceanic domains.

One key question is related to the formation of detachment faults, the way these fault systems work, the angle at which they slip and how they are related to the thinning of the crust and exhumation of mantle. Buck et al. (1988) proposed a model in which faults are downward concave and can explain the formation of extensional allochthons (e.g. Rolling Hinge model). More recently, Nirrengarten et al. (2016) showed that in the hyper-extended domain detachment faults may be explained by the Mohr Coulomb theory. Gillard et al. (2016b) also showed that detachment systems in ultra-distal domains can be complex and can form either in-sequence or out-of-sequence and may play an important role during final rifting.

In this study, I will address questions such as: How do detachment systems work during final stages of extension? Where do they root at depth and how do they evolve along strike? How do detachment faults develop during mantle exhumation and how do they interact with

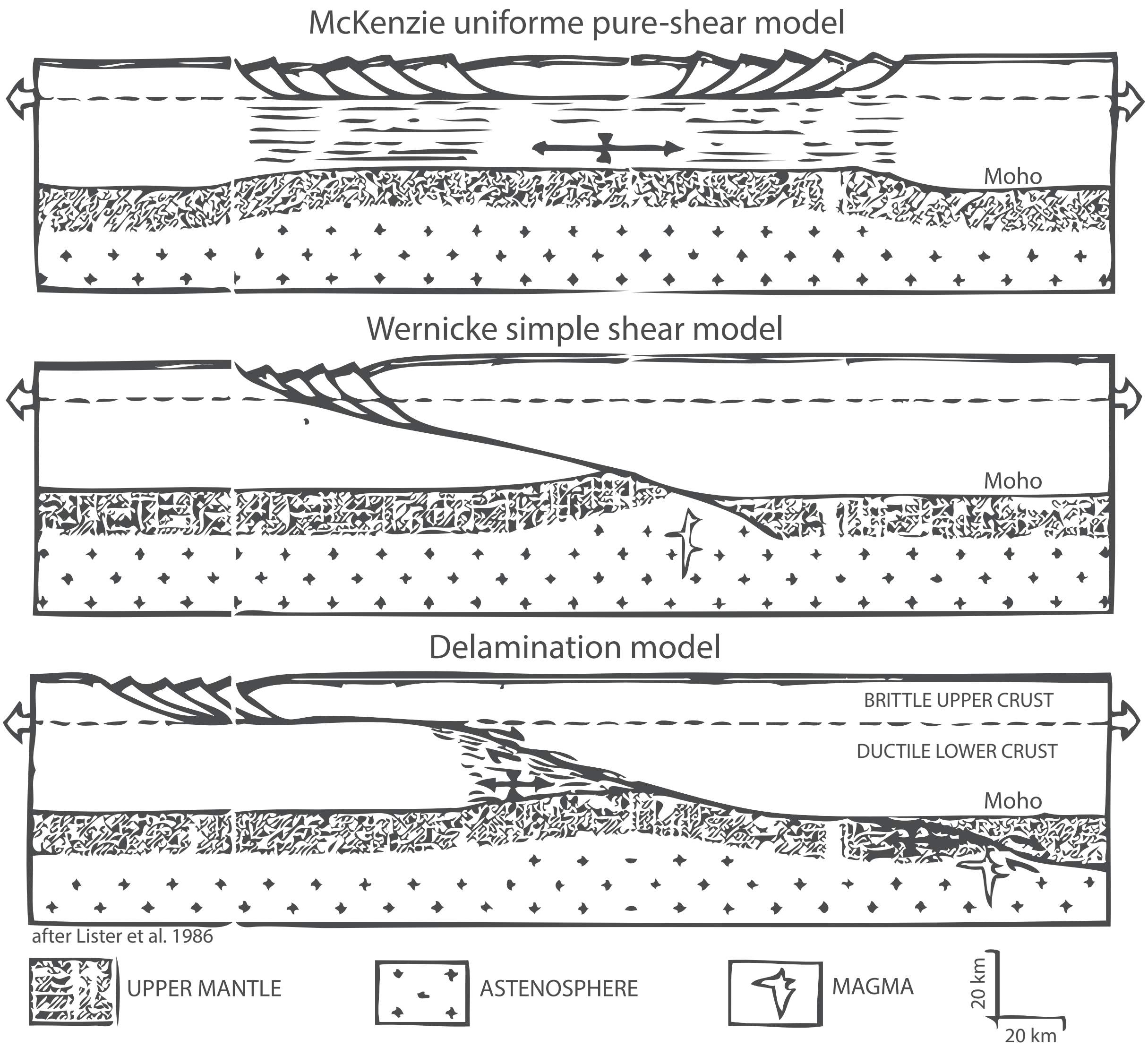


Fig. 1-6: *Three models proposed for continental extension (after Lister et al., 1986).*

magma during final rifting preceding lithospheric breakup? I will try to find answers to these questions by looking at field examples and by comparing these field observations with seismic sections from present-day deep-water rifted margins (Chapter 7 to 11).

3.2.2 Passive rifted margins

Passive rifted margins are located between non-extended continental and oceanic crusts. Although not active anymore, during their formation, rifted margins are at the origin of the creation of a first plate boundary. Passive rifted margin are classically subdivided in 3 types: magma-rich, magma-poor and transform margins. The 3 types correspond to different geodynamic and plate kinematic processes (see repartition of type of passive margins in Fig. 1-2). Transform margins are often related to strongly segmented margins that can be separated by magma-rich and magma-poor segments. Magma-rich and magma-poor margins are characterised by different magmatic budgets (Fig. 1-7). Magma-rich margins show voluminous magmatic systems that include Seaward Deeping Reflector (SDR) sequences, which correspond to syn-tectonic magmatic systems (Fig. 1-7A). The East Greenland margin is considered to represent the archetype of a classical magma-rich margin. All examples investigated in this study correspond to magma-poor rifted margins. Therefore I will not further discuss magma-rich and transform margins.

Magma-poor rifted margins are characterised by stretched and thinned crust, including tilted blocks, hyper-extended and exhumed crust and mantle with variable amounts of magmatic additions (Fig 1-7B). The Iberian margin is the archetypal magma-poor rifted margin. Magma-poor rifted margins are classically subdivided into rift domains which include: (1) a little extended proximal domain with a crust of 30±5km, (2) a necking domain corresponding to the domain where the major thinning of the crust occurred, (3) a hyper-extended domain formed by a crust that is < 10 km, (4) an exhumed mantle domain where subcontinental serpentinized mantle is exhumed at the seafloor, and (5) an oceanic domain (Fig. 1-7B).

The transition between the exhumed mantle domain and first steady state oceanic

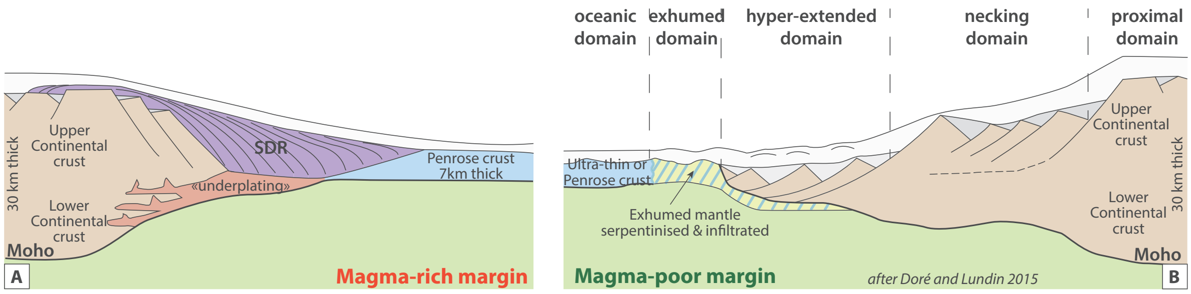


Fig. 1-7: *Two archetypes of passive rifted margins (modified after Doré and Lundin, 2015).* **A** *Magma-rich passive margin;* **B** *Magma-poor passive margin.*

crust, also referred to as Penrose crust (Penrose conference, 1972), 6 to 7km thick and made of gabbros, sheeted dikes and basalts, is in reality complex and in some examples transitional (e.g. example of the southern Australia-Antarctica margins; *Gillard et al.*, 2015). Indeed, how magmatic processes in hyper-extended and exhumed domains interact with tectonic processes and how and where first magma is produced and emplaced during final rifting is yet little understood. Chapters 7 and 8 provides a detailed description of the most distal parts of the Adriatic rifted margins, exposed in the Err and Platta nappes in southeastern Switzerland. It describes the tectonic and magmatic processes that occur during final rifting, which are little understood at present-day systems, principally due to the difficulty to access these systems that are buried beneath thick sediments and/or are deep water depth.

3.2.3 Spreading centres and oceanic crust

Spreading centres at mid-ocean ridges are the places where oceanic crust is formed and correspond therefore to active plate boundaries. Spreading centres can form at different spreading rates and are referred to as either fast to intermediate (> 40 mm/yr), slow (< 40 mm/yr), or ultra-slow (< 20 mm/yr). The magmatic budget is linked, on a first order, to the spreading rate (*Morgan and Chen*, 1993). Ultra-slow spreading systems tend to be magma-poor whereas fast spreading systems are magma-rich.

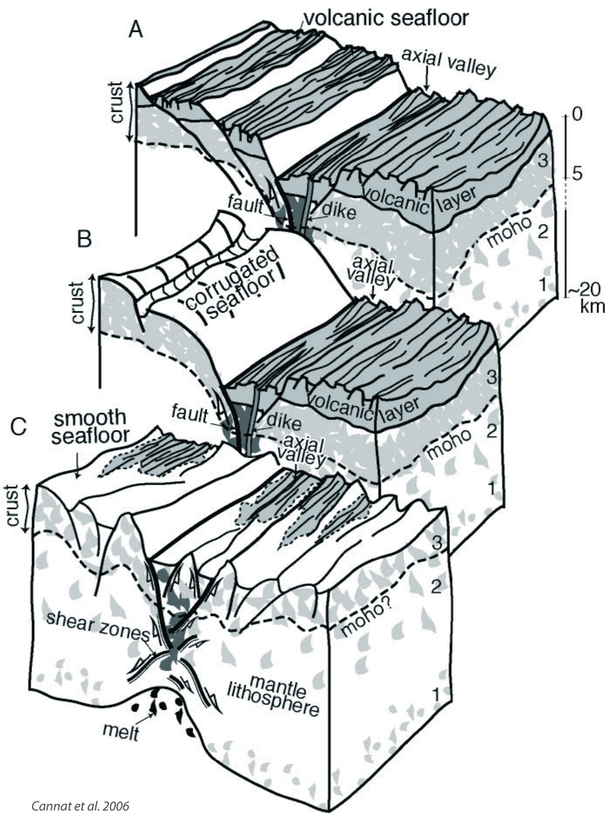


Fig. 1-8: *Lithosphere-scale sketches of the axial region of three types of spreading ridges (Cannat et al., 2006).* **A** *Volcanic-volcanic type, corresponding to classical Penrose type oceanic crust.* **B** *Corrugated-volcanic type corresponding to slow spreading ridges.* **C** *Smooth-smooth type corresponding to ultra-slow spreading ridges.*

Fast and intermediate-spreading ridges (> 40 mm per year) (*Smith*, 2013) have a magmatic supply that enables to form a "classical" magmatic crust, also referred to as a Penrose crust. This crust shows a thickness of 6-7 km and is made of gabbros, a sheeted dyke complex and an extrusive magmatic top layer (i.e. Penrose conference 1972) (Fig. 1-8A).

Slow-spreading ridges (*Smith*, 2013) can be associated to the corrugated-volcanic type (after *Cannat et al.*, 2006) (Fig. 1-8B). In this case the tectonic plates move apart at rate less than 40 mm per years. The magmatic supply does not allow compensating all the extension by creation of magmatic crust. As a consequence exhumation of mantle and gabbroic lower crust is possible. Domes of peridotite and gabbro with corrugations oriented parallel to the extensional direction are observed, corresponding to windows of exhumed lower crust and mantle. The deformation occurred along detachment faults producing offsets of tens of kilometres. This kind of asymmetric accretion is often observed at the end of segments of the mid-Atlantic ridge (*Cann et al.*, 1997; *Tucholke et al.*, 1998).

Ultra-slow-spreading ridges (*Smith*, 2013) can be associated to smooth-smooth or smooth-volcanic type (after *Cannat et al.*, 2006) (Fig. 1-8C). In this case, the tectonic plates move apart at rates less than 20 mm per year. The magmatic seafloor is almost non-existent and the basement is composed of exhumed peridotites, rare gabbros and is covered by patchy basaltic flows and sealed by sediments. Poly-phase systems of detachment faults enable to exhume this basement and result in a 1st order symmetric architecture (*Cannat et al.*, 1997; *MacLeod et al.*, 2009; *Sauter et al.*, 2013; *Gillard et al.*, 2016b). This morphology can be reproduced by numerical models in which the magmatic budget is less than 20 % (*Tucholke et al.*, 2008). A present-day example of the ultra-slow-spreading ridge is described at the SW India ridge (*Sauter et al.*, 2013).

It is interesting to note that the nature of the spreading centre seems to be independent of the magmatic evolution of the margin. Thus, magma-rich margins are not necessarily resulting in magma-rich spreading systems and vice versa. Unfortunately, examples where new spreading centres form as a consequence of rifting and lithospheric breakup are very rare. The best-documented example is the Red Sea where seafloor spreading initiated in the southern part 5myr ago, while in the northern part the breakup did not yet occur (*Bosworth et al.*, 2005).

In this study, I do not observe directly remnants of a spreading centre. However, present-day slow and ultra-slow spreading ridges present many analogies to exhumed mantle domains found at ultra-distal magma-poor rifted margins described in this study. Therefore, in my study I will compare the exhumed mantle domain in the Platta nappe with present-day structures exposed and imaged at slow to ultraslow spreading systems (Chapter 8 - 9 and 10).

3.2.4 Formation of a plate boundary in an extensive system

While many studies investigated rifts or spreading systems, much fewer focused on the transition (in time and space) from rifts to spreading systems. As a consequence, the evolution from final rifting to initiation of seafloor spreading is still little understood. The evolution of a rift system at a magma-poor rifted margin can be subdivided in 5 stages (Fig. 1-9): (1) initiation of distributed normal faulting that affects the brittle layers and is decoupled at mid-crustal ductile levels (e.g. stretching phase of *Lavier and Manatschal*, 2006); (2) localisation of extension and necking of the crust to less than 10km; (3) hyper-extension starting when no ductile layers prevail in the crust and faults can cut across the crust and penetrate and start serpentinizing the underlying mantle (e.g. coupling); (4) exhumation of the mantle and onset of emplacement of magmatic additions; and (5) formation of a steady state spreading centre. In this thesis, I investigated the processes that correspond to stages 3 and 4, that post-date necking and predate seafloor spreading, and are documented in the distal to ultra-distal parts of the Adriatic margin today exposed in the Err and Platta nappes in southeastern Switzerland.

At present-day margins it is difficult to study the distal parts and their transition to first oceanic crust, due to the important water depth and the thick sedimentary sequences. Drill holes are rare in these domains, and apart from the Iberia-Newfoundland margin, this type of data sets is not accessible to the academic community. This is also true for most high-resolution seismic data sets including long offset seismic data and 3D blocks. Moreover, at many margins thick evaporites and/or magmatic additions mask the underlying syn-tectonic sequences and related extensional structures. Therefore, I decided to study remnants of a fossil distal margin preserved in the Alps that show many analogies with observations made at the seismically imaged and drilled Iberia-Newfoundland margins.

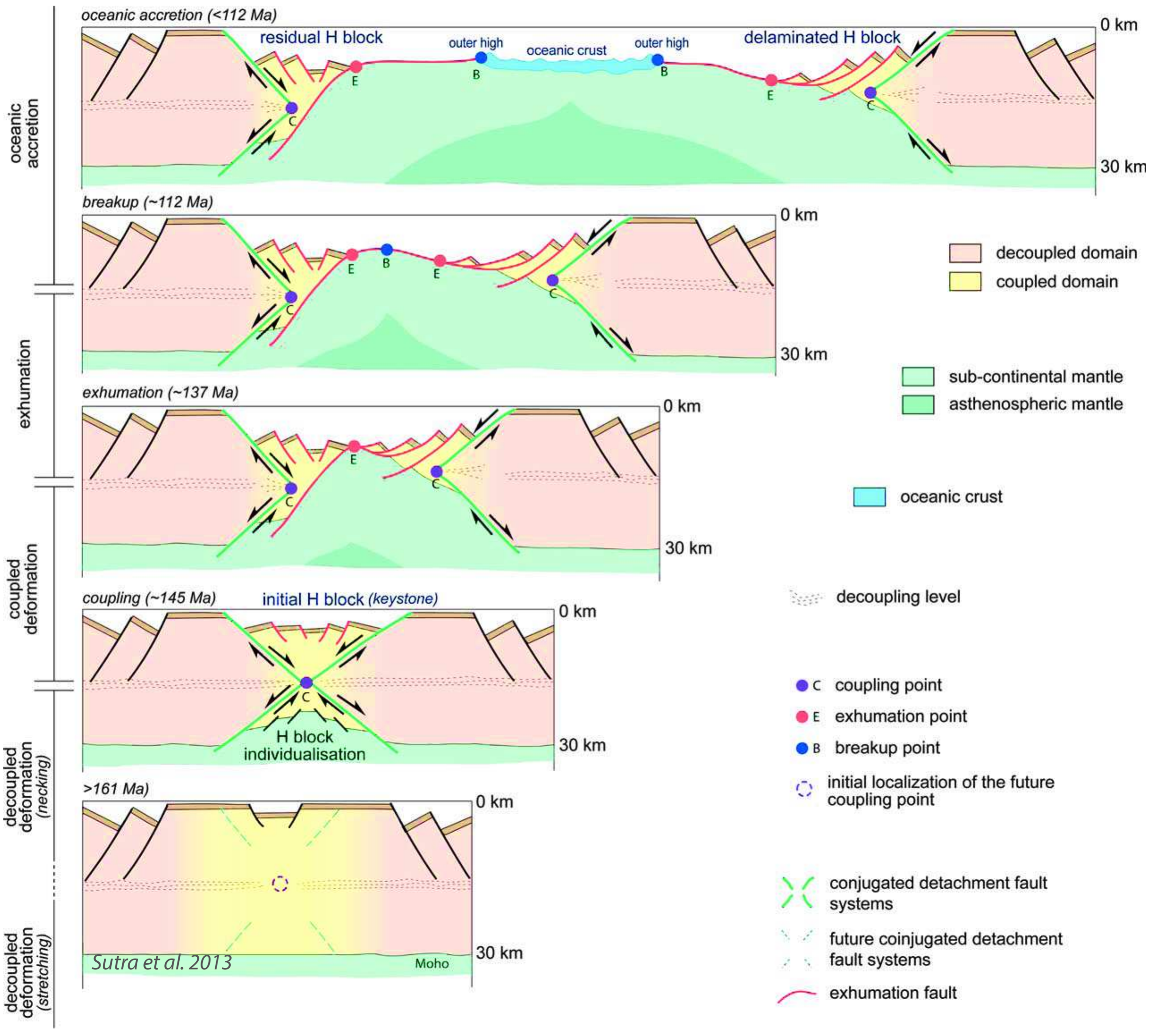


Fig. 1-9: *Conceptual model showing the temporal and spatial evolution and the different modes of rifting defined along the Iberia-Newfoundland rift system (Sutra et al., 2013).*

CHAPTER 2: INVESTIGATION SITES

In this study I choose to work on fossil and present day ultra-distal margins, combining a field approach with comparison to study of seismic sections and drill holes. Although at the very beginning it was planned to develop a more global approach, it became very soon clear that in order to answer to the ambitious questions of how continents break apart and oceans form, work needed to be concentrated on sites where these domains are accessible and were enough open domain data sets exist. For present-day magma-poor rifted margins, this is only the case for the Iberia-Newfoundland margins. For fossil margins, the choice of the Alpine Tethys margins and in particular of the Err and Platta nappes preserved in the Central Alps in southeastern Switzerland was crucial for this study (Fig. 2-1). Although the Err and Platta nappes have been studied before, the combination of new questions and new mapping of the area enabled to make many new observations that are described in Part II and discussed in Part III of my PhD thesis. In parallel to the field work in the Err and Platta nappes, I visited and worked on other remnants of ultra-distal domains preserved in the Western Alps (Prorel unit exposed in southeaster France, near Briançon), the Bonassola unit exposed in the northern Apennine, and the Mauléon basin in the western Pyrenees. The study of present-day margins focused on the Iberia-Newfoundland margins (Fig. 2-1), but although other seismic examples have been investigated, including examples of ultra-distal margins belonging to the internal data set of Total. For time reasons as well as confidentiality reasons these examples have not been introduced in this study. However, the access to these confidential data enabled me to get direct insights on the architecture of present-day ultra-distal rifted margins. The study of these seismic examples and its comparison with the field observations made during my PhD will be part of my Post-Doc that will follow this PhD project.

1. Remnants of the ultra-distal Alpine Tethys margins exposed in the Alps

The Alps result from the collision of the European and Adriatic margins following the closure of the Alpine Tethys Ocean, also referred to as the Piemonte-Liguria oceanic basin (Fig. 2-1). In the Alps in Western Europe, remnants of the ultra-distal former Alpine Tethys margins have been identified since the beginning of the 70's (*Dietrich*, 1969; *Elter*, 1972; *Lemoine et al.*, 1987). In the Western Alps, most of the distal and oceanic domains have been subducted, with the exception of few remnants such as the Chenaillet ophiolite, some units belonging to the Prépiemonte units (e.g. Prorel, Rio Secco; see PhD thesis of Haupert 2015) and to the internal Briançonnais units (e.g. *Decarlis et al.*, 2015). All other units show a strong Alpine metamorphic overprint and are disrupted from their pre-Alpine context. In the Apennines, remnants of the former distal margin are preserved in the Ligurian units. However, these units are within an accretionary prism and the link to the former margin is difficult to reconstruct. In contrast, in the

Lower Austroalpine and South Penninic units exposed in the Central Alps in Grisons, remnants of the former ultra-distal margin are preserved in a nappe stack that was emplaced during Late Cretaceous in an external part of an eo-Alpine orogen. These units remained in the hanging wall of the main Alpine subduction zone. Thus, the exceptional preservation of pre-Alpine, rift related structures in the eo-Alpine nappe stack exposed in southeastern Grisons and northern Italy, together with the excellent work that has been done in describing the locale geology over the last 150 years, is at the origin of what can be considered as the world best studied examples of an ultra-distal magma-poor rifted margin.

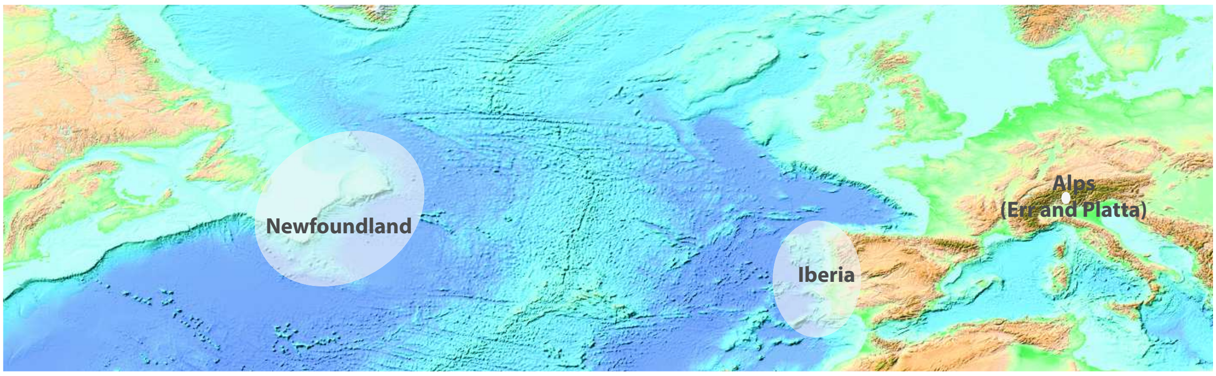


Fig. 2-1: *Location and scale of investigation site, National Geophysical Data Centre.*

In the last decades, detailed mapping, combined with structural, petrological and sedimentological studies enabled to define and reconstruct remnants of a complete section through a fossil magma-poor margin including the stretched (proximal) domain (e.g. Upper Austrolapine units), the necking domain (Campo-Grosina nappe), the hyper-extended domain (Bernina-Err nappes) and the exhumed mantle domain (Platta nappe) (e.g. *Mohn et al.*, 2012). While previous studies and thesis focused on the crustal architecture associated to the stretching, necking, and hyper-extended domains, this study focus on the ultra-distal part, also referred to as the Ocean-Continent-Transition (OCT). The part studied in this paper is made of hyper-extended crust and remnants of the pre-rift section, exhumed mantle and magmatic additions, altogether sealed by syn- to post rift sediments of Jurassic and Cretaceous age.

The aim of my thesis is to describe in detail the geology of the OCT and to investigate the relation between the structures responsible for the extreme crustal thinning and exhumation of mantle and its link to the magmatic systems that developed during and after final rifting. The investigation area of my thesis is located around the village of Bivio, in the Sursse valley, in Grison in southeastern Switzerland. This area preserves the transition from the hyper-extended crust (Err nappe) to the exhumed mantle domain (Platta nappe) (see present day and paleo-location of the study area, Fig. 2-2). The Err and Platta nappes have previously been studied by

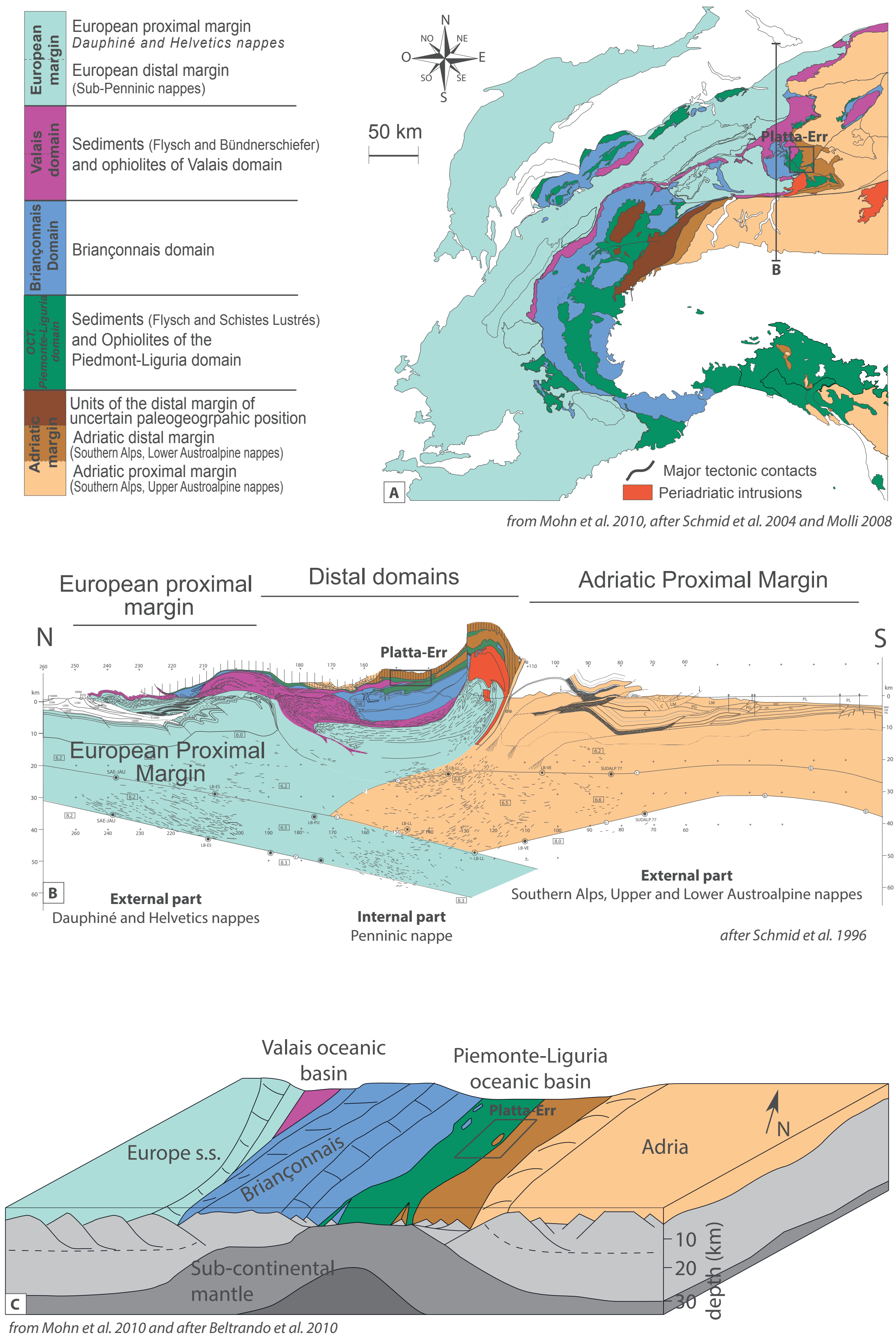


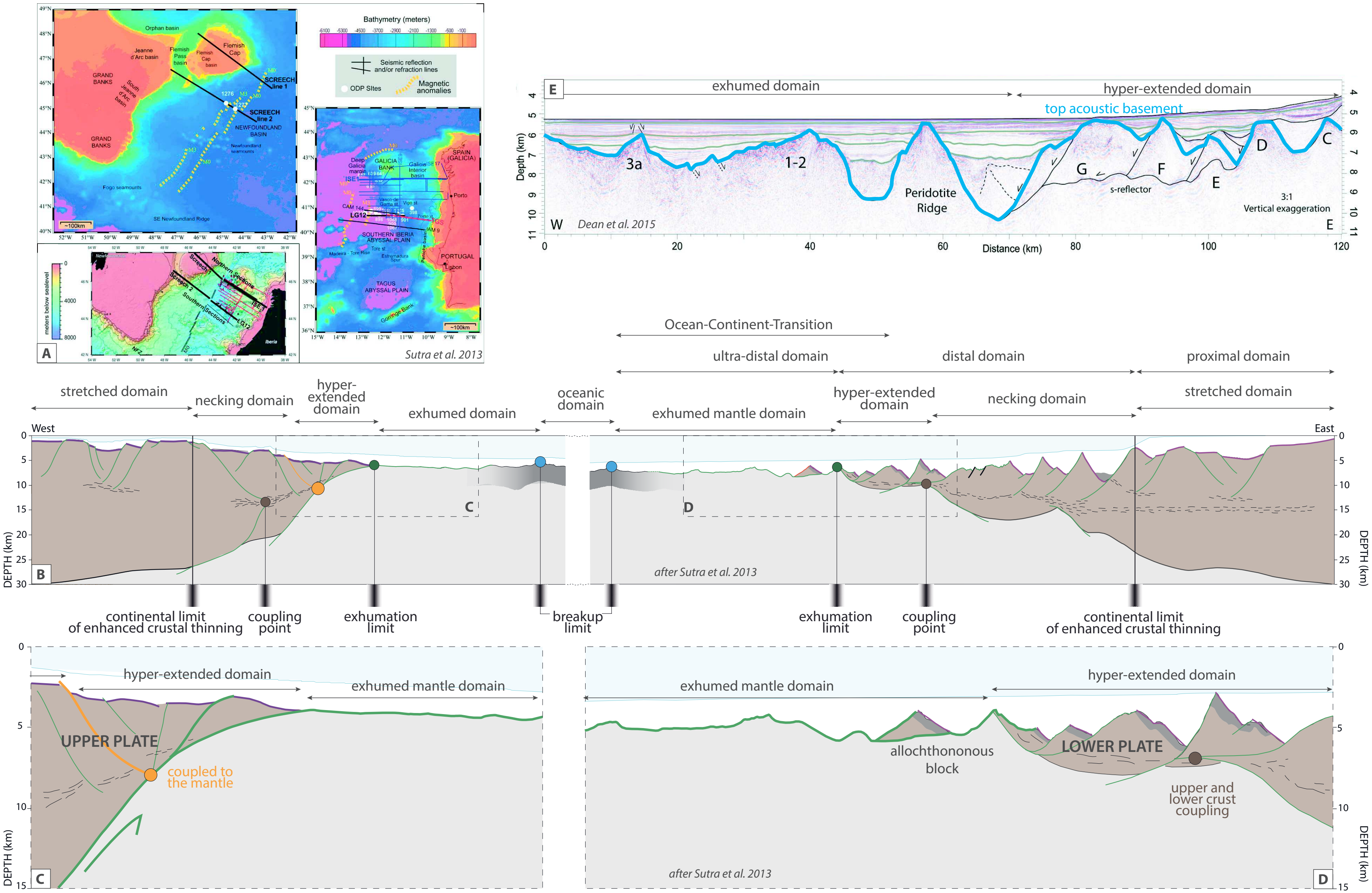
Fig. 2-2: **A** *Geological map of the Alps showing the distribution of major tectonic units(after Schmid et al., 2004; Molli, 2008; Mohn et al., 2010) and location of the Platta-Err investigation site.* **B** *Cross section across the Alps (from Schmid et al., 1996b) and location of the Err-Platta nappes.* **C** *Paleogeographic 3D model for the Alps (Beltrando et al., 2010a; Mohn et al., 2010) and location of the Err and Platta domains.*

several generations of geologists (for more detail see Chapter 5). With the advanced knowledge made on the distal margin in the last decade, thanks to the development of seismic imaging methods and exploration in ultra-distal rifted margins, a re-evaluation of these units became necessary.

2. Iberia-Newfoundland margins: the archetypal example of a magma-poor margin

Due to the large number of open domain geophysical and geological data sets, the Iberia-Newfoundland margins constitute a natural laboratory to study magma-poor rifted margins. These conjugate margins are located in the southern North Atlantic and face the Iberian Peninsula and Newfoundland/eastern Canada (Fig. 2-3). In particular the DSDP and ODP Legs (DSDP Leg 11; ODP Legs 102, 149, 173, 210) provided a unique data set at the distal rifted margins. Studies of this conjugate pair of margins resulted in a number of new concepts and ideas that have been developed in the last three decades, including first drilling of exhumed mantle (ODP Site 103; *Boillot et al.*, 1987), characterisation of exhumed mantle domains (*Whitmarsh and Wallace*, 2001) and hyper-extension (*Perez-Gussinye and Reston*, 2001; *Sutra et al.*, 2013) and the in-sequence faulting (*Péron-Pinvidic et al.*, 2007; *Ranero and Pérez-Gussinyé*, 2010). Several recent studies reviewed and described the structural evolution of the two conjugate margins (*Tucholke et al.*, 2007; *Péron-Pinvidic and Manatschal*, 2009) and described the restoration of the conjugate margins in 2 and 3D (*Sutra et al.*, 2013; *Mohn et al.*, 2015). Several plate kinematic restorations have been proposed, (see *Olivet*, 1996; *Sibuet et al.*, 2007; *Barnett-Moore et al.*, 2016; Nirregarten et al. in press) debating the validity of the M-series magnetic anomalies (*Sibuet et al.*, 2007; *Nirrengarten et al.*, 2017) and the amount of extension in the hyper-extended domain. There are also numerous studies that investigated the sedimentary evolution (*Wilson et al.*, 2001), the nature of the mantle and the magmatic additions (*Grange et al.*, 2008; *Müntener and Manatschal*, 2006; *Jagoutz et al.*, 2007).

In this thesis, I was mainly investigating the nature of the basement highs seismically imaged and drilled along the distal and ultra-distal Iberia-Newfoundland margins. I performed several seismic interpretations and analysed the basement highs that enabled me to distinguish between different types of basement highs and to propose a typology of basement highs including “Hobby High” type highs, extensional allochthone blocks, peridotite ridges and outer highs. Although these results have not been further developed, this study enabled me to define and understand the nature of basement highs at present-day ultra-distal margins. The results of this study are included in the appendix (see Annex 2).



A
Sutra et al. 2013
Bathymetry (meters)
Seismic reflection and/or refraction lines
ODP Sites
Magnetic anomalies
Orphan basin
Jeanne d'Arc basin
Flemish Pass basin
Flemish Cap
GRAND BANKS
SCREECH line 1
SCREECH line 2
NEWFOUNDLAND BASIN
Fogo seamounts
SE Newfoundland Ridge
GALICIA BANK
SPAIN (GALICIA)
PORTUGAL
SOUTHERN IBERIA ABYSSAL PLAIN
TAGUS ABYSSAL PLAIN
LG12
meters below sealevel
E
exhumed domain
hyper-extended domain
top acoustic basement
Depth (km)
3a
1-2
Peridotite Ridge
G
F
E
D
C
s-reflector
3:1 Vertical exaggeration
W
E
Dean et al. 2015
Distance (km)
Ocean-Continent-Transition
ultra-distal domain
distal domain
proximal domain
stretched domain
necking domain
hyper-extended domain
exhumed domain
oceanic domain
exhumed mantle domain
West
East
B
DEPTH (km)
after Sutra et al. 2013
continental limit of enhanced crustal thinning
coupling point
exhumation limit
breakup limit
C
UPPER PLATE
coupled to the mantle
D
LOWER PLATE
allochthonous block
upper and lower crust coupling

Fig. 2-3: **A** *Bathymetric maps of the Iberia-Newfoundland rifted margins with the location of the principal seismic section (Sutra et al., 2013).* **B** *Schematic section across the southern transect (SCREECH 2 and TGS/LG 12) illustrating the limits and domains (after Sutra et al., 2013).* **C and D** *Zoom on distal domain (after Sutra et al., 2013). E Seismic section of a Western extension showing the complex top basement geometry (from Dean et al., 2015).*

3. Ultra-slow spreading MOR: analogies with exhumed mantle domains at ultra-distal margins

The investigation of slow to ultra-slow spreading ridges, in particular along the Mid Atlantic Ridge (MAR) and the South West Indian Ridge (SWIR) resulted in the discovery of exhumed mantle domains associated with mega-mullions, also referred to as Oceanic Core Complex (OCC) (*Blackman et al.*, 1998; *Tucholke et al.*, 1998; *Ranero and Reston*, 1999; *Tucholke et al.*, 2008). An OCC can be generally defined as an oceanic tectonic structure with a dome shape made of gabbros and/or serpentinite and capped by an exhumation surface, also referred to as a detachment fault. These structures can be between 10 and 150 km wide in strike direction and 5 to 15 km wide in dip direction and can create topographies between 500 and 1500 m (for a description see *MacLeod et al.*, 2009; *John and Cheadle*, 2010; *Whitney et al.*, 2013). Volcanic and sedimentary rocks are often associated with these structures. DeMartin et al. (2007) published a section through the MAR at 26°N showing the thermal structure and strain distribution across an OCC. More recent studies include drilling and high resolution imaging of these structures (e.g. *Ildefonse et al.*, 2007; *MacLeod et al.*, 2009; *Hayman et al.*, 2011) showing that OCC can be accompanied by a number of other OCC or can be more isolated and located in an inside-corner situation associated with transform faults (*Blackman et al.*, 1998). The proportion of rock types either dredged or drilled along these slow or ultra-slow spreading centres is highly variable, but it appears that mantle exhumation is a common process.

Although OCC are formed at or in the vicinity of MOR, i.e. in a geodynamic context that may be different from ultra-distal margins, there may be many similarities between these two systems. Cannat et al. (2009) compared structures, rock types and processes between slow to ultra-slow spreading MORs and OCT. In this study I did not directly work on examples of OCC, however, the results obtained from the Platta nappe (Chapter 8) showed many similarities with these systems and are discussed in Chapter 9 and 10.

CHAPTER 3: APPROACH AND METHODS USED IN THE THESIS

In the last century the development of new concepts and models of rifted margins has been linked to the development of new methods, including geological, geophysical and modelling techniques (Fig. 3-1). While initial models were made of observations in the Alps and other orogens (*Argand*, 1916; *Steinmann*, 1925; *Elter*, 1972), the development of seismic imaging methods coupled with deep sea drilling enabled to propose models that integrate the architectural and lithological features observed at present-day rifted margin. More recently the development of numerical models (*Lavier and Manatschal*, 2006; *Brune et al.*, 2014) enabled to propose models that are able to develop tectonic simulations of rifted margins and to retrieve the physical parameters controlling these systems. However, these models remain largely 2D and the lateral evolution, i.e. the 3D architecture of these systems and their temporal evolution remain yet little understood.

One of the aims of my PhD thesis was to develop a multi-scale approach, based on the study of field analogues and comparison to seismic data. Indeed, in contrast to the present trend to use geophysical and modelling tools, my study is mainly based on the study of field analogues of ultra-distal rifted margin. The initial goal of the study was to investigate, based on seismic observations, the tectonic, magmatic and stratigraphic evolution of so called "Outer-Highs" (see definition of *Péron-Pinvidic and Manatschal*, 2010) located in the most distal parts of hyperextended rifted margins. However, the lack of drill hole data makes it difficult to investigate these structures without having access to field analogues. Therefore, the aim of the thesis project changed and became the description of possible field analogues exposed in the Err and Platta nappes. The mapping of these nappes and the field description of the relations between basement rocks, sediments and basalts enabled to analyse the Alpine and pre-Alpine rift related structures. Apart from the study of the Err and Platta nappes that constitute the core of the PhD, I visited and worked on other field areas in order to compare and better understand the geology of these domains. These studies are part of publications that are in preparation (e.g. Bonassola; see paper of *Decarlis et al. in prep*.). The same applies to seismic studies where I participated in different projects including the Iberia-Newfoundland margin (see Annex 2) the study of magmatic additions at present day rifted margins, or the Ocean Continent Transition in the Guinea margin (see Annex 3.1, *Gillard et al. 2017*) that are in the frame of collaborations with the Strasbourg group. Moreover, during my PhD I also initiated collaborations and co-supervised Master students in order to better understand the magmatic and sedimentary evolution, the fluid evolution and the nature and significance of Radiolarian cherts that form the first post-rift sediments in the Alpine Tethys system.

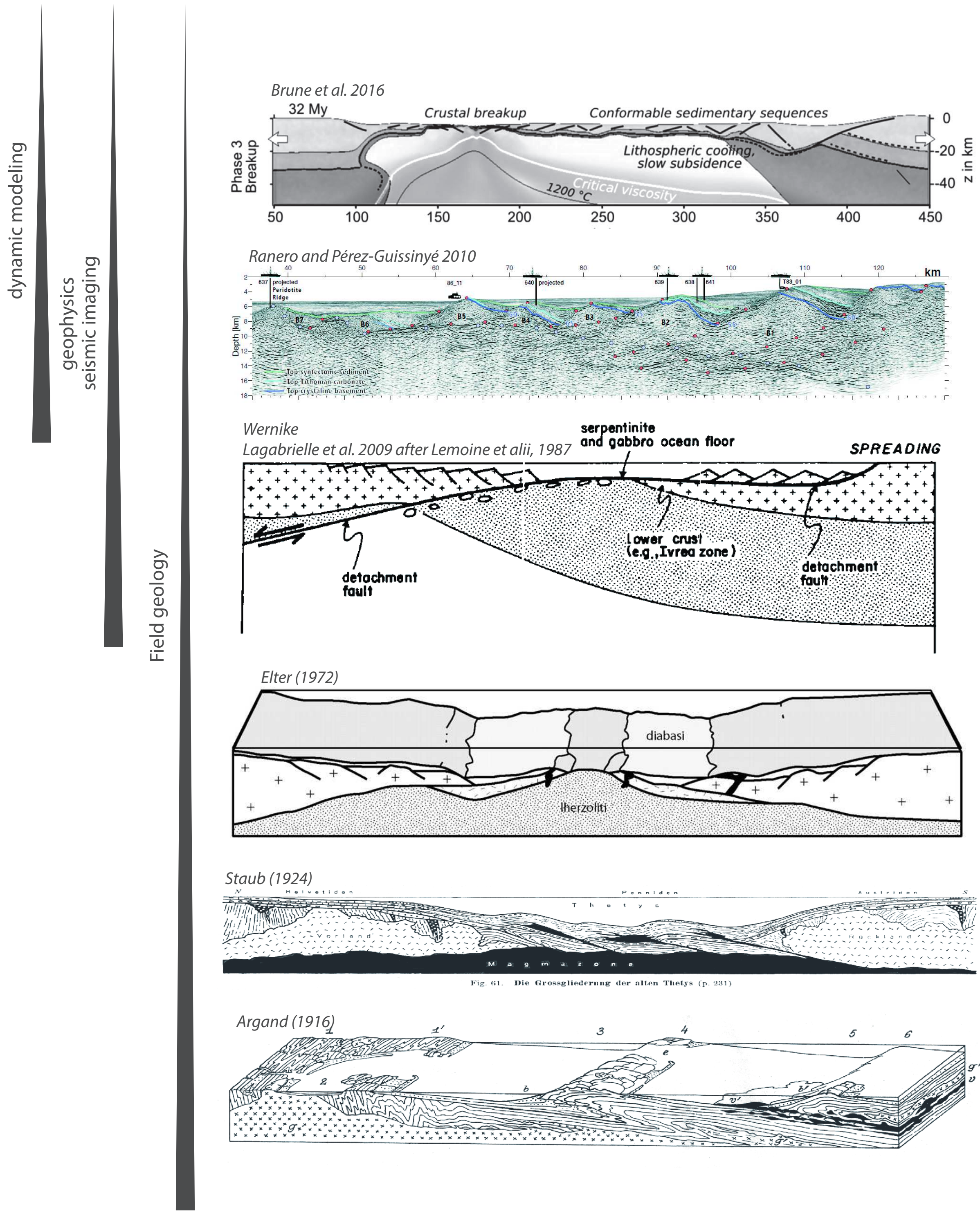


Fig. 3-1: *Schematic representation of the evolution of concepts and methods used to investigate rifted margins.*

CHAPTER 4: AIM AND ORGANISATION OF THE THESIS

1. Aim of the thesis

The aim of my thesis is to develop an observation driven approach using field analogues to scrutinize, test and improve the geological understanding of ultra-distal margins. The study focused on the investigation of hyper-extended and exhumed mantle domains of the former paleo-Adriatic margins of the Alpine Tethys domain today exposed in the Err and Platta nappes in the Central Alps in southeastern Switzerland. Based on classical fieldwork I investigated the polyphase tectonic, magmatic and fluid evolution of these domains. To better integrate the new field observations at a margin scale I compared the results with present-day analogues. Key questions addressed during my study are:

- How, when and under what conditions does extreme crustal thinning and lithospheric breakup occur?
- How do detachment faults thin the crust and eventually exhume mantle, where do these structures root at depth, how do they accommodate strain and how do they develop in time and space?
- What is the architecture of an exhumed mantle domain, how do tectonic and magmatic processes interact during their formation and what is the role of fluids during exhumation?
- What is the role of inheritance during extension and reactivation of distal magma-poor rifted margins?

2. Organisation of the thesis

The thesis consists of three parts: an introduction part, one part describing the main results and a final part that discusses the results. The core of the thesis comprises three main chapters, each one corresponding to a precise, well-defined theme corresponding to a scientific article that is preceded and followed by a short introduction and a discussion.

The first result chapter deals with the description of the study area (Err and Platta nappes) and includes a methodological approach to map and extract rift-related information from Alpine nappes, a conceptual restoration technique that enables to restore the pre-collisional situation and to discuss the relation between rift inherited structures and collisional reactivation (see Chapter 6, Paper 1).

A second chapter describes an exposed detachment system within the Err nappe that structured the former distal margin. It discusses the geometry and kinematics of this detachment system and its role in structuring the former hyper-extended rifted margin (see Chapter 7, Paper 2).

The third chapter describes the exhumed mantle domain and the related polyphase relationships between tectonic, magmatic and fluid systems and the related processes forming the ultra-distal margin preserved in the Platta nappe (see Chapter 8, Paper 3).

Finally I integrate the field observations at the scale of present-day distal rifted margins and compare them to present-day seismic sections of the Iberia-Newfoundland margin and slow and ultra-slow spreading ridges and numerical modelling results.

Additional data, field observations and interpretations, which have been used but not developed in the articles, are added in an appendix.

Part II: The distal and ultra-distal Alpine Tethys Margins exposed in Grisons: from observations to interpretations

Part II presents the main results of the thesis that are presented by an introduction to the studied field area (Chapter 5) and three chapters including one published paper and two that are in preparation to be submitted. The first result paper (Chapter 6) deals with the Alpine reactivation of the former Jurassic hyper-extended and exhumed ultra-distal rifted margin exposed in the Err and Platta nappes. The main goal is to discuss the role of rift inheritance during onset of convergence and its importance in structuring the Alpine nappe stack. The second result paper (Chapter 7) presents the architecture and evolution of a hyper-extended domain exposed in the Err nappe. This chapter aims to discuss the evolution of a detachment system and the related 3D architecture of a detachment system as well as the role of inheritance controlling their formation. The third result paper (Chapter 8) presents the interaction between tectonic, magmatic and fluid processes during the formation of an exhumed mantle domain. This chapter highlights the complex interaction between different processes and the final architecture of an exhumed mantle domain.

CHAPTER 5: REMNANTS OF THE DISTAL ADRIATIC MARGIN EXPOSED IN GRISONS: AN INTRODUCTION

Remnants of the distal Adriatic margin are exposed in Grisons (SE Switzerland) within the Austroalpine and South-Penninic nappe stack that formed during Late Cretaceous E-W directed convergence. During this collisional stage, remnants of the proximal margin were thrust onto the former distal margin resulting in a nappe stack that consists, from top to bottom of the Ortler nappe (proximal domain), the Campo-Grosina nappe (necking domain), the Bernina and Err nappes (hyper-extended domain) and the Platta nappe (exhumed mantle domain) (Fig. 5-1). In this study we focus on the Err and Platta nappes.

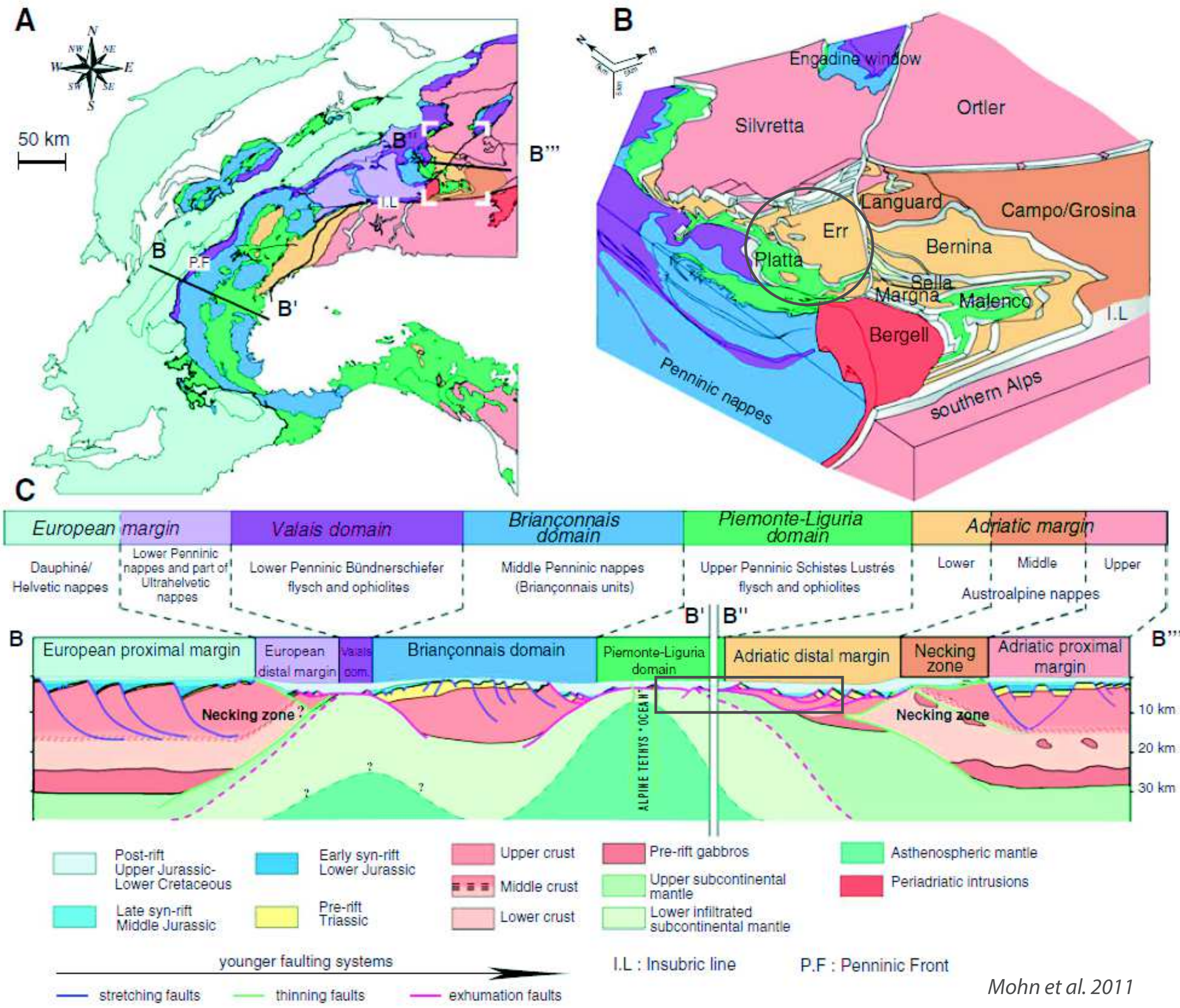


Fig. 5-1: **A** *Tectonic overview map of the Alps (Mohn et al., 2011 modified after Schmid et al., 2004).* **B** *Schematic block diagram of SE-Switzerland and N-Italy showing the position of the Austroalpine and Penninic nappes (Mohn et al., 2011 modified after Froitzheim et al., 1994).* **C** *Cross-section across the Alpine Tethys margin in Late Cretaceous time (Mohn et al., 2011 modified after Mohn et al., 2010).*

1. The Err and Platta nappes: an overview

The Err and Platta nappes have been studied since the 19^{teens} century. Steinman was the first to describe the "ophiolites" present in the Platta nappe. In his 1905 paper, and long time before the final acceptance of the Plate Tectonic theory, Steinman described the occurrence of serpentinite, diabase, and radiolarian cherts, and suggested that this rock association (e.g.

Steinman trinity) presented remnants of a fossil oceanic domain (*Steinmann*, 1925; *Steinmann*, 1927). The first comprehensive geological map of the Err nappe and eastern Platta nappe was made by Cornelius (1932a). Within this pioneering work, all structures were interpreted to be related to Alpine convergence. A number of thesis and Master studies followed (for reference see *Manatschal and Nievergelt*, 1997). Stöcklin (1949) mapped and described in detail the northern Err nappe. Dietrich (1970) mapped the western part of the Platta nappe and described the cover sequence exposed in the Platta nappe. This study provided the stratigraphic and tectonic framework and described the magmatic sequences in the Platta nappe. Trommsdorff and Evans (1974) established the Alpine metamorphic imprint of the Err and Platta nappes. Trümpy (1975) and Dietrich (1970) were the first to propose, based on the similar sedimentary and metamorphic evolution observed in the Err and Platta nappes that these units derived from a former rifted margin and constituted a part of an Ocean-Continent-Transition (Fig. 5-2). However, with the advent of the Plate Tectonic theory, the juxtaposition of continent and mantle derived rocks and the scattered magmatic additions have been interpreted to represent a “mélange” zone that formed during subduction of the oceanic domain underneath the European margin (*Hsü and Briegel*, 1991). Detailed mapping of the area together with the study of the magmatic rocks and stratigraphic sequences (e.g. *Dietrich*, 1970 and *Furrer et al.*, 1985a) combined with detailed structural analysis showed, however, that the Err and Platta nappes are the result of a complex tectonic evolution but do not represent a “mélange” zone.

Finger (1978), Furrer (1985a) and Eberli (1988) described the sedimentary evolution of the Triassic (pre-rift) and Jurassic (syn-rift) series in the Err and other Austroalpine nappes in Grisons. However, it was mainly the work of Froitzheim and Eberli (1990) that is at the origin of the understanding of the peculiar rift evolution of the Err nappe. These authors described a Jurassic low-angle detachment fault in the area of Piz Laviner in the Err nappe. The discovery of this extensional detachment fault in the Err nappe was the start of a research that lasted until today and that enabled and still enables to investigate the architecture and evolution of the distal Tethys margin. Indeed, the discovery of characteristic black gouges and their occurrence in Jurassic sedimentary breccias (*Froitzheim and Eberli*, 1990), enabled to identify the pre-Alpine age of this detachment system.

Handy (1993; 1996) and Froitzheim et al. (1994) investigated the structural evolution of parts of the Err nappe. Their studies documented the complex inherited architecture of the crustal basement, established systematic structural observations of the different deformation phases associated to the pre-Alpine and Alpine evolution of the area. Based on these structural

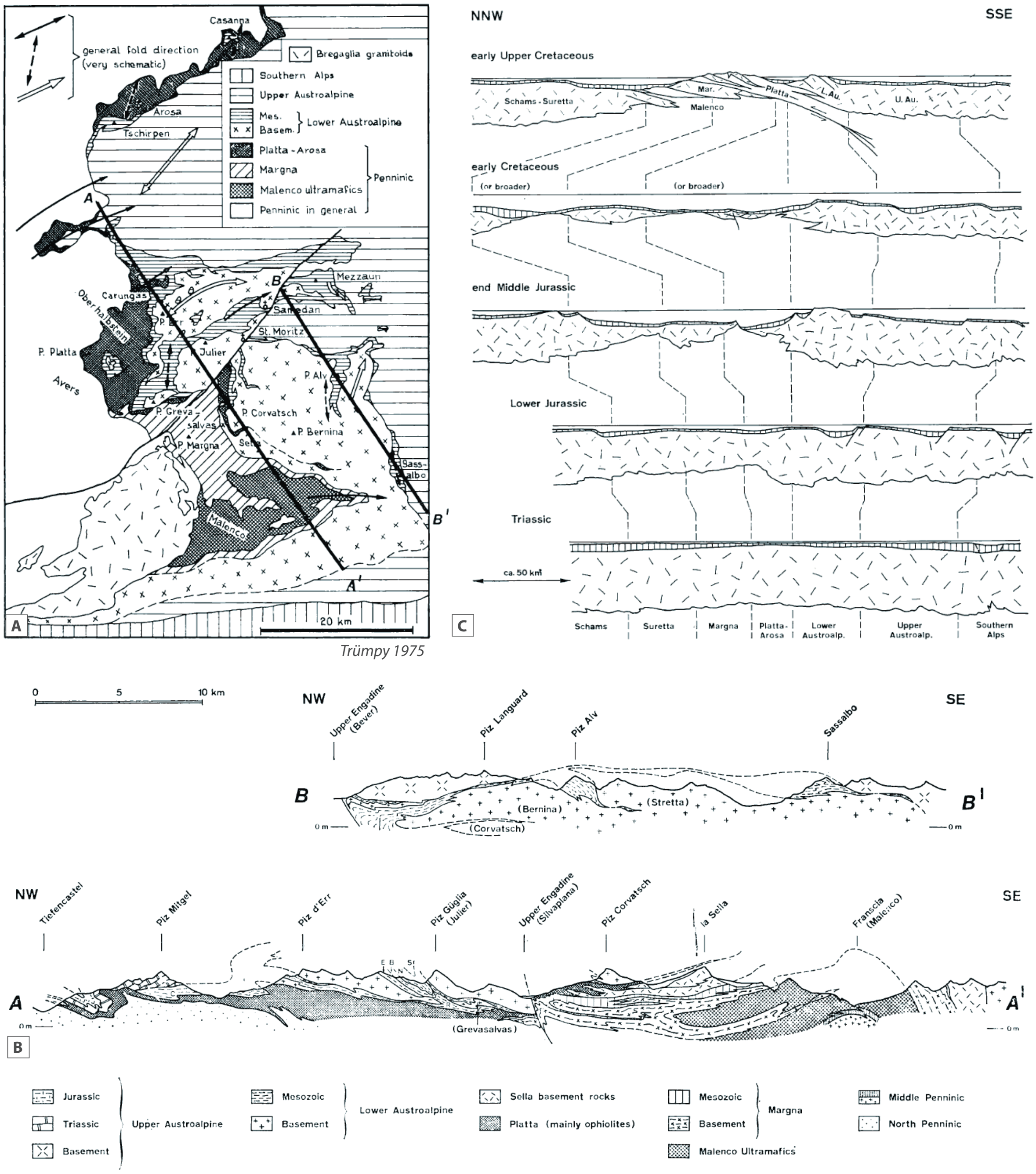


Fig. 5-2: **A** *Sketch map of the Upper Penninic and Lower Austroalpine nappes in southern and central Graubünden.* **B** *Simplified section and nappe stack.* **C** *Hypothetical palinspastic restoration through the Austroalpine and Penninic boundary zone. (Trümpy, 1975)*

studies and integrating the stratigraphic and petrological observations, these studies proposed a restoration of the area, in which tilted blocks bounded several sedimentary basins (Fig. 5-3).

Handy et al. (1996), Ferreiro-Mählmann (1996) and Eppel (1997) performed geochronological, petrological and geochemical studies that enabled to date the timing and thermal conditions of nappe emplacement, which are, in the area north of Bivio, below green-schist facies. Manatschal and Nievergelt (1997) (see Fig. 5-4) built on the work of Froitzheim

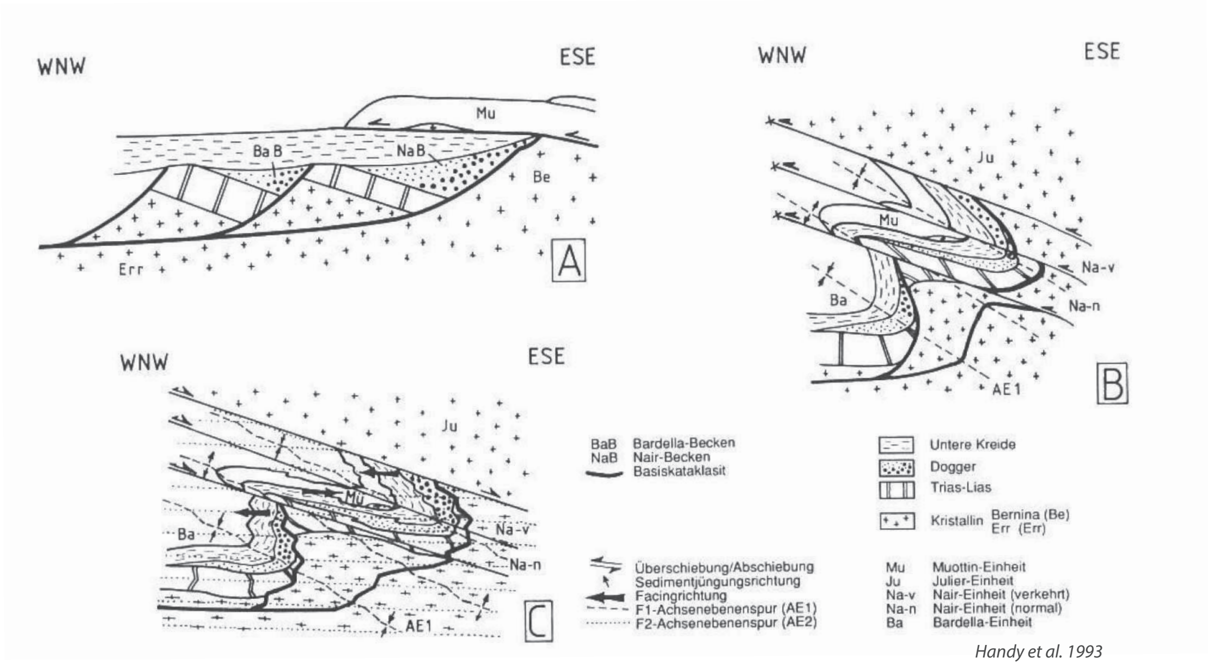


Fig. 5-3: *Model for the early Alpine deformation of the Jurassic Bardella and Nair basins in the Zone of Samedan.* **A** *Pre-D1 deformation phase.* **B and C** *Progressive reactivation of the Jurassic extensional faults within a fold and thrust belt (Handy et al., 1993).*

and Eberli (1990) and showed, based on a detailed study, the evidence of allochthonous blocks of pre-rift sediments onto detachment faults, characterized by characteristic black gouges that can also be found reworked into syn-rift sediments. These authors could also show that syn-rift sediments seal locally the detachment fault, which enabled to demonstrate that this detachment system was locally exposed at the seafloor. Moreover, allochthonous, continent derived blocks were also described to occur, along extensional detachment faults, over the exhumed mantle, These observations let to the suggestion that the Err and Platta nappes preserves remnants of a former OCT, which was magma-poor, sediment-starved and corresponded to a lower plate margin with a detachment system dipping toward the west, beneath the European margin. Although the occurrence of at least two detachments faults (Err and Jenatsch detachment faults) has been described, the significance and relationship between the two structures was not yet understood.

Manatschal (1999) showed, based on a structural and chemical study of the fault rocks related to the detachment, the importance of fluid and weakening reaction assisted controlling the strain localisation along the long offset detachment faults. This work has been completed and further developed by Pinto et al. (2013; 2015) and Incerpi et al. (2017). These studies supported the previous interpretation that the Err and Platta nappes were already juxtapose during final rifting and also highlighted the importance of hydrothermal activity associated to extreme crustal thinning and mantle exhumation. Masini et al. (2011; 2012) investigated the

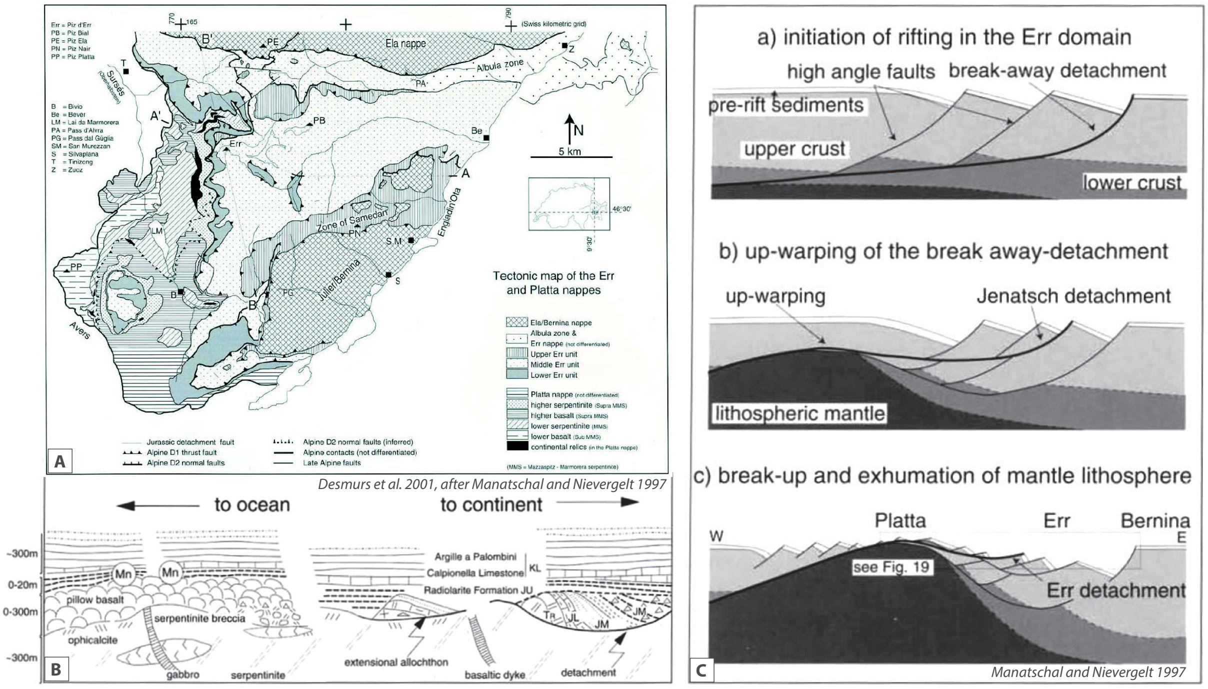


Fig. 5-4: **A** *Tectonic map of the Err and Platta nappe.* **B** *Schematic stratigraphic relationships between serpentinites, gabbros, basalt, post-rift sediments and relics of continental crust in the South Penninic Platta nappe.* **C** *Model of the detachment system showing the evolution from initial rifting to first mantle exhumation (Manatschal and Nievergelt, 1997).*

tectono-sedimentary evolution of the Err nappe and demonstrated the syn-tectonic nature of the Bradella and Saluver formations. Moreover, these authors improved the map of the Err detachment system, and focussed on the study of the syn-tectonic sedimentary processes.

In contrast to the Err nappe, the Platta nappe has been much less investigated in the last decades. Desmurs et al. (2001; 2002) and Schaltegger et al. (2002) published a structural and geochemical study on the Platta nappe. They differentiated between an Upper and a Lower Platta unit (i.e. upper and lower serpentinite units). In the Lower Platta unit, they demonstrated the occurrence of "oceanic" gabbros exhumed at the seafloor along detachment faults and reworked in breccias containing serpentinite, basalt and gabbro clasts. They also discussed the structural, petrological and geochemical relations between the gabbros and the basalts. Their results showed the evolution from T-MORB (Mid Oceanic Ridge Basalt) close to the continent, to N-MORB further oceanwards within the OCT. Müntener et al. (2004; 2009) described the nature of the mantle rocks within the OCT. They showed the occurrence of two types of mantle: cold and inherited and refertilized sub-continental mantle (for more details see *Picazo et al.*, 2017). Müntener et al. (2009) interpreted ultra-mylonites present in the top of the Lower Platta unit formed along a shear zone along which the hotter infiltrated mantle was exhumed underneath the colder, inherited mantle. A new version of the geological map of Bivio, which includes parts of the Err and Platta nappes which is essentially based on the map of Dietrich (e.g. PhD thesis of Dietrich, 1969) has been published by Peters (2007). This map formed the foundation of my field work and enabled me to create a new structural and geological map of the Err and Platta nappes.

2. The Err and Platta nappes revisited

The main question that was at the origin of my PhD thesis was related to the understanding of the origin and nature of basement highs at ultra-distal rifted margins. The Err and Platta nappes were chosen as field analogues, since they represent at present the best-studied and preserved example world-wide where the architecture and morpho-tectonic evolution of an ultra-distal domain can be investigated in 3D. My main contribution to the Err and Platta nappes consists in the mapping of rift and Alpine structures and the new interpretation of these structures in the light of the latest discoveries made in present-day ultra-distal margins. Improvements made in my thesis are presented in the following chapters and include a:

Compilation of structural data and creation of a detailed mapping method that enables to propose the restoration of Alpine deformation within the Err and Platta nappes. This study highlights the importance of inherited rift structures during the subsequent reactivation.

Re-mapping the Err detachment system, which enables to propose the 3D description of a detachment system made of 4 successive detachment faults (Err, Jenatsch, Agnel and Upper Platta detachment faults). This work highlights the complex architecture of a detachment fault system in a hyper-extended domain, the importance of inherited structures on the location of detachment faults, and explains the lateral termination of allochthonous blocks.

Mapping of the Lower Platta detachment and its paleo-topography thanks to the variation of the cover (sediments and basalts), and the description of the interaction between tectonic, magmatic and fluids during exhumation of the mantle in an ultra-distal magma-poor rifted margin.

CHAPTER 6: RESTORATION AND REACTIVATION OF A DISTAL RIFTED MARGIN

Preface

In this chapter, I discuss the key observations and methods used to restore the remnants of the distal and ultra-distal margins preserved in the Err and Platta nappes. This chapter provides the foundation of the thesis work and enables to get access to the main rift structures of the pre-Alpine, Jurassic rift architecture of the Adriatic ultra-distal rifted margin exposed in the Err and Platta nappes. In this chapter, I show that in order to unravel the ultra-distal margin architecture, the understanding of the subsequent reactivation leding to its emplacement in the Alpine mountain belt is a prerequisite. On the other hand, the reactivation can only be comprehended, if the pre-Alpine template is understood, since it has a major control on the early reactivation.

Mohn et al. (2011) presented a model that showed, at the scale of the Adriatic margin, the importance of the inherited-paleogeography of the margins during the subsequent reactivation and the formation and localization of 1st order thrust systems (Fig. 6-1). They showed that the 2 major structures reactivating the Adriatic margin were the Albula-Zebru and the Lunghin-Mortirolo movement zones. Between these two first order D1 structures (D1 phase

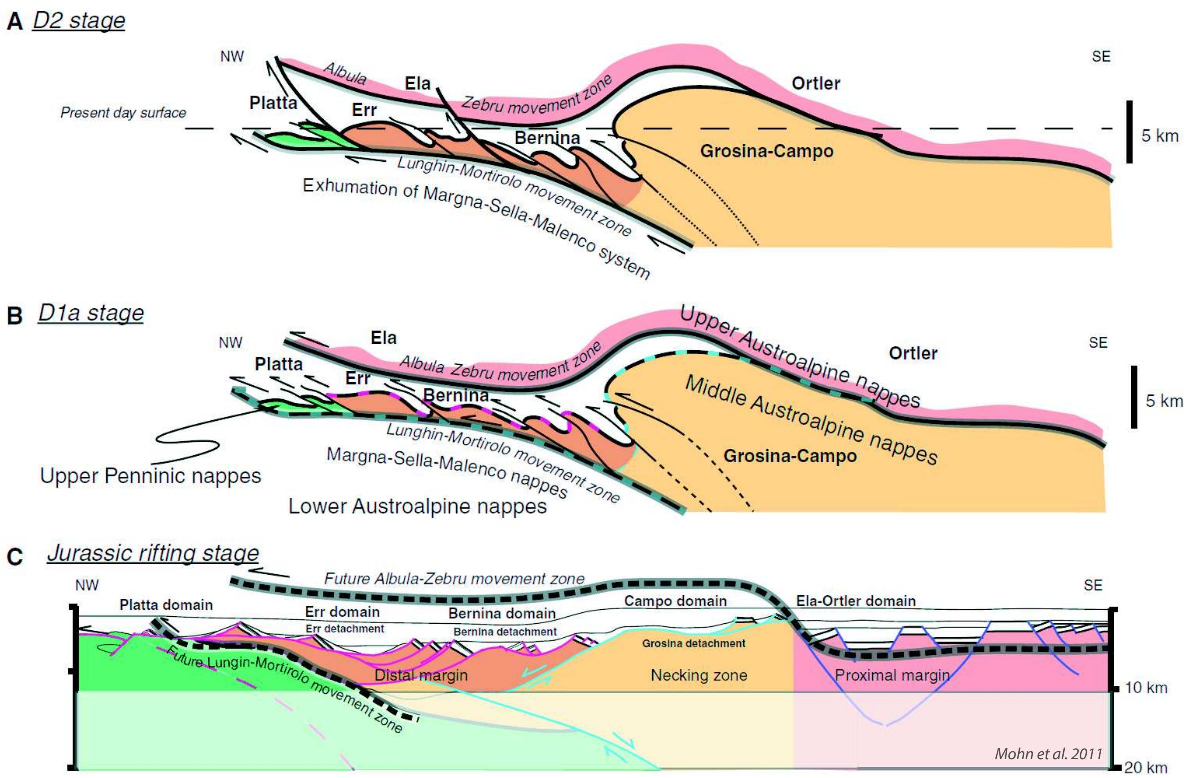


Fig. 6-1: *Large-scale restoration of the Austroalpine and Upper Penninic nappe stack in SE-Switzerland and N-Italy (Mohn et al., 2011).*

after *Froitzheim et al.*, 1994, first order D1 thrust after *Epin et al.*, 2017, see paper 1), minor, second and third order Alpine thrusts occurred. In this chapter (Paper 1), I focus on 2^{nd} and 3^{rd} order D1 thrusts that explain the reactivation of rift structures in the former distal and ultra-distal margin (Err and Platta nappes), and show their link to inherited rift structures of the former distal margin.

The aim of this chapter (Paper 1) is to understand the reactivation of the distal margin, the role of inherited structures and to propose a restoration of these rift domains.

Paper 1 (published in Swiss Journal of Geosciences)

Defining diagnostic criteria to describe the role of rift inheritance in collisional orogens: the case of the Err-Platta nappes (Switzerland).

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Abstract

It is commonly accepted that collisional orogens involve the reactivation of former rifted margins. While it remains debated how rift inheritance can be identified and how it controls the architecture of orogens this case study analyses the importance of rift-inheritance during reactivation of a passive margin. The study analyses complex, non-layer cake rift structures within the well-exposed Err and Platta nappes (SE Switzerland), representing the former distal Adriatic margin of the Alpine Tethys. Diagnostic criteria for rift inheritance includes: (1) typical fault rocks with a mantle derived fluid signature, and (2) tectonosedimentary breccias made of reworked exhumed basement and grading upwards into late syn- and post-rift sediments. Based on the study of ‘‘recognisable’’ features, a methodology is established, which enables to (1) map rift related detachment faults and (2) to analyse their role during reactivation and formation of a thrust stack. First, second and third order thrust systems are defined. First order thrust systems juxtapose different rift domains (proximal, necking, and distal). Second order systems are dominantly made up of basement sheets sampling the former footwall of an extensional detachment fault. Third order systems mainly consist of the former hanging wall of an extensional detachment fault. A major result of this study is that thrust faults commonly reactivate former extensional detachment faults, especially in the exhumed mantle domain (Platta nappe), while in the hyperextended domain (Err nappe) reactivation of rift-inherited structures is more complex and often incomplete. The results of this study may help to better identify remnants of former distal margins and to define and analyse their complex stacking patterns observed in many internal parts of collisional orogens.

Keywords: Reactivation, Rift inheritance, Distal margin, Err-Platta nappes, Grisons, Alps

1. Introduction

The Lower Austroalpine Err and Upper Penninic Platta nappes in SE-Switzerland preserves one of the best-documented distal margins including an Ocean-Continent Transition (*Dietrich*, 1970; *Trümpy*, 1975; *Froitzheim and Eberli*, 1990; *Manatschal and Nievergelt*, 1997; *Masini et al.*, 2012). Therefore, the study of these nappes enables to investigate how rift-inherited structures of a former distal rifted margin control the reactivation and formation of a collisional orogen.

The Err-Platta nappe system has been intensely studied for almost a century (*Steinmann*, 1925; *Steinmann*, 1927; *Staub*, 1946; *Trümpy*, 1975) using stratigraphic (*Furrer et al.*, 1985b; *Eberli*, 1988), petrological (*Trommsdorff et al.*, 1993; *Desmurs et al.*, 2002; *Müntener et al.*, 2004) and structural (*Dürr*, 1992; *Froitzheim and Manatschal*, 1996 and references therein) methods highlighting a complex Alpine and pre-Alpine evolution. In the past, tilted blocks bounded by high-angle normal faults were considered to be the major building blocks inherited from the rifted margin (*Montadert and others*, 1979; *Handy*, 1996). Recent investigations showed, however, that extensional detachment faults and related extensional allochthons are the dominant structures forming distal parts of magma-poor rifted margins (*Boillot et al.*, 1980; *Whitmarsh and Wallace*, 2001; *Osmundsen and Ebbing*, 2008; *Reston*, 2009; *Unternehr et al.*, 2010). The discovery of such structures in the Err and Platta nappes (*Froitzheim and Eberli*, 1990; *Manatschal and Nievergelt*, 1997; *Wilson et al.*, 2001; *Masini et al.*, 2011) went along with the description of similar structures in other locations in the Alps (e.g. Tasna nappe; Florineth and Froitzheim 1994; Manatschal et al. 2006).

At present, the extensional detachment faults found and described in the Alps by Froitzheim and Eberli (1990), Florineth and Froitzheim (1994), Manatschal and Nievergelt (1997) are the best described and exposed examples of these types of structures related to hyperextension and mantle exhumation world-wide. Although most of these structures were partly reactivated during their emplacement in the Alpine orogen, remnants of the extensional detachment system are still locally preserved. This enables to identify diagnostic criteria of these systems, which helps to discriminate between inherited rift structures and compressional structures. Indeed, distinguishing between rift inherited and orogenic structures is a prerequisite to interpret the structural evolution of collisional orogens (*Mohn et al.*, 2011; *Beltrando et al.*, 2014). In most cases the penetrative compressional overprint makes it difficult to recognize the former rift related structures. However, several recent studies described remnants of former distal margins in orogenic belts (e.g. Beltrando et al., 2014) and discussed their importance during reactivation (*Butler et al.*, 2006; *Mohn et al.*, 2014; *Tugend et al.*, 2014). Since in the case of the Err and Platta nappes Alpine overprint is relatively minor, remnants of the former extensional rift system can be confidently identified. In this study we use the Err-Platta nappe system to: 1) define diagnostic criteria of former distal margins, and, 2) show the control of rift-inherited structures during compressional reactivation.

2. Regional geological setting

2.1 Remnants of the distal margin preserved in the Err and Platta nappes

The study area discussed in this paper is located in SE-Switzerland. It comprises the Lower Austroalpine Err and the Upper Penninic Platta nappe system, comprising remnants of the former Jurassic distal Adriatic margin located along the south-eastern Piemonte basin belonging to the Alpine Tethys system. This rift system initiated during Late Triassic – Early Jurassic as a distributed and diffuse rift system before it localized in Late Sinemurian to Pliensbachian time leading to the formation of the future distal margin (*Eberli*, 1988; *Froitzheim and Eberli*, 1990; *Mohn et al.*, 2010). Final rifting related to the exhumation of crustal and mantle rocks and the formation of an embryonic oceanic domain occurred between 180 and 160 Ma (Middle Jurassic), as indicated by the dating of magmatic rocks (*Schaltegger et al.*, 2002) and diagnostic sediments (e.g. *Masini et al.*, 2013 for an overview).

Convergence in the greater Alpine domain started with the closure of the Meliata-Vardar domain during Jurassic time (*Ferriere et al.*, 2016) and migrated into the domain of the Austroalpine nappes discussed in this paper in Cretaceous time (Fig. P1-1). In the working area the transport direction of the main thrusts was from east/southeast to west/northwest and resulted in the emplacement of a nappe stack that telescoped the former western margin of the northern Adriatic microplate in Late Cretaceous time (for details see chapter below). The external part of this nappe stack includes remnants of the most distal parts of the Adriatic margin, exposed in the Lower Austroalpine and Upper Penninic nappes in the Central and Eastern Alps. During latest Cretaceous to early Cenozoic time, a new subduction zone initiated near the southern margin of the Piemonte basin (*Froitzheim et al.*, 1994; *Froitzheim and Manatschal*, 1996; *Froitzheim et al.*, 2006; *Mohn et al.*, 2012). At this stage, the previously formed, W to NW-vergent nappe stack became the hanging wall of the south-directed subduction that resulted in the closure of the Piemonte basin and eventually the collision of the northern Adriatic microplate with the European plate (Fig. P1-1). It is important to mention that the Err-Platta nappes were mainly affected, as further discussed below, by the initial and earlier W to NW-vergent stacking resulting in the reactivation and sampling of remnants of the former western Adriatic margin in a fold and thrust belt. Following the work of Froitzheim et al. (1994), this phase will be referred to

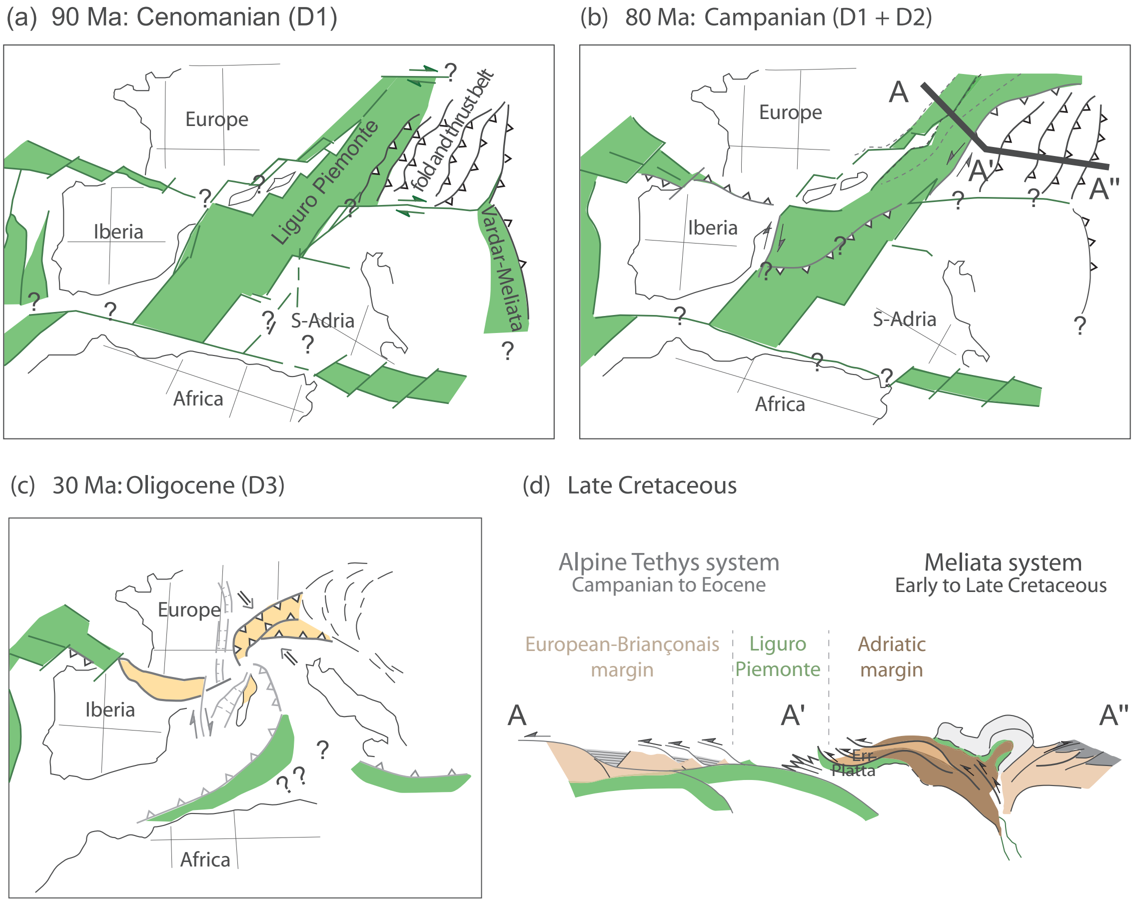


Fig. P1-1: *Paleogeographic maps of the Alpine realm for:* **(a)** *Cenomanian,* **(b)** *Campanian to Maastrichtian, and* **(c)** *Oligocene.* **(d)** *Section shows the Adriatic-European margins during the Late Cretaceous convergence. During this event, the distal part of the Adriatic margin was stacked in a fold and thrust belt. Note that the western part of the distal northern Adriatic margin was stacked in a fault and thrust belt already before the onset of subduction in the Liguria-Piemonte Ocean (figure modified after Manatschal and Müntener, 2009).*

as the D1 deformation phase. During D1 higher units belonging to the former proximal margin were thrusted westward onto the more distal domains of the western Adriatic margin. These Austroalpine and Upper Penninic units remained in the hanging wall of the Alpine subduction and were, as a consequence, relatively little affected by the subsequent latest Cretaceous to Oligocene subduction and collision, which was, in this part of the Alps, N-S directed (Fig. P1-1). The Err-Platta nappes were located, during this N-S shortening, above the singular point of the subduction system, i.e. the point separating retro from pro-thrusting/folding (*Beaumont et al.*, 1996). As a consequence, these units did neither show a strong tectonic nor metamorphic overprint during Cenozoic Alpine convergence. Metamorphism in the study area never exceeded prehnite-pumpellyite facies conditions (*Dunoyer de Segonzac and Bernoulli*, 1976; *Ferreiro Mählmann*, 1994; *Ferreiro Mählmann*, 1996). This explains the excellent preservation of the rift structures in the northern Err and Platta nappes, which enables to study the early stages of reactivation of the former western Adriatic distal margin.

2.2 Alpine deformation history

The main Alpine structural evolution leading to the formation of the Late Cretaceous W to NW-vergent nappe stack and its overprint during the subsequent N-S shortening has been reviewed by *Froitzheim et al.*, (1994) and has classically been subdivided into D1 to D5 phases of deformation (*Froitzheim et al.*, 1994). More detailed structural descriptions of the Err and Platta nappes have been published in Ring et al. (1990), Dürr (1992), Handy et al. (1993), Manatschal and Nievergelt (1997). The most important structures in the study area are the D1 structures, which are manifested by the emplacement of a top to the west to northwest thrust system (Fig. P1-1) resulting in the stacking of different rift domains, including the proximal, necking, hyperextended and exhumed mantle domains (*Mohn et al.*, 2011). It appears that the first order D1 structures juxtapose different rift domains. Second and third order D1 thrust structures juxtapose, as discussed later in this study, units derived from the same rift domain. While in the past these D1 structures and their kinematics have been well described, this study will present new observations that enable to describe and discuss the role of inherited rift structures in controlling the formation of D1 structures. The subsequent structures (D2 to D5) are less important in the study area. They include D2 structures that are mainly expressed by top-to-the-SE normal faults that formed during an extensional event predating the onset of N-S shortening (D3) related to the subduction of the Piemonte basin. These structures locally reactivate, but also cut D1 thrusts (*Handy et al.*, 1993; *Froitzheim et al.*, 1994; *Handy et al.*, 1996; *Manatschal and Nievergelt*, 1997; *Masini et al.*, 2011). The D3 structures correspond to Cenozoic north-south shortening, which is expressed by long wavelength fold structures with E-W trending fold axes and subvertical E-W striking fold axial planes. Locally north to northwest as well as south-vergent, steeply dipping thrusts with displacements in the order of hundreds of meters can be observed. Younger structures (D4 and D5) are related to late Alpine deformation (e.g. *Froitzheim et al.*, 1994). They consist of high angle normal faults presumably linked to activity along the sinistral Engadine fault, which is a conjugate fault of the Oligocene to Miocene Periadriatic dextral strike-slip system (for further discussion see *Trümpy*, 1977, *Schmid and Froitzheim*, 1993, *Handy et al.*, 1996).

3. Diagnostic criteria of a distal magma-poor rifted margin

3.1 Rift related Jurassic detachment faults

The Lower Austroalpine Err and Upper Penninic Platta nappes are one of the word's few examples where remnants of a distal margin, including well preserved extensional detachment faults, are beautifully exposed and described. Parts of the Err detachment were first mapped and described by Cornelius (1932) in terms of an Alpine structure. The occurrence of characteristic black indurated fault gouges along this structure (*Rath (von)*, 1857) and their reworking in Mid-Jurassic sedimentary breccias led Froitzheim and Eberli (1990) to interpret this fault as a Jurassic rift-related detachment fault. This structure preserves primary relationships between crustal and mantle rocks and pre-, syn- and post-rift sediments and magmatic additions. The footwall of the detachment fault system consists either of continental basement, exhumed serpentinised mantle or intrusive magmatic rocks (gabbros). The hanging-wall comprises allochthonous blocks made of continental basement, pre- and syn-rift sediments that are overlain by post-rift sediments or magmatic additions.

3.2 Fingerprints of fossil extensional detachment faults

Two major features characterize the paleo-distal margin (Fig. P1-2): 1) characteristic fault rocks and tectono-sedimentary breccias that are closely linked to the formation of extensional detachment faults, and 2) discontinuous pre- and syn-tectonic sequences associated with continuous post-rift sequences. Moreover, the juxtaposition of rock types derived from different crustal and mantle levels, sometimes erroneously interpreted as the result of convergence, can also be explained as the result of extreme extension as shown below.

3.2.1 Characteristic fault rocks and tectono-sedimentary breccias in hyperextended domains

Remnants of Jurassic extensional detachment faults in the Err and Platta nappes can often be identified thanks to characteristic black and green fault rocks, leucocratic bodies and ophicalcites (*Manatschal and Nievergelt*, 1997, Desmurs et al. 2001). The fault rocks associated with these extensional detachment faults can be distinguished from their Alpine counterparts by the mineralogy, the geochemical signature and their fabrics as well as by the relationship of the fault rocks with the overlying hanging wall, in particular where the faults were exhumed at the seafloor (*Manatschal and Bernoulli*, 1999; *Pinto et al.*, 2015; *Incerpi et al.*, 2017). Indeed, extensional detachment faults can, in contrast to thrust faults, be exhumed at the seafloor and be covered by syn- to post-rift sediments. Due to the fact that they are exhumed, the fault and underlying footwall rocks can also be reworked in the overlying syn-tectonic sedimentary sequence, which is not possible along thrust faults. Therefore, the occurrence of footwall-derived clasts in sedimentary breccias overlying a fault surface is an important criterion to define extensional detachment surfaces.

In the Err nappe, gouges, cataclasites and breccias constitute the principal fingerprints

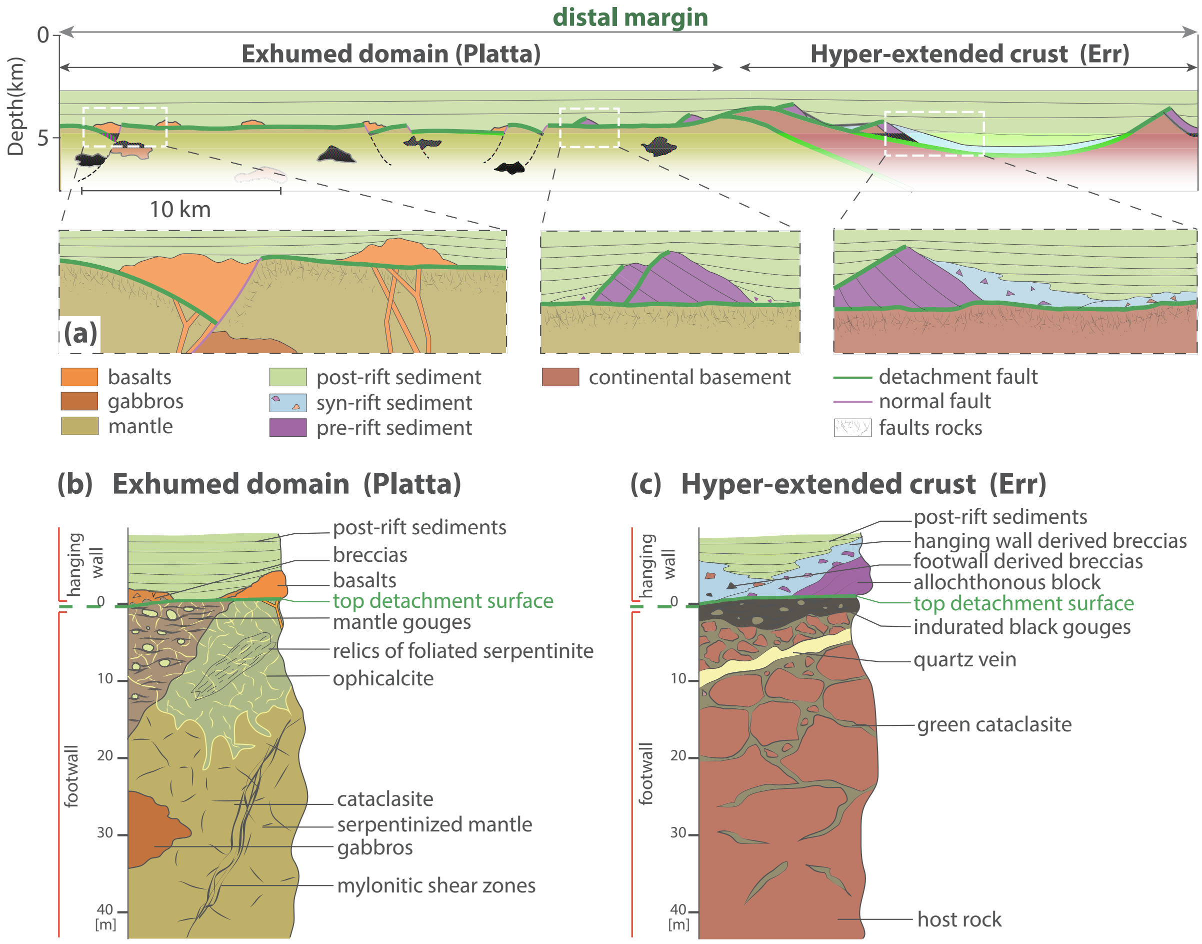


Fig. P1-2: **(a)** *Schematic cross-section across the distal Adriatic margin showing the first order architecture of the distal margin before offset of Alpine convergence. Cartoons illustrate the stratigraphic and structural relationships at different locations along the distal margin. Conceptual sections representing the fingerprints of a detachment system are shown in:* **(b)** *the exhumed mantle domain, and* **(c)** *the hyperextended domain.*

of the Jurassic detachment faults (Fig. P1-2). They are commonly located at the top of the basement, locally also within the basement (*Manatschal and Bernoulli*, 1999; *Manatschal et al.*, 2000; *Pinto et al.*, 2015). An idealized section across a top-basement detachment fault is represented in Figure 2c. Such sections start some tens to hundreds of meters below the top of the basement with green, cemented cataclasites (damage zone). The cataclasites have angular clasts of variable size and a fine-grain matrix/cement made of quartz, albite, chlorite and illite. The occurrence of albite, illite and chlorite results from the intense fluid- and reaction-assisted breakdown reactions of feldspars (*Manatschal*, 1999). The main slip surface of the detachment system (core zone) is characterized by indurated black gouges (*Froitzheim and Eberli*, 1990; *Manatschal and Bernoulli*, 1999; *Manatschal et al.*, 2000). They either occur between the hanging wall and the footwall, or, where the basement has been exhumed, at the interface between basement and syn-rift sediments (exhumed detachment surface). In the latter case they are often found reworked within tectono-sedimentary breccias forming the base of the syn-rift sequence overlying exhumed detachment surfaces. These black gouges are centimetre to several metres thick and form sharp contacts with the green cataclasites. They show a matrix-supported texture and a scale-independent/fractal fabric. Pinto et al. (2015) showed that in the Err nappe these rocks have a "mantle" chemical signature (enriched in Cr, Ni, and V), and Incerpi et al. (2017) also demonstrated the important hydrothermal fluid flow. The clasts are derived mainly from the footwall and include green cataclasites. Clasts are rounded or elongated and are embedded in a phyllosilicate-rich foliated black matrix. Hanging-wall derived Triassic dolomite clasts are less common but can be observed in the black gouges, clearly showing that these gouges have to be Triassic or younger. Similar fault rocks have also been observed along extensional detachment systems at other hyperextended domains, such as in the Tasna Ocean-Continent-Transition, in the Mauléon basin in the Western Pyrenees or drilled in the present-day Iberia distal rifted margin (*Manatschal et al.*, 2006; *Masini et al.*, 2013). In all these cases they occur along exhumation surfaces showing similar textures, mineralogy and chemical signatures. Another important marker of extensional detachment surfaces is the occurrence of footwall derived breccias (tectono-sedimentary breccias) (*Masini et al.*, 2012). In the Err nappe these breccias correspond to the Saluver A formation (*Finger*, 1978; e.g. basal track of *Masini et al.*, 2012). These breccias are made of polymictic breccias and reddish litho-arenites consisting of the resedimentation of fault rocks and basement rocks derived from the exhumed footwall of the detachment. Similar breccias in an identical position have been drilled along the Iberia margin (ODP Site 1068; *Wilson et al.*, 2001) and are found along all known detachment systems in hyperextended margins (*Masini et al.*, 2011).

3.2.2 Characteristic fault rocks and tectono-sedimentary breccias in exhumed mantle domains

In the Platta nappe, which corresponds to the exhumed mantle domain, serpentinised mantle, serpentinite cataclasites and gouges, ophicalcites and tectono-sedimentary breccias constitute the main fingerprints of Jurassic extensional detachment faults (e.g. Falotta outcrops). These rocks are similar to fault rocks and breccias drilled at several ODP sites along the Iberia-Newfoundland margins (e.g. ODP Sites 1068, 1070, 1277; *Manatschal et al.*, 2001), dredged over slow spreading oceanic ridges or observed in other Alpine type ophiolites (e.g. *Manatschal and Müntener*, 2009; *Picazo et al.*, 2013). An idealized section across a top-basement detachment fault starts some tens to some hundred metres below the top of the basement, with a protolith, often corresponding to a foliated, massive serpentinised peridotite or a gabbro (Fig. P1-2b). Up-section, fractures and veins filled by syn-kinematic chlorite and serpentine minerals mark the transition into serpentinite or gabbro cataclasites. Bands of localized deformation formed by foliated serpentinite cataclasites occur locally. Mylonitic shear zones are locally observed in mantle rocks and gabbros but they are always overprinted by brittle deformation. The intensity of brittle deformation increases up-section and develops into a core zone, which is formed by serpentinite gouges (for a description see *Picazo et al.*, 2013). Penetrative impregnation and replacement by calcite (*Manatschal et al.*, 2001; *Robertson*, 2007) is observed near the seafloor, which forms characteristic "ophicalcites" (*Bernoulli and Weissert*, 1985; *Treves and Harper*, 1994; *Treves et al.*, 1995). The occurrence of tectono-sedimentary breccias made of reworked exhumed mantle rocks, locally also containing continent-derived clasts, overlies the exhumed subcontinental mantle. The occurrence of ophicalcites resulting from the interaction between serpentinised mantle and seawater, and indicating exhumation of mantle at the seafloor, was firstly interpreted by Decandia and Elter (1972), *Bonatti et al.*, (1974) and Bernoulli and Jekyns (1974) and Jenkyns (1974). Today, brittle fault rocks, i.e. cataclasites and gouges associated with ophicalcites and tectono-sedimentary breccias are widely recognized from mid-ocean ridges (e.g. *Bonatti et al.*, 1974; *Escartín et al.*, 2003; *Boschi et al.*, 2006; *Lagabrielle and Bodinier*, 2008) and have been drilled along the Iberia–Newfoundland margins (e.g. ODP Sites 1068, 1070, 1277; *Manatschal et al.*, 2001). Indeed, all drill sites that penetrated basement along the Iberia-Newfoundland margins sampled sedimentary breccias that pass down-hole into tectono-sedimentary breccias that overlie brittle, hydrated fault rocks forming the top of the basement. The detachment surface is sealed by post-rift sediments or by magmatic additions; locally it is overlain by continent derived blocks. This complex, but very characteristic association of rocks, with well-defined textures, chemical signatures and mineralogy as exemplified in the Platta nappe, enables to identify and map remnants of ancient extensional detachment surfaces in the exhumed mantle domain. In this study we use these criteria to map remnants of former detachments faults.

3.2.3 Discontinuity of pre- and syn-rift sequences and continuity of post-rift sequences

As shown in Figure 2a, the rift architecture at distal margins is characterized by non-continuous layers with isolated continent derived blocks and punctual magmatic extrusions constructing over exhumed fault surfaces, altogether sealed by post-rift sediments. The best-documented example is the large allochthonous block drilled at ODP Site 1069 along the Iberia Abyssal Plain (*Wilson et al.*, 2001; *Péron-Pinvidic et al.*, 2007). The occurrence of such extensional allochthons, floored by a continuous, hydrated top basement is probably the principal characteristic of present-day and fossil distal margins.

In the Err and Platta nappes the hanging walls of the Jurassic extensional detachment faults are preserved in the area of Piz Err - Piz Jenatsch in the northern Err nappe (Fig. P1-3). The allochthonous blocks observed in this area consist of continental basement and pre- and early syn-rift sediments. It is important to note that such pre-rift sequences form isolated allochthonous blocks that are bounded by syn-tectonic sediments and sandwiched between two continuous marker horizons, namely the detachment fault surface and the base of the post-rift sequence. In the example of the Err and Platta nappes, the Upper Jurassic Radiolarian Chert Formation is defined as the first post-rift sediment in the sense that it is the first sediments that the cherts overlie embryonic oceanic crust (Mid Ocean Ridge Basalts; MORB) and seal the rift structures in the adjacent continental margin (*Trümpy*, 1975). They are overlain by micritic limestones with intercalations of shales and calcarenites referred to as Aptychus or Calpionella limestone, Upper Jurassic to Lower Cretaceous in age; and the Argille a Palombini Fm., which is considered to be of Lower Cretaceous to Albian age (*Weissert and Bernoulli*, 1985). In the Platta nappe, magmatic additions (MOR-basalts) occur locally over exhumed mantle and are time-equivalent of the early post-rift sediments, i.e. the Radiolarian Chert Formation. The magmatic additions consist principally of tholeiitic MOR-basalts (*Desmurs et al.*, 2002) that become more voluminous oceanwards and are locally observed to cover exhumed mantle rocks. In most of these examples, the basalts are formed by pillow breccias and hyaloclastites.

Thus, while post-rift sediments were deposited in a sub-horizontal position and where passively onlapping on a residual topography inherited from the rift stage, the pre- and syn-rift sequences show more complex and less continuous sequences. They were disrupted already before the onset of convergence and can therefore not be considered as simple “layer-cakes”. This is important when studying remnants of former distal margins in orogens, since the lack of continuity is often misinterpreted as the result of poly-phase compressional deformation.

3.2.4 Continent derived blocks associated with serpentinised mantle

The occurrence of blocks of continental origin within sequences made of serpentinites, MOR-basalts and gabbros have often been interpreted as tectonic “mélanges” formed during subduction (*Hsü and Briegel*, 1991). However, similar rock associations have been drilled at present day Ocean-Continent-Transitions (see results of ODP drill Sites 1068, 1070, 1277; *Manatschal et al.*, 2001). Yet, tectonic mélanges related to subduction should result in random mixing of basement and sediments and should therefore lack any stratigraphic layering (see *Gerya et al.*, 2002; *Beltrando et al.*, 2010b), while associations derived from distal margins show the characteristic fingerprints discussed in the previous sections. Thus, looking for these fingerprints enables to distinguish between the two scenarios i.e. juxtaposition of crustal and mantle rocks in a subduction or collisional setting or during the formation of a distal margin. In the latter case, the juxtaposition typically occurs along brittle extensional faults that are formed by characteristic fault rocks and along which footwall derived rocks are found reworked in tectono-sedimentary breccias overlying an exhumation fault (for details see previous section; Fig. P1-2).

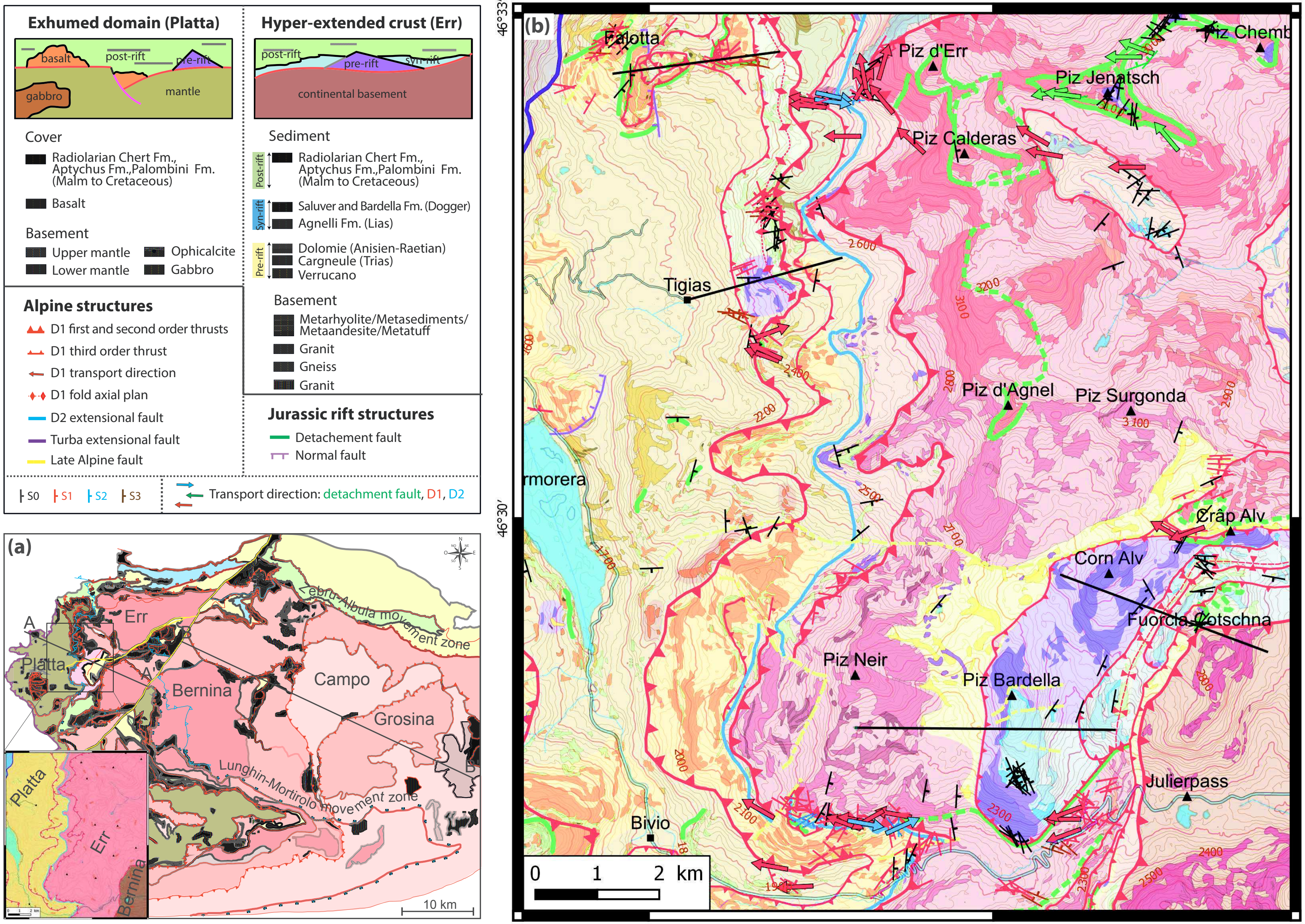
4. Distribution and kinematics of major Jurassic rift-related and Alpine orogenic structures

In figure P1-3 we present a new geological and structural map using existing and own observations of the area north and west of the Julier valley and confined in the north along a line linking Falotta-Piz Err-Piz Jenatsch. We mapped the distribution of Jurassic detachment faults (green lines in Fig. P1-3b) using the previously described diagnostic criteria, which enables to define and map the continuity of these structures.

Alpine structures include D1 Alpine thrust faults that are represented in the map in Figure 3 by thick red lines. D1 structures separate nappes that were stacked in sequence from east to west and include from top to base the Bernina, Err and Platta nappes (Fig. P1-3a). Second and third order D1 Alpine thrust faults are represented by thinner red lines (Fig. P1-3b). In this study we will show that most of the third order D1 thrust faults reactivate former Jurassic detachment faults. Alpine D2 structures (blue line in the map Fig. P1-3) are only locally observed in the study area and do not affect the areas further discussed in this study. Alpine D3 structures are manifested by large scale; east and west plunging folds with subvertical steep east-west striking fold axial planes and minor south and north vergent thrust faults. Since offsets along these faults never exceed 300 meters and transport direction is always N-S directed, we will not include these faults in our E-W oriented restored sections.

In Figure 3b we compiled existing and new kinematic and structural data for both the Jurassic and Alpine structures. Our data show, in line with previous studies (*Froitzheim et al.*, 1994; *Manatschal and Nievergelt*, 1997; *Masini et al.*, 2011) that the kinematics of the two major fault systems, the Jurassic and Alpine D1 faults, are approximately co-linear both associated with E-W to SE-NW trending transport directions.

Fig. P1-3: *Tectonic and geological map of the Lower Austroalpine and Upper Penninic Err and Platta nappes in SE-Switzerland.* **(a)** *Geological map of the Austroalpine and Upper Penninic nappes modified after Mohn et al., 2011, showing location of the geological map Fig. 1-3b and section AA' BB' in Fig. 1-8b. Inset shows simplified tectonic map of the tree major tectonic units (Bernina, Err, and Platta) and major, first order D1 structures.* **(b)** *Geological map of the Err and Platta nappes compiled after Cornelius, 1932b; Cornelius and Clar, 1935; Staub, 1946; Cornelius, 1950; Spillmann and Büchi, 1993; Froitzheim et al., 1994;Manatschal, 1995a; Peters, 2005; Trommsdorff et al., 2005; Peters, 2007 and own observations.*


Exhumed domain (Platta)
basalt
post-rift
pre-rift
gabbro
mantle
Hyper-extended crust (Err)
post-rift
pre-rift
syn-rift
continental basement
Cover
Radiolarian Chert Fm., Aptychus Fm.,Palombini Fm. (Malm to Cretaceous)
Basalt
Basement
Upper mantle
Ophicalcite
Lower mantle
Gabbro
Sediment
Post-rift
Radiolarian Chert Fm., Aptychus Fm.,Palombini Fm. (Malm to Cretaceous)
Syn-rift
Saluver and Bardella Fm. (Dogger)
Agnelli Fm. (Lias)
Pre-rift
Dolomie (Anisien-Raetian)
Cargneule (Trias)
Verrucano
Basement
Metarhyolite/Metasediments/ Metaandesite/Metatuff
Granit
Gneiss
Granit
Alpine structures
D1 first and second order thrusts
D1 third order thrust
D1 transport direction
D1 fold axial plan
D2 extensional fault
Turba extensional fault
Late Alpine fault
Jurassic rift structures
Detachement fault
Normal fault
S0
S1
S2
S3
Transport direction: detachment fault, D1, D2
(a)
Err
Platta
Bernina
Campo
Grosina
Engadin-Albula movement zone
Lunghin-Mortirolo movement zone
10 km
A
A'
B
Platta
Err
Bernina
(b)
9°39′
9°42′
46°33′
46°30′
Falotta
Piz d'Err
Piz Chemb
Piz Jenatsch
Piz Calderas
Tigias
Piz d'Agnel
Piz Surgonda
rmorera
Crap Alv
Corn Alv
Fuorcla Cotschna
Piz Neir
Piz Bardella
Julierpass
Bivio
0 1 2 km

5. Reactivation of rift-inherited structures

In this chapter we focus on two examples where the interplay between rift-inherited structures and Alpine D1 structures is well exposed and not heavily overprinted by later Alpine events. The aim is to describe the interplay between rift-structures and Alpine D1 structures during reactivation. Based on the observation that the two phases are co-linear and show the same E-W to SE-NW directed kinematic transport direction we will construct and cinematically restore E-W directed sections that correspond to the former dip sections across the distal margin.

5.1 Bardella - Fuorcla Cotschna area (hyperextended domain)

5.1.1 Geological overview

The Piz Bardella - Fuorcla Cotschna area is well-exposed over 50 km^2 in the area north of the Julier Pass (Fig. P1-4). Maps and detailed structural analysis have previously been presented in Handy et al. (1993), Froitzheim et al. (1994), Manatschal and Nievergelt (1997). In this study we define 5 subunits, all separated by third order Alpine D1 thrusts, and sandwiched between the Bernina and the Platta nappes along major D1 structures (Fig. P1-3). This top to the west nappe stack has been overprinted by minor south and north vergent D3 thrusts that will not be further discussed.

As shown in figure P1-4c, subunit 1 is limited at its top by the Bernina thrust and at the base by a minor thrust that juxtaposes a granitic basement over syn-rift sediments. Subunit 2 is delimited at its base by a thrust that juxtaposes little deformed syn-rift sediments against post-rift sediments. Subunit 3 consists of a kilometre scale D1 fold that is delimited at its base along a thrust by pre- and syn-rift sediments. The fold axial plane of this north to northwest vergent synclinal fold dips with 30° to the south. It includes a complete section of pre- to syn-rift sediments (Bardella and Saluver Fms.) and post-rift sediments (Upper Jurassic Radiolarian Chert Formation and Upper Jurassic to Lower Cretaceous limestones). Subunit 4 is confined at its base by a thrust that juxtaposes Verrucano and meta-rhyolites onto cargneules and dolomites belonging to the pre-rift sequence. The evaporitic pre-rift sequence occurs only locally along the contact and is substituted by cargneules, leaving only relics of gypsum in cargneules to the south of the Corn Margun area (*Naef*, 1987; *Peters*, 2007). Further west subunit 5 contains thick meta-rhyolite, Verrucano sandstones, cargneules and relics of pre-rift dolomite. This unit overlies, along a D1 thrust contract, basalts and serpentinites belonging to the Platta nappe. All thrust contacts show old over young and a consistent top-to-the west sense of shear.

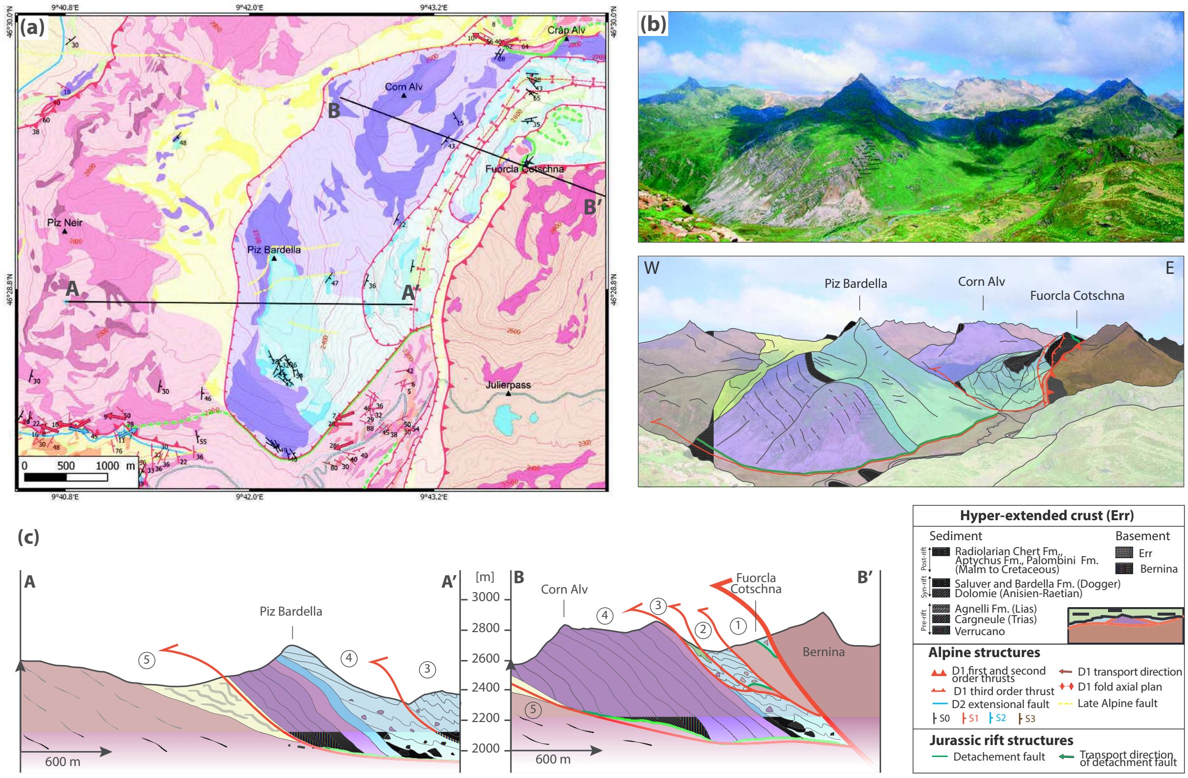


Fig. P1-4: **(a)** *Geological map of the Bardella-Fuorcla Cotschna area.* **(b)** *Photograph and line drawing of the panoramic view of the Piz Bardella - Fuorcla-Cotschna area (view from the south).* **(c)** *Geological section AA' and BB' located on the geological map shown in (Fig. 4a). Subdivision in subunits (1 to 5) defined on the basis of Alpine D1 thrusts.*

5.1.2 Composition of the subunits

Remnants of basement and pre-rift sediments occur in subunits 1, 3, 4 and 5 (Fig. P1-4c). Subunits 1 and 4 contain cataclasites and black gouges that are fingerprints of former Jurassic detachment faults (see previous section and Fig. P1-2). In subunit 1 a pre-Alpine rift related detachment structure is well preserved. This structure, previously described by Handy et al. (1993), Manatschal and Nievergelt (1997) and Masini et al. (2012) shows a granitic basement dominated by a strong cataclastic overprint and the occurrence of characteristic black gouges, overlain by syn-tectonic sediments. A key observation is that the overlying sediments are only little deformed and the contact to the strongly deformed basement is depositional. This is further supported by the fact that the black fault gouges are reworked within the overlying sediments. This observation shows that this structure had to be pre-Alpine and that the detachment had to be exposed at the seafloor in Jurassic time. The shallow angle between the sediments deposited over the exhumed basement and the exposed top basement shows that the footwall had to be shallow dipping to sub-horizontal when exposed at the seafloor.

In subunit 4 (Fig. P1-4c) another remnant of the detachment system is preserved as indicated by the occurrence of back gouges and green cemented cataclasites. These rocks occur along the contact between crystalline basement, meta-rhyolite and red immature sandstones (Verrucano) in the footwall and pre-rift Triassic dolomites dipping with 46° towards the east in the hanging wall. Panoramic view and map (Figs. P1- 4a and b) show that these pre-rift dolomites wedge out south-eastwards. The top of the pre-rift sediments corresponds to an angular unconformity between early syn-rift (Agnelli Fm.) and late syn-rift sediments (Bardella and Saluver Fm.; *Masini et al.*, 2011).

Except for subunit 5 (Fig. P1-4c), syn-rift sedimentary breccias can be found in all other subunits. It is important to note that their composition changes from only pre-rift derived carbonate dominated breccias (Bardella Fm.) in subunit 4 to predominantly basement derived breccias and sandstones (Saluver Fm.) in subunit 1. The increase of basement derived clasts going from subunit 3 to 2 and 1 (Fig. P1-4c) reflects the disappearance of the Triassic dolomites as a local source and the appearance of basement as a new source. This observation is compatible with the disappearance of the pre-rift Triassic dolomites in subunits 3 to 1 (Fig. P1-4c) and deposition of syn-rift sediments directly over exhumed basement. These observations show that the pre-rift Triassic dolomite had to be discontinues and floored by a Jurassic extensional detachment fault.

The change in composition of the breccias from hanging wall to footwall derived has been explained by Masini et al. (2011) to reflect the progressive extension along detachment faults. Thus, despite of the changes in composition in the syn-tectonic sedimentary sequence within the different subunits, the sediments have been interpreted to derive from one and the same depositional environment (e.g. *Masini et al.*, 2011). This is supported by the observation that the post-rift sediments are the same in all subunits.

5.1.3 Links between rift inheritance and reactivation

In the Bardella-Fuorcla Cotschna area characteristic fault rocks (cataclasites, black gouges, and basement derived breccias) can be found together with isolated blocks of pre-rift units, interleaved by syn-tectonic sequences and continuous post-rift sediments stacked within top-to-the west thrust sheets. Detailed mapping shows that the thrust sheets form complex Alpine subunits containing remnants of a Jurassic extensional detachment system. The field observations also indicate that the thrust partly reactivated the inherited Jurassic detachment that was used as a decollement level during reactivation (Fig. P1-5). Since the kinematics of the Jurassic and Alpine fault systems were approximately co-linear, both trending E-W to SE-NW, a simple qualitative restoration of the Piz Bardella-Fuorcla Cotschna area can be proposed in a section parallel to the transport direction (Fig. P1-5). The restoration of the 5 subunits, which are at present stacked one on top of each other, puts them back to their pre-Alpine position. Along

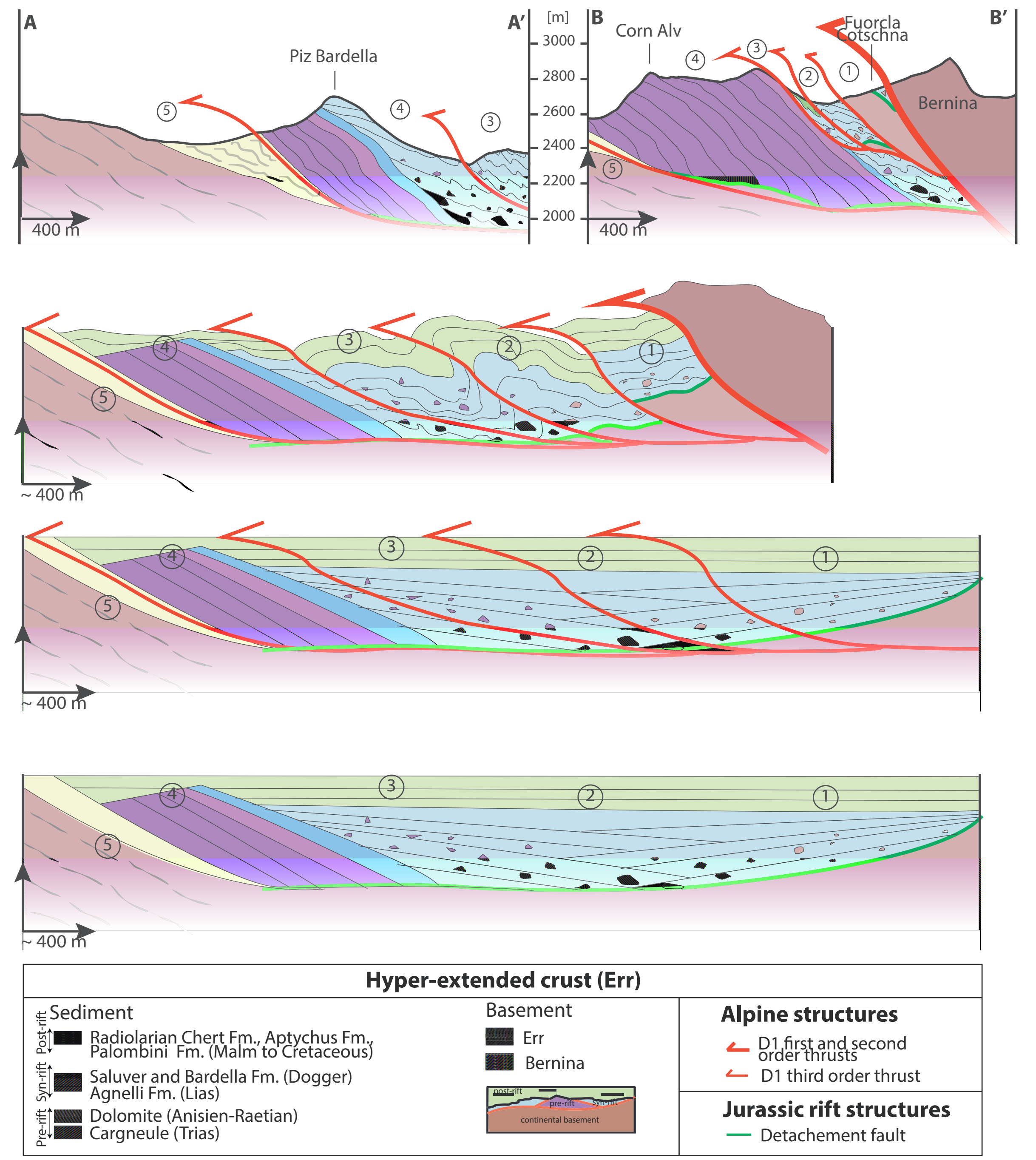


Fig. P1-5: Restoration of the present-day geological section AA' and BB' back to the end of rifting in late Middle Jurassic time (for location of the present section see Fig. 4a). Note interference between D1 thrust structures and inherited Jurassic rift structures (for further explanations see text).

with the restoration of the thrust sheets, also the major fold observed in subunit 3 has been restored back to the paleo-architecture of the Bardella-Fuorcla Cotschna area prior to Alpine convergence. Based on the observations reported above, the pre-Alpine configuration was not a simple layer cake, but consisted of discontinuous pre-rift blocks (extensional allochthons) floored by a detachment system and sealed by syn- to post-rift sediments. It is important to note that in our restoration we do not restore the pre-rift units back to continuous layers, as often done in restorations, but we align remnants of the detachment system and the post-rift sequence. Thus, the observed juxtaposition of different lithologies (basement, pre- and syn-rift sediments) is not the result of a complex Alpine deformation, but the result of in-sequence thrusting during D1 shortening (Fig. P1-5) that reactivated a complex rift architecture.

5.2 Falotta-Tigias area (exhumed mantle domain)

5.2.1 Geological overview

The Falotta-Tigias area (Fig. P1-6) belongs to the Lower Platta unit, which is confined at its top by a major D1 thrust along which the Upper Platta unit was thrust westwards over the Lower Platta unit (Desmurs et al. 2001). At its base the Lower Platta unit is floored by the Turba fault, an mid-Eocene to Early Oligocene normal fault (*Nievergelt et al.*, 1996; *Desmurs et al.*, 2001). The geology of the area is complex due to thrust slices, lateral thickness variations of the basalts and the occurrence of continent derived blocks interleaved between serpentinites, basalts and post-rift sediments.

Mapping of the Tigias-Falotta area enables a subdivion into 7 subunits (Fig. P1-6). Subunit 1 (Fig. P1-6c) is constituted of serpentinised mantle that is capped by serpentinite gouges and ophicalcites. This unit can be mapped throughout the Platta nappe and forms the backbone of the Lower Platta unit. In the Falotta area further north, subunit 1 can be subdivided into 1a and 1b (Fig. P1-6c) subdivided by a high-angle normal fault shown in the map in Fig. 6a with magenta colour. This contact is truncated by a D1 thrust fault and has therefore to be older. Subunit 1 is overlain by subunits 2 to 7 that represent thin slices typically floored by ophicalcites and serpentinites and overlain either directly by post-rift sediments (subunit 6), by basalt and post-rift sediments (subunits 2, 4, 5, 7), or by remnants of crustal basement and a larger piece of a pre-rift Triassic dolomite that is overlain by isoclinally folded Jurassic to Lower Cretaceous post-rift sediments (subunit 3). The overall geometry of the thrust stack is defined by thin duplexes that are separated by top-to-the-west to northwest vergent thrust faults (subunits 2 to 7) sandwiched between two continuous mantle bodies, corresponding to the upper and lower mantle serpentinite units, the latter corresponding to subunit 1 (*Desmurs et al.*, 2001). Thrust faults limiting the duplexes are typically decoupled along the top of subunit 1 within ophicalcites or along exhumation related serpentinised fault zones. The thrust faults ramp westwards across the cover (basalts and/or post-rift sediments) leading to local repetitions and tectonic thickening of the cover sequence.

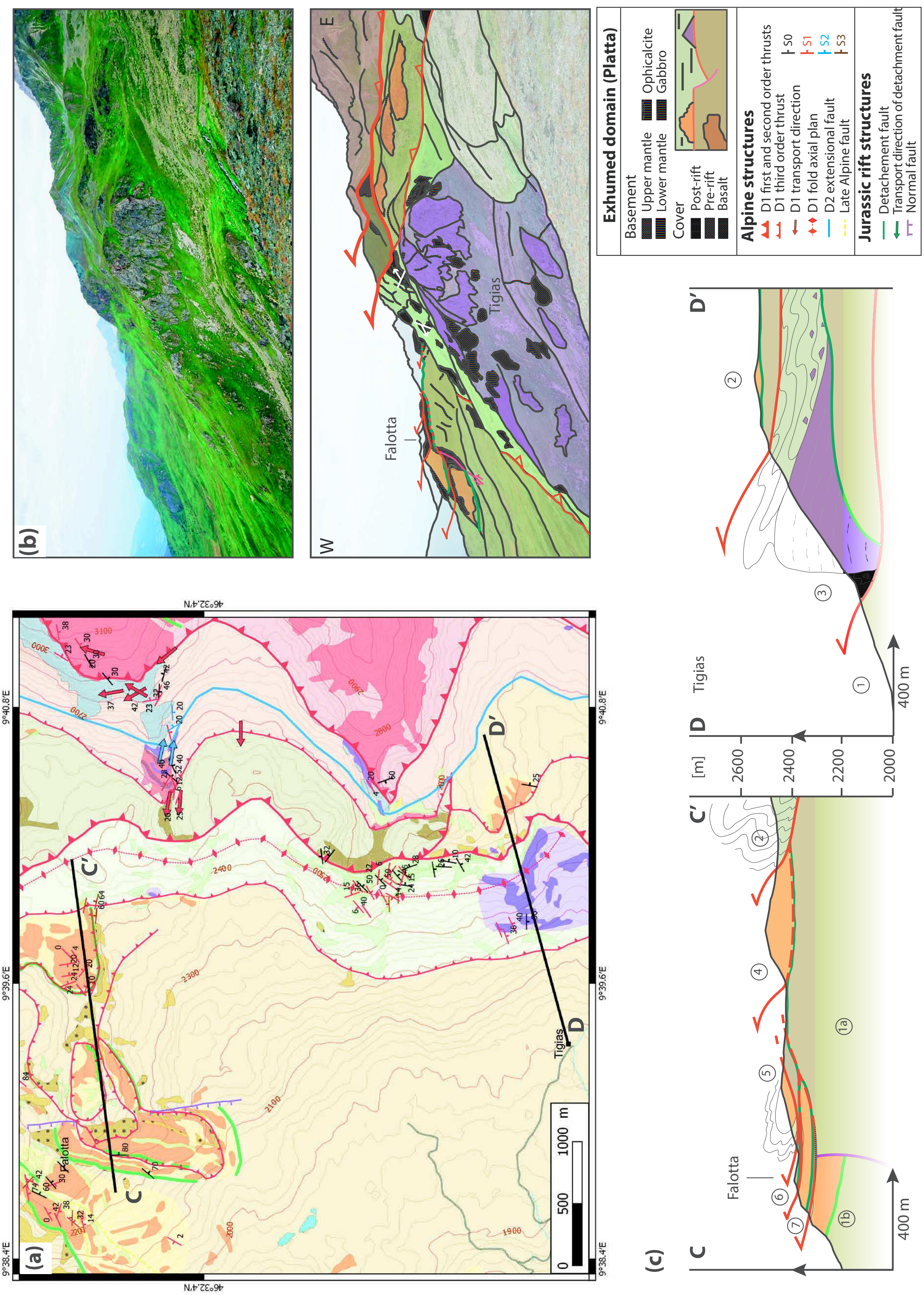


Fig. P1-6: **(a)** *Geological map of the Falotta-Tigias area.* **(b)** *Photograph and line drawing of the panoramic view of the Tigias - Falotta area (view from the south).* **(c)** *Constructed sections CC' and DD' across the Falotta-Tigias area (for location of the sections see geological map shown in Fig. 6a. Subdivision in subunits (1 to 7) defined by Alpine D1 thrust faults.v*

5.2.2 Content of the subunits

The occurrence of cataclasites and gouges, ophicalcites and tectono-sedimentary breccias observed at the top of subunit 1 (Fig. P1-6c) is reminiscent of an extensional detachment fault capping exhumed mantle. Indeed, these rocks are very similar to those drilled during ODP Legs 103, 149, 173 and 210 at the top of exhumed mantle along the Iberia and Newfoundland margin (*Picazo et al.*, 2013).

Another potential pre-Alpine structure is the steep normal fault separating subunits 1a and 1b (Fig. P1-6c). This structure coincides with thickness variations of basalts and the occurrence of hydrothermal systems and ore deposits (magnetite, chrome, *Geiger*, 1948, Peters, 2007). It is important to note that these ore deposits are aligned along this steep, N-S striking structure separating subunits 1a and 1b. Since this steep normal fault is truncated by a D1 Alpine thrust we interpret it as an oceanic normal fault that offset a previously exhumed mantle surface.

The continent derived block in subunit 3 (Fig. P1-6c) is overlain by the Radiolarian Chert Formation containing detritic layers with clasts of gneiss, pillow basalts and grains of spinel (*Manatschal and Nievergelt*, 1997). The mixt detritus shows the proximity of continental and proto-oceanic units during Jurassic time. Thus, the remnants of continental basement and pre-rift dolomites in subunit 3 are best interpreted as representing an allochthonous block overlaying mantle and sealed by post-rift sediments.

5.2.3 Links between rift inheritance and reactivation

Since the kinematics of the Jurassic and Alpine fault systems were approximately co-linear, both trending E-W to SE-NW, subunits 1 to 7 mapped in the Falotta - Tigias area (Fig. P1-6) can be restored in an E-W section (Fig. P1-7). The occurrence of serpentinite gouges and ophicalcites at the top of subunit 1 as well as at the base of most of the other subunits show that the major decoupling surface was the top basement. Thus, the exhumation surface corresponding to a Jurassic detachment fault played a key role during reactivation of the margin. The thick slices corresponding to subunits 2 to 7 sampled the former hanging wall of the exhumed mantle made of volcanic edifices, continent derived blocks and sealed by post-rift sediments. More complex structures such as the stacking of subunits 5 to 7 may coincide with the occurrence of an oceanic normal fault. Across this fault thickness variations of the basalts can be observed. The occurrence of small continent derived allochthonous blocks or volcanic edifices, laterally confined by post-rift sequences, may have played an additional control on the formation of small duplexes and folds in the post-rift sequence.

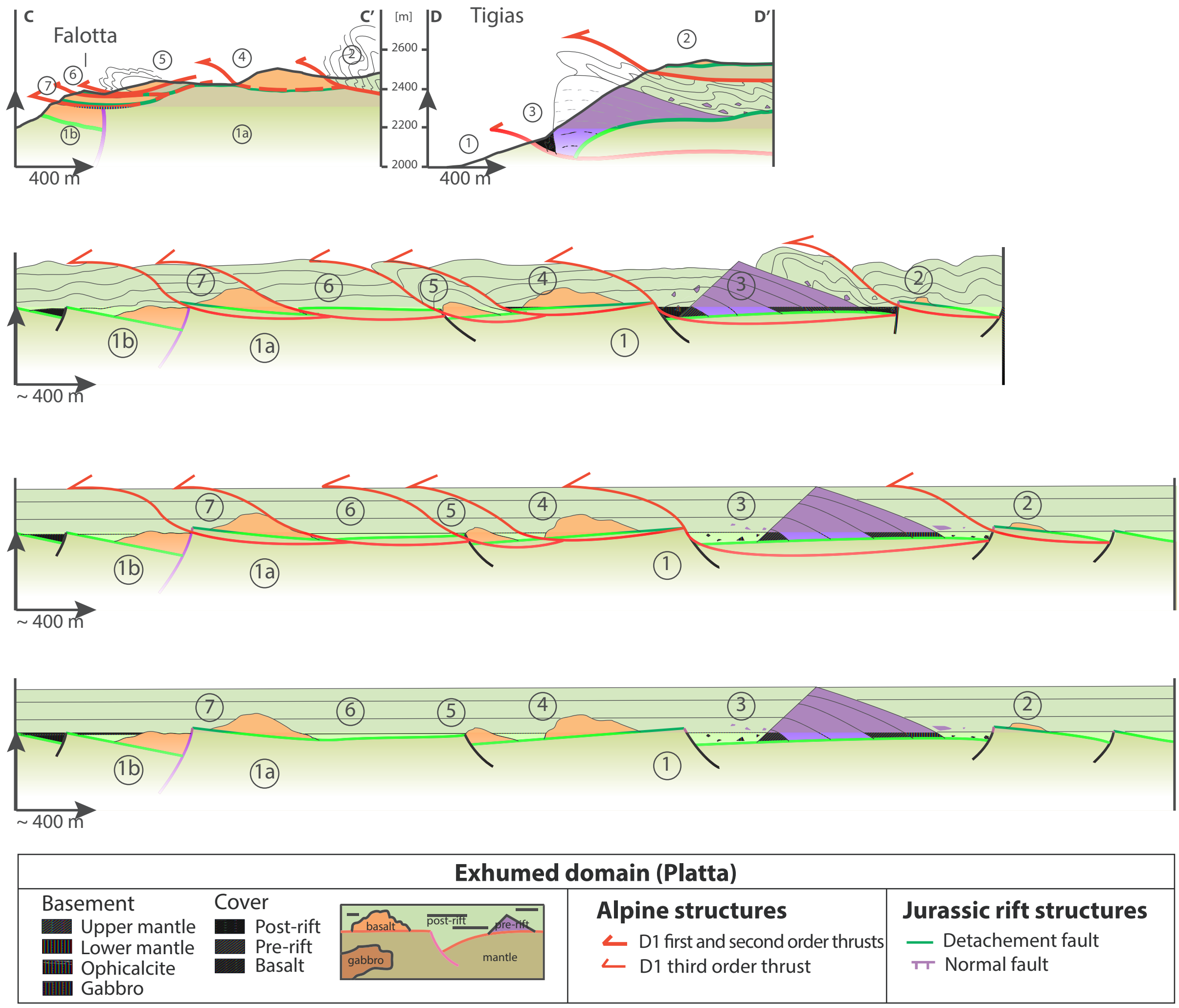


Fig. P1-7: Restoration of the present-day geological sections CC' and DD' back to the late Middle Jurassic situation (for location of the sections see Fig. 6a). Note interference between D1 thrust structures and inherited Jurassic rift structures (for further explanations see text).

6. Discussion

Magma-poor distal rifted margins consist of a complex arrangement of hyperextended continental crust and exhumed mantle. Key structures that can be identified in these settings are extensional detachment faults overlain by allochthonous blocks that are interleaved with syn-rift sediments and sealed by post-rift sediments. Oceanwards magmatic additions, often associated with syn-magmatic faults, occur and overprint older exhumation faults. Due to the complex, non-layer cake nature of these domains, their identification in collisional orogens is difficult and as a matter of fact very controversial. Therefore we focus here on the Err and Platta nappes, where the extensional detachment system has been described in detail (e.g. *Masini et al.*, 2012 and references inhere). The results of this previous work, together with the weak Alpine tectonic and metamorphic overprint, enable to identify diagnostic fingerprints of former distal margins and to map their structures and investigate their role during Alpine reactivation.

Therefore the following discussion focusses on three main questions: 1) what criteria can we use to identify remnants of a fossil distal margin in an orogenic setting, 2) how does rift inheritance control reactivation, and 3) how can small scale outcrop observations be up-scaled and thrust structures be hierarchized and linked to inheritance. The discussion is based on the observations and maps realised in the Err-Platta nappes presented in this work.

6.1 Using diagnostic criteria to identify remnants of distal margins in orogenic domains: a methodological approach

The pioneering studies of Steinman (1925), Cornelius (1932b), Dietrich (1970) and Stöcklin (1974) suggested, based on field observations, a very similar tectono-stratigraphic evolution of the Err and Platta nappes. These observations were refuted after the advent of the Plate Tectonic theory. The major argument was that the juxtaposition of rocks of crustal and mantle origin could not be reconciled with Plate Tectonic models. As a consequence, all structural complexities became imperatively interpreted as being related to complex collisional processes. In the case of the Platta nappe, the occurrence of continental and mantle derived material was interpreted by some workers as the results of “tectonic mélanges” (*Hsü*, 1995; *Dürr*, 1992). However, drilling and seismic imaging of the most distal parts of the Western Iberia rifted margin and its comparison with outcrops in the Err and Platta nappes showed that the observed “complexity” is not the result of Alpine deformation only, but is also partly inherited from the former rifted margin (*Manatschal and Bernoulli*, 1999; *Wilson et al.*, 2001). The studies of Froitzheim and Eberli (1990), Desmurs et al. (2001), Manatschal (2004) and Masini et al. (2012) provided a description of the structures related to hyperextension and exhumation during Jurassic rifting. Based on these studies and their comparison with present-day rifted margins, it became possible to define diagnostic criteria that enable to identify remnants of former distal margins in collisional orogens. However, at present there are only few systematic studies in which these diagnostic criteria have been defined and used to map and describe the role of these structures for the subsequent reactivation. The Err and Platta nappes represent, due to the weak tectonic and metamorphic overprint, one of best places to develop and test a methodological approach to identify and study the role of rift inheritance during reactivation of a distal margin. The approach used in this study includes four major steps, which are:

1) Identification of the major and minor Alpine deformation phases responsible of the stacking of so called “coherent thrust sheets” corresponding to internally coherent remnants preserving structures inherited from the former margin;

2) Mapping of these coherent units and identification of the kinematics of their emplacement;

3) Search for diagnostic criteria to identify the occurrence of inherited rift structures in these coherent thrust sheets;

4) Kinematic and palinspastic restoration of the thrust sheets.

The major difference to classical restorations is step 3. Classical restorations tend to overemphasise the importance of tilted blocks and to restore post-rift sedimentary units back to continuous sub-horizontal layers (e.g. “layer cake concept”). However, observations at modern, seismically imaged and drilled distal magma-poor rifted margins (e.g. *Peron-Pinvidic et al.*, 2013) show that these domains are characterized by: 1) discontinuous pre- and early syn-rift sequences and continuous post-rift sediments, and 2) juxtaposition of crustal and mantle rocks along brittle extensional detachment systems. Although in detail the mapped units (e.g. coherent thrust sheets, here called subunits) consist of complex associations of rocks, the occurrence of characteristic rocks-types such as ophicalcites, silicified cataclasites and gouges with characteristic geochemical fingerprints and tectono-sedimentary breccias reworking exhumed basement rocks enable to identify and map remnants of former extensional detachment faults and to reconstruct them by the kinematic inversion of the Alpine deformation. This paper is the first which uses this approach in a rigorous way to map the inherited structures and to investigate their control on the reactivation of a former distal margin. Ignoring “rift” inheritance in orogenic settings, in particular in internal parts of orogens, may significantly change the structural interpretations of collisional belts as shown in the example of the Err and Platta nappes.

6.2 Role of rift inheritance in reactivation of distal margins

6.2.1 Reactivation of a hyperextended domain

In the Piz Bardella - Fuorcla Cotschna area (Fig. P1-4) folds and thrusts overprint inherited rift- structures. The most prominent inherited structure is an extensional detachment fault, which can be identified in subunits 1 and 4 (Fig. P1- 4 and 5). While in the case of Fuorcla Cotschna in subunit 1 (Fig. P1-6c) the detachment is not reactivated and its contact with syn-rift sediments is preserved (Fig. P1-7), the former detachment has been reactivated in subunits 3 and 4. Thus, only some of the pre-existing detachment surfaces are reactivated. Potential factors that may have controlled the reactivation are the original orientation and the morphology of the fault plane. In the cases of complex fault morphologies (lateral ramps, domes or discontinuities due to offsets along later faults), thrust faults cannot copy and reactivate the complete inherited fault surface. In this case the thrust fault can either incise into the footwall or excise into the hanging wall of the inherited detachment system. This can explain the local preservation of primary contacts between extensional detachment faults and the sediments (e.g. Fuorcla Cotschna, Fig. P1-5), but also their absence (e.g. subunits 2 and 3, Fig. P1-5). In the example of subunit 4, the extensional detachment fault was partly overlain by Triassic evaporates. The occurrence of these evaporates may have facilitated the reactivation of this surface.

A second observation made in the Piz Bardella - Fuorcla Cotschna area is the occurrence of kilometre scale folds within the syn- and post-rift sediments in subunits 2 and 3 (Fig. P1-5). These large-scale folds are not observed in subunit 4 that is made of a massive block of Triassic pre-rift sediments. This block is interpreted as a kilometre scale, NE-SW trending extensional allochthon, floored by an extensional detachment fault and defining the north-western termination of a massive syn- to post rift sequence found in subunits 1 to 3. We therefore propose that the allochthonous block may have acted as a local buttress for the syn- and post-rift sediments controlling the formation of large-scale folds observed in subunits 2 and 3. This interpretation is compatible with the observation that the strike of this block is parallel to the fold axes of the kilometre scale fold (Figs. P1- 4 and 5).

6.2.2 Reactivation of an exhumed mantle domain

In the Falotta - Tigias area (Fig. P1-6) D1 thrust faults are predominantly located at the top of subunit 1, i.e. at the top of the massive serpentinite mantle. The overlying duplexes (subunits 2 to 7) are made up either of basaltic bodies (subunits 2, 4, 5, 6, 7) or of continent derived blocks (subunit 3). All subunits (Fig. P1-6c) include the same post-rift sequence, some also serpentinites and/or ophicalcites. These observations suggest that top-basement topography played a major control during reactivation (Fig. P1-7). Volcanoes and extensional allochthons that likely can be attributed to positive topography occur in duplexes. This suggests that the occurrence of “ramps” was controlled by the existence of inherited topography, while the “flats” correspond to the reactivation of the former detachment fault localized at the top of the exhumed mantle.

An inherited syn-magmatic oceanic normal fault truncating and offsetting the top of the mantle is observed at Falotta. This fault dips to the west i.e. it was not preferentially oriented for a reactivation by a top-to-the-west thrust system. This may explain the preservation of this structure; however, its presence may also explain the local complexity and stacking of three subunits (5, 6, and 7). In contrast, faults with paleo-dips to the east may have been completely reactivated.

Prominent large-scale isoclinal D1 folds occur in the sediments associated with the major block of pre-rift sediments observed in subunit 3. These folds may be explained, like in the example of the Bardella-Fuorcla Cotschna area, by local top basement topography acting as local buttresses during convergence (Fig. P1-7). Other examples may be normal faults offsetting top basement or volcanoes.

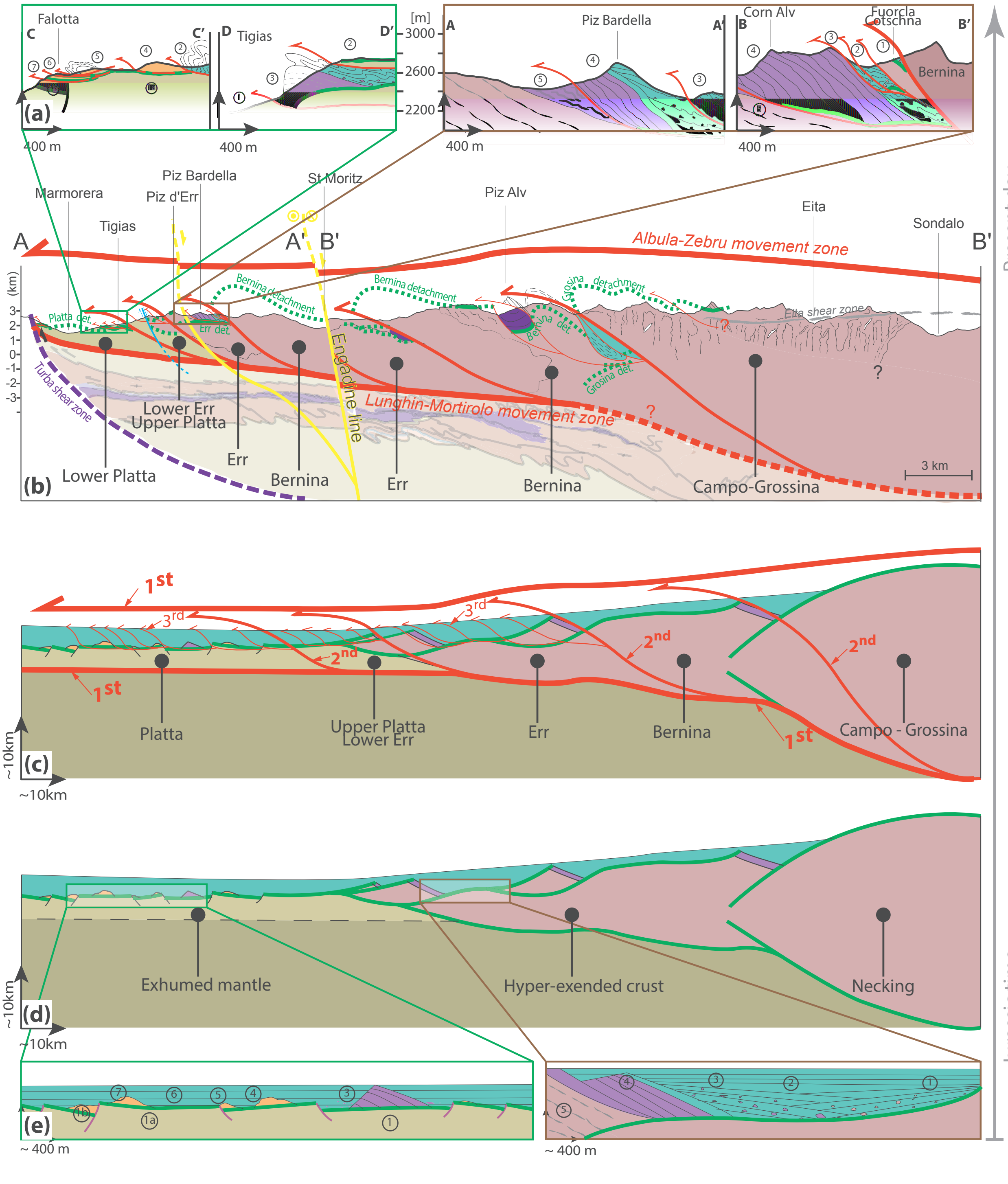
6.2.3 Reactivation of distal margins: hyperextended crust vs. exhumed mantle domains

The study of the Bardella-Fuorcla Cotschna and the Falotta-Tigias areas enables to investigate and compare the reactivation of two domains that underwent a similar reactivation history but are floored by different types of basement rocks. In both examples reactivation results in thin duplexes that sample supra-detachment material. In both cases decoupling levels are very shallow. It appears, however, that in the hyperextended domain detachment surfaces are more difficult to reactivate, while in the exhumed mantle domain detachment surfaces are commonly reactivated. Extensional detachment systems in the continent may have a more complex geometry due to inherited heterogeneities in the crust. Our observations suggest that they are preferentially reactivated when they are juxtaposed against evaporate and/or clay-rich levels. In the exhumed mantle domain the major decoupling levels are essentially serpentine-rich fault gouges and/or ophicalcites forming the top of the exhumed mantle.

Another factor that appears to be important in controlling reactivation is top-basement topography that is either related to late normal faults, magmatic additions, or extensional allochthons. It appears that in both examples fold amplifications in syn- and post-rift sequences are directly linked to the occurrence of local basement topography, which may act as a local buttress. Basement topography may, however, also favour incision and local preservation of detachment fault segments. Thus, the spatial organization of inherited structures (offsets of top basement, magmatic additions or extensional allochthons) and their relation to the imposed shortening direction can become key-factors in controlling local structures during reactivation.

6.3 Control of inherited rift structures on the stacking of thrust sheets

One of the major results based on the study of the Err and Platta nappes is that the apparent complexity observed on a map-scale (juxtaposition of lithologies of different origin) is due to the reactivation of a complex, non-layer cake rift architecture (Fig. P1-8). Indeed if Alpine D1 thrusts are analysed, they show a surprisingly simple thrust geometry made of major thrust contacts interleaved by duplex structures. More detailed studies of the Bardella-Fuorcla Cotschna area by *Masini et al.*, (2012) showed that the sedimentary sequences observed in each of the subunits belong to one and the same supra-detachment basin and the composition of the breccias reflects the nature of the underlying basement. Thus, the apparent complexity is largely



Cover	Basement	Alpine structures	Jurassic rift structures
basalt	continental crust	D1 first and second order thrusts	Extensional fault
syn- and post-rift sediments	serpentinised mantle	D1 third order thrust	Normal fault
pre-rift sediments	mantle		

Fig. P1-8: Schematic sections across the present-day nappe stack and the former distal margin showing the main inherited structures and their role during reactivation (D1 stage). **(a)** *Present-day constructed sections across the Bardella-Fuorcla Cotschna and Falotta-Tigias area (for more detail see Fig. 4 and 6).* **(b)** *Present-day Alpine section across the Upper Penninic and Austroalpine nappes, for loction see Fig. 3a.; modified after Mohn et al. 2011.* **(c)** *Architecture of the Adriatic margin based on the restoration of the Austroalpine nappe system, whith the location of futur D1 first, second and third order thrust.* **(d)** *Architecture of the Adriatic margin based on the restoration of the Austroalpine nappe system.* **(e)** *Restoration of the present-day geological sections discussed in this paper (for more detail see Fig. 5 and 7) . Note the hierarchy of D1 thrust systems and the role of the inherited rift structures, in particular of the detachment systems during reactivation (for a more detailed discussion see text).*

due to the complex inherited geology and less to the reactivation structures.

For the example of the Falotta-Tigias area, detailed mapping pointed out that the major serpentinised mantle forming subunit 1 (Fig. P1- 6 and 7) forms the backbone of the lower Platta unit, while the other subunits are only local, and they disappear laterally over short distances. Thus, in contrast to previous interpretations (*Ring et al.*, 1989; *Dürr*, 1992; *Hsü*, 1995) suggesting that the observed discontinuities may be the result of large offsets, the interpretation proposed here is that the subunits 2 to 7 results from the sampling of the former hanging wall of the fault exhuming the mantle. This result is, however, at odds with the fact that the Err and Platta are part of a nappe stack that can be mapped through large parts of the Alps, being part of the suture zone. Thus, their continuity as paleogeographic domains assumes that important shortening had to be accommodated within the mountain belt during the emplacement of these units. This leads to the question about where and how strain has been accommodated during convergence. In classical fold and thrust belts major shortening preferentially occurs along some few master faults. In the example of the Err and Platta nappes, we suggest that the major structures that accommodated the offset are those that are in the footwall of the major basement units, which define second-order thrust faults (Fig. P1-8). First order thrust faults (thick red line Fig. P1-8) are, as previously described by Mohn et al. (2012) the Albula-Zebru and Lunghin-Mortirolo fault systems that juxtapose different rift domains and accommodated most of the shortening in the nappe stack during Alpine convergence.

6.4 Reactivation of inherited rift structures: from the local to the orogen scale

Rift inheritance, in particular in former distal rifted margins, challenges the classical concept of nappe tectonics. While in classical interpretations most of the deformation found in the orogens is allocated to convergence, the question remains how important the inherited component may be and how far it may control the structure of the final orogen. Although the results of this study do not allow providing definitive answers to this question, the example of the Err and Platta nappes shows that it is fundamental to introduce rift inheritance in the study of collisional orogens. This is particularly true for examples that reactivate former distal margins. However, the scale of investigation and the hierarchy of fault systems may be important.

At a local scale “coherent thrust sheets” can be defined and are here referred to as subunits. These subunits are separated by thrusts (thin red line, Fig. P1-8) that decouple at very shallow levels, typically into ophicalcites or serpentinised top basement (e.g. Tigias-Falotta area, Fig. P1- 7 and 8). In this example the thrust sheets are locally derived, very thin and strongly controlled by the basement topography. While decoupling levels (e.g. former exhumed extensional detachment) can be continuous over several kilometres, the blocks and magmatic additions between the decoupling level and the post-rift sediments can disappear over short distances. This complex top basement architecture seems to strongly control the lateral variability found in subunits. In areas with more intense compressional overprint or in subduction related settings this variability can be erroneously interpreted as a tectonic mélange. In our study, we can show that these very thin slivers result from the accretion of hanging wall derived material without having accommodated minor amounts of shortening. We therefore classify these units as third order duplex-systems.

At a regional scale larger "coherent thrust sheets" can be mapped extending over wider areas (e.g. Upper and Lower Platta units; *Desmurs et al.*, 2001). These units include a "basement" that forms the backbone of these units (in this case large slices of exhumed mantle, e.g. subunits 1 in the Tigias-Falotta example (Fig. P1- 7 and 8). These units form the backbone of the thrust sheets (e.g. Lower Platta unit and Upper Platta unit; e.g. *Desmurs et al.* 2001) that are interleaved by the third order duplex structures. These units are characterised by a continuous, massive "basement". The thrusts that bound these units can be mapped over tens of kilometres and have to be decoupled within the basement. We classify these structures as second order thrust systems.

At an orogenic scale first order nappe systems can be defined (e.g. Lower, Middle, Upper Austroalpine). Each of these systems originate from a different paleogeographic entity of the former margin (proximal, necking and distal margins) as indicated by the stratigraphic record (e.g. *Mohn et al.*, 2011). The major thrusts systems corresponding to the Albula-Zebru and Lunghin-Mortirolo (thick red line, Fig. P1-8), and referred to as first order structures, typically juxtapose nappe systems with different paleogeographic content.

7. Conclusion

As shown in this study and independent of the scale of observation, at least some of the complexity observed in orogens can be explained with the occurrence of inherited rift structures.

The definition of nappe systems on an orogenic scale (1st order structures) is manly based on the stratigraphic and petrological content of the units. In contrast, defining and mapping 2nd and 3rd order regional and local scale structures in orogens is more difficult. In this study we focused on local scale, 2nd and 3rd order structures and we showed that at this scale, geological "complexity" is strongly linked to the existence of inherited rift structures. In particular top basement topography (allochthonous blocks, magmatic additions,top basement offset by normal fault) and the existence or absence of efficient decoupling levels at the top basement appears to be controlling factors. Two major types of reactivations can be defined at a local scale: 1) classical thin-skin thrust systems associated with the formation of duplex along ramp flat systems; and 2) fold nucleation and amplification associated to local buttresses that may consist of either magmatic bodies, extensional allochthons or half graben type structures. While the first type depends mainly on the presence of potential decoupling horizons (detachment faults, hydration fronts, salt layers) the latter depends on the structure and orientation of the rift induced inheritance.

Although it may be too early to draw definitive conclusions, our study of the Bardella-Fuorcla Cotschna and Tigias-Falotta areas shows that the role of rift inheritance is a key to understand reactivation and final architecture of convergent systems on a local scale. Moreover, the role of inheritance may be scale dependent and obviously only applicable to domains that suffered rifting. Thus, detailed structural analysis of the post-rift sequence can be more meaningful to determine the more regional deformation history, if the occurrence of local buttresses can be excluded. In contrast, detailed structural studies of pre-, and syn-rift sequences need to include the potential existence of discontinuous, “non-layer cake” units, i.e. pre-rift sediments can no more be restored back to continuous undeformed units prior to onset of shortening. Since orogens and in particular internal parts of Alpine type orogens are ideally sampling remnants of former distal margins, the detailed study of these units needs to verify if rift inheritance is present, and if yes, it needs to be included in the structural analysis. Therefore defining and using diagnostic criteria to describe and map the role of rift inheritance in collisional orogens is a prerequisite to describe reactivation in collisional orogens.

Acknowledgements

The authors are grateful for the financial support of Total supporting the PhD of the first author and for the very helpful and constructive remarks of the editor Stefan Schmid and critical reviews by Mark Handy and an anonymous reviewer. We would also like to thank the numerous colleagues from academia and industry that participated in field excursions through the study area and contributed in a constructive way to the work that we present in this paper.

Post face

In this paper we firstly summarized the diagnostic criteria used to identify extensional detachment faults in hyper-extended and exhumed mantle domains. We secondly presented a method that enable to hierarchize Alpine structures and define units and sub-units that contain preserved parts of the former rifted margin architecture. Key results are:

- The definition of nappe systems on an orogenic scale (1st order structures) is manly based on the stratigraphic and petrological content of the units. In contrast, defining and mapping 2nd and 3rd order regional and local scale structures in orogens is more difficult.
- At a more locale scale, the geological "complexity" is strongly linked to the existence of rifted structures, which is particularly true for former distal margins commonly exposed in internal parts of collisional orogens.
- Two major types of reactivation can be defined at a local scale: classical thin-skin thrust systems associated with the formation of duplexes along ramp flat systems, and fold nucleation and amplification associated to local buttresses that may consist of magmatic bodies, extensional allochthons or half graben type structures.
- Reactivation manly depends on the presence of potential decoupling horizons (detachment faults, hydration fronts, salt layers) and depends on the structure and orientation of the rift induced inheritance.

My study focused on the Err and Platta nappes that resulted from the reactivation of the distal Adriatic rifted margin. Questions that remain concerning the reactivation of rifted margins in general and that need to be further investigated are: How can it be explained that the Platta nappe preserves relatively well rift inherited structures and was not subducted like most of the oceanic domain in the Alps? Where and why did the subduction initiate, and what controlled the location of localization? What is the role of serpentinization in the reactivation of distal rifted margins?

CHAPTER 7: DETACHMENT FAULTS IN A HYPER-EXTENDED DOMAIN

Preface

In this chapter, I describe and discuss a detachment system associated to the formation of a hyper-extended domain, preserved in the Err nappe. In this chapter, I present the results of a detailed mapping of detachment surfaces that enables to show the complex architecture of a detachment system in a hyper-extended domain.

Numerous observations from present-day margins show that hyper-extended domains at magma-poor rifted margins are complex and controlled by in-sequence faulting (*Péron-Pinvidic et al.*, 2007; *Ranero and Pérez-Gussinyé*, 2010). In this study I focus on the hyper-extended domain in the Err nappe, which has been interpreted as a lower plate margin (*Manatschal et al.*, 2007). Nirrengarten et al. (2016)) proposed that the critical Coulomb wedge theory can explain the geometry of hyper-extended magma-poor rifted margins. They proposed that in a hyper-extended, completely brittle continental crust, the asymmetry is controlled by in-sequence detachment faulting (Fig. 7-1). In their model, extension during hyper-extension initiates with a pseudo rolling hinge model with the active fault localizing in the hanging wall of the previous inactive fault. At this stage, the lower plate hyper-extended domain will become tectonically inactive. The final geometry in the lower plate is the one of a taper. In this chapter (Paper 2), we focus on the detachment system exposed in the Err nappe, that represents a field example of a lower plate hyper-extended domain. The aim is to improve and validate the model of hyper-extended domains by new observations and data.

This chapter (Paper 2) focuses on the rift-related deformation structures observed in the Err nappe. The aim is to understand the formation and evolution of a detachment fault system, to discuss how a detachment fault system evolves in a hyper-extended domain, and where the faults root at depth? Moreover, the lateral evolution of detachment faults in a hyper-extended domain and the rule of inherited structures and lithologies in controlling the evolution of a detachment system is discussed.

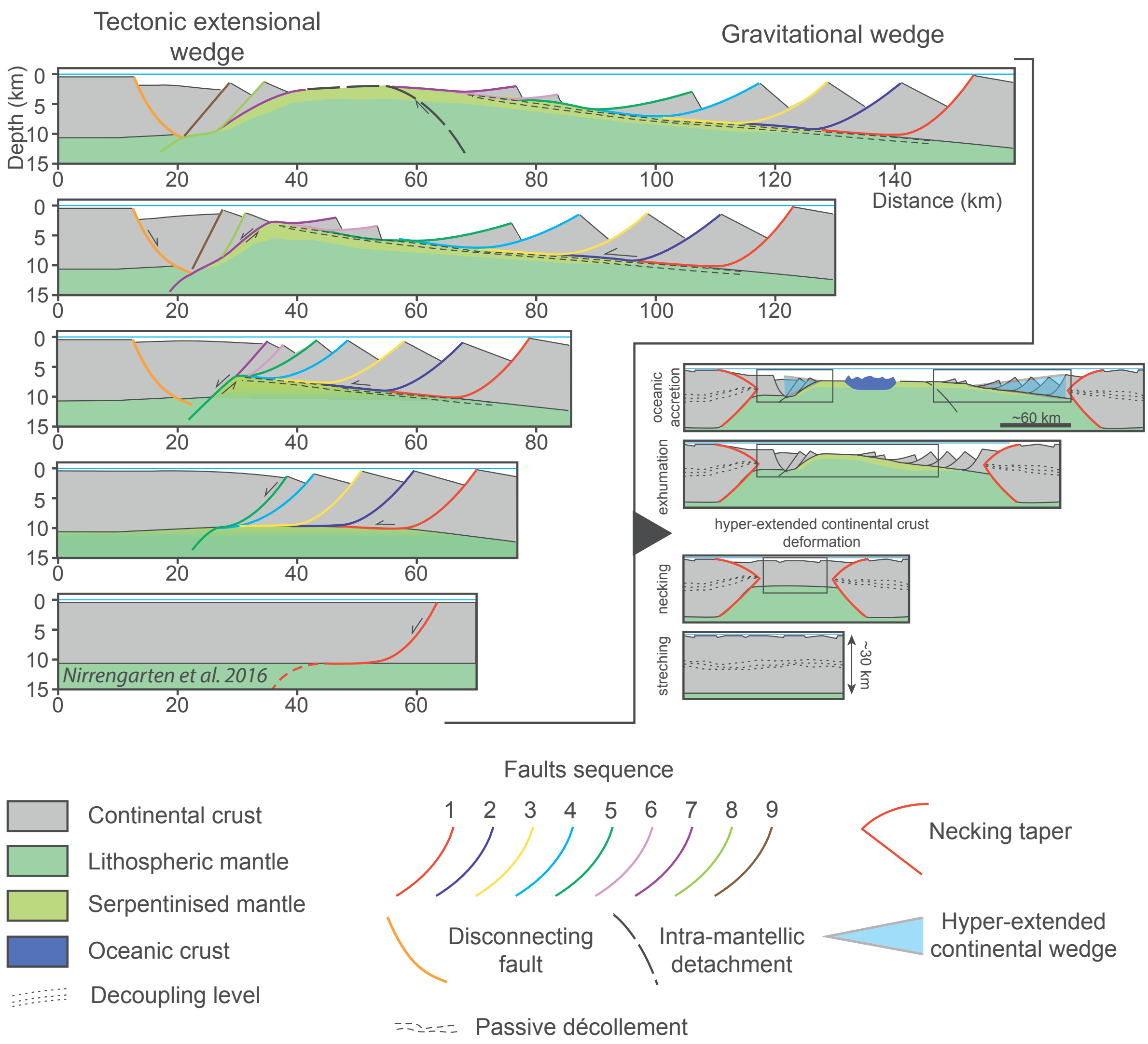


Fig. 7-1: *Conceptual evolution of the most distal part of a hyper-extended, magma-poor rift system (Nirrengarten et al., 2016).*

Paper 2 (in prep. for tectonics)

3D architecture, structural evolution and role of inheritance controlling detachment faulting at a hyperextended distal margin: the example of the Err detachment system (SE Switzerland).

Epin Marie-Eva and Gianreto Manatschal

Abstract

While extensional detachment systems linked to post-orogenic or oceanic settings have been described from many places, examples linked to hyper-extension and formation of magma-poor margins remain rare. Here we describe one of the best-described examples of a detachment system worldwide that is exposed over 200 km^2 in the Err nappe in SE Switzerland. Based on the review of preexisting work and new mapping, we realized a new map that enables to discuss the 3D structure of the detachment system and its role in thinning the crust and controlling the architecture and structural evolution of the hyperextended crust. We show that the current described detachment system can be defined by different detachment faults that developed in-sequence. The sequential evolution of these faults allows interpreting the detachment system by the rolling hinge model. However, we show that the occurrence of a Permian basin and the presence of evaporates in the Triassic pre-rift sequence strongly controlled the local geometry of the detachment system and of its hanging wall. From the existing observations it remains unclear how and where the detachment fault rooted at depth. The overall observations made in the Err nappe allowed to describe how extensional detachment systems can explain the final rift evolution preceding mantle exhumation and how it shapes the hyper-extended continental wedge at distal margins. While these questions are difficult to answer at present-day margins due to the lack of drill hole data, the access to a well-exposed field analogue can provide important insights and enable to find answers to these questions. In addition, the use of a kilometer scale field analogue can help to up-scale and to interpret extensional detachment systems at present-day margins.

1. Introduction

Deformations in hyperextended margins and in particular extensional detachment faults, also referred to as long offset normal faults, have been investigated and discussed using field and seismic observations (*Manatschal*, 2004; *Reston and McDermott*, 2011; *Sutra and Manatschal*, 2012) and numerical modelling (*Brune et al.*, 2014; *Huismans and Beaumont*, 2011). However, how these detachment faults form, the angle at which they slip (low vs. high angle), and how they evolve (in-sequence vs. out-of-sequence) remains debated. A popular model to explain how these faults form is the rolling hinge model, which suggests that these faults form at high angles and rotate near the surface to low angles (e.g. *Axen and Hartley*, 1997). This model has been used to describe extensional detachment faults at metamorphic and oceanic core complexes, i.e. in settings undergoing post orogenic collapse or at slow to ultra-slow spreading systems. In contrast, the processes that explain detachment faults forming in hyperextended domains remain ill constrained, mainly due to the lack of high-resolution seismic imaging and direct observations. One of the best examples of such a detachment system that formed in a hyper-extended domain is exposed in the Err nappe in Grisons in southeastern Switzerland.

The aim of this paper is to discuss the architecture of a detachment system related to hyperextension and crustal thinning. We describe, based on field observations and mapping, the 3D architecture of the Err detachment system and the type of rocks preserved in their footwall and hanging wall. We restore the initial 3D architecture of this detachment system over a surface of 225 km^2, discuss the tectonic evolution of this detachment system and the role of inheritance, in particular of an inherited Paleozoic basin and Triassic evaporates. Our observations enable to demonstrate that the detachment system consists of at least 3 faults that formed in sequence. The overall geometrical relationships, in particular the occurrence of allochthonous blocks and the cross-cutting relationships of the single faults can be best explained by a rolling hinge model.

2. Geological setting and previous studies

2.1 Geological and geographical overview

Among the best exposed and described extensional detachment systems associated to the formation of hyperextended rifted margins are those belonging to the fossil southwestern Adriac margin today exposed in the Austroalpine and Penninic nappes in SE Switzerland (Fig. P2-1A). These nappes resulted from the reactivation of the hyperextended Alpine Tethys margin that underwent a polyphase rift and compressional history that started in the Late Triassic (e.g. *Mohn et al.*, 2010). In this study we focus on an extensional detachment system that is well preserved and exposed in the Central Alps, more precisely in the Bernina, Err and Platta nappes (Fig. P2-1B). These nappes were stacked in an external part of the eo-Alpine system (Fig. P2-1C), during the closure of the northern Meliata-Vardar domain. Thrusting occurred in a top-to the west fold and thrust belt that initiated in Late Cretaceous. Within the Bernina, Err and Platta nappes the metamorphic overprint never exceeded lower greenschist facies conditions (*Ferreiro Mählmann*, 1994; 1996). During Late Eocene to Oligocene time a subsequent south - north directed shortening overprinted and locally reactivated the Late Cretaceous nappe stack. The northern parts of the Bernina, Err and Platta nappes, preserving the Jurassic detachment system, were only weakly affected by this later deformation phase. This is due to the fact that these units were located in the neutral zone above the singular point, i.e. the northernmost tip of the Adriatic buttress (*Schmid et al.*, 1996a) separating pro-and retro thrusting. As a consequence, the main pre-Alpine structures in the Bernina, Err and Platta nappes are relatively well preserved. In the past, the complex rift structures and in particular the lack of continuity of pre- and syn-rift sedimentary sequences made it difficult to describe and evaluate the Alpine overprint. Only more recently, Epin et al. (2017) were able to distinguish between pre-Alpine and Alpine structures and to describe the role of rift-inheritance during the formation of the nappe stack. This study enabled to re-evaluate separated parts of an extensional detachment system, previously described by Froitzheim and Eberli (1990), Handy et al. (1993), Handy (1996), Froitzheim and Manatschal (1996), Manatschal and Nievergelt (1997) Masini et al. (2011; 2014). Mapping of the whole Err nappe enabled to find new, not yet published fault segments, and to demonstrate that the extensional detachment system consists of multiple faults that formed in-sequence. In the Err and adjacent Platta and Bernina nappes, at least five single faults, belonging to a Jurassic extensional detachment system are preserved, extending over more than 600km². This study will first describe the different parts of the detachment system exposed in the Bernina, Err and Platta nappes, before it will focus on the Middle Err unit, where three fault branches of the extensional detachment system are exposed in one single thrust sheet.

2.2 Historical discovery

The discovery of extensional detachment systems in the Basin and Range (*Davis et al.*, 1980; *John*, 1987; *Davis and Lister*, 1988; *Lister and Davis*, 1989; *Spencer and Chase*, 1989; *John and Foster*, 1993) are at the origin of new models describing extensional systems (e.g. simple shear and rolling hinge models; *Wernicke*, 1985; *Buck*, 1988). Although, at present, extensional detachment faults are common and described from different extensional regimes,

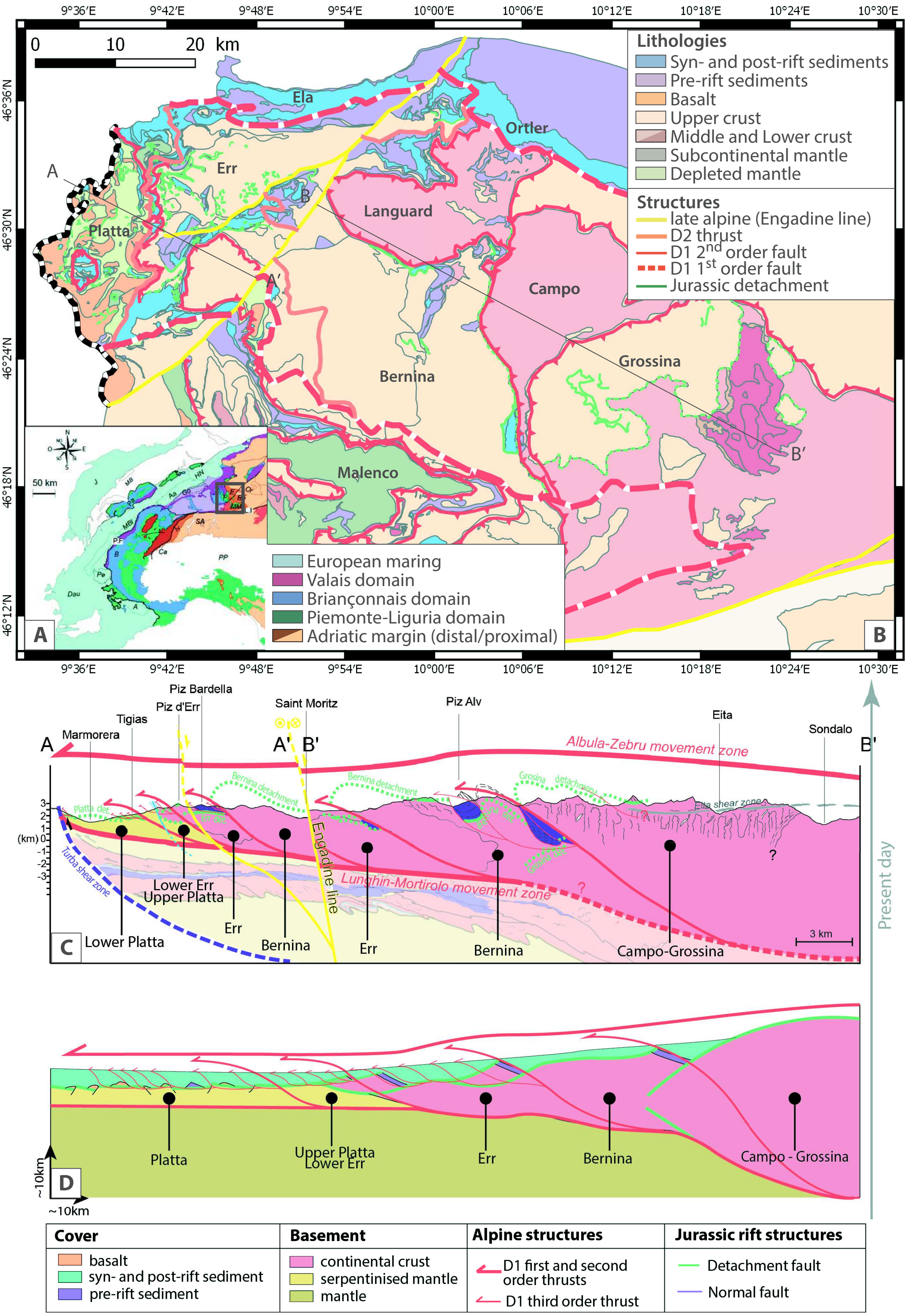


Fig. P2-2: **A:** *Tectonic overview map of the Alps (Mohn et al., 2011 modified after Schmid et al., 2004).* **B:** *Geological map of the Austroalpine and Upper Penninic nappes in SE-Switzerland and N-Italy. Map modified after a compilation of Mohn et al. (2011).* **C:** *Present-day Alpine section across the Upper Penninic and Austroalpine nappes (modified after Mohn et al., 2011).* **D:** *Architecture of the Adriatic margin based on the restoration of the Austroalpine nappe system, with the location of future first, second and third order D1 thrusts (modified after Epin et al. 2017).*

ranging from late to post-orogenic to slow and ultraslow spreading ridges (see *John and Cheadle*, 2010 and *Whitney et al.*, 2013 for reviews), examples related to the formation of hyperextended margins are rare. This is due to the difficulty to access these structures in a present-day margin, where these types of structures are commonly overlain by kilometres of sediments and water. Boillot et al. (1987), proposed a detachment fault model for the Iberia rifted margin in order to explain the occurrence of exhumed subcontinental mantle rocks at the seafloor (ODP drill, Leg 103). At the same time, Lemoine et al. (1987) proposed a simple shear detachment model for the formation of the Alpine Tethys rifted margins. The first descriptions and interpretations of preserved and exposed extensional detachment faults in the Alps were made by Froitzheim and Eberli (1990), Florineth and Froitzheim (1994), Froitzheim and Manatschal (1996) and Manatschal and Nievergelt (1997). These detachment faults are located in the Err and the Tasna nappes in SE Switzerland. They are formed by tens of meter thick damage zones constituted of characteristic green fault rocks (cataclasites) and a core zone made of black fault gouges showing a specific geochemical signature (*Manatschal et al.*, 2000; *Picazo et al.*, 2013; *Pinto et al.*, 2013; *Pinto et al.*, 2015; *Incerpi et al.*, 2017). Masini el al. (2012) investigated the tectono-sedimentary evolution of the detachment system in the Err unit (e.g. Samedan basin; *Masini et al.*, 2011). Although at present the occurrence of extensional detachment systems is well accepted and the examples in the Alps well documented, the 3D architecture and structural evolution of these fault systems are still debated as well as the role of inheritance in shaping the final architecture of these fault systems.

2.3 Pre-Alpine and Alpine structures

The recognition and study of rift related structures in the Alpine belt became possible because of the long and detailed geological description of this mountain belt. Pioneering work by several generations of geologists including Steinmann (1925), Elter (1972), Bernoulli (1974), Lemoine et al. (1987), Lagabrielle and Cannat (1990), Froitzheim and Eberli (1990) and many others enabled to define pre-Alpine structures within the Alpine mountain belt. Although the control of the rift inheritance has been proposed by many authors (*Butler*, 1989; *Handy et al.*, 1993; *Handy*, 1996; *Butler et al.*, 2006; *Beltrando et al.*, 2014; *Mohn et al.*, 2014), the details of this interaction between inherited structures and their reactivation are still debated and little understood in collisional mountain belts. Epin et al. (2017) presented, using the example of the Err and Platta nappes, a detailed analysis of the role of rift inheritance during reactivation of a hyperextended domain. This study is built on the work of Epin et al. (2017), in which the main Alpine and pre-Alpine structures and their importance have been described and a restoration of these units have been proposed (see Fig. 1-5 to 7, *Epin et al.*, 2017). The main Alpine structures and deformation phases can be described as follow:

- The D1 phase (e.g. Trupchun phase of *Froitzheim et al.*, 1994) is related to the major, top to the west Alpine shortening manifested by the emplacement of the Austroalpine nappe-stack during Late Cretaceous convergence (*Froitzheim et al.*, 1994). In the study area, this phase is responsible for the sandwiching of the Err nappe between the underlying Platta nappe (exhumed mantle and proto-oceanic crust) and the overlying Bernina nappe (hyperextended continental crust) along major D1 thrust faults. Second order D1 thrusts subdivide the Err nappe in Upper, Middle, and Lower Err units (for more details, see *Manatschal and Nievergelt*, 1997 and *Epin et al.*, 2017).
- The D2 phase (e.g. Ducan-Ela phase of *Froitzheim et al.*, 1994) is mainly expressed by normal faults reactivating and/or crosscutting older D1 structures (e.g. *Handy et al.*, 1993; *Manatschal and Nievergelt*, 1997).
- The D3 phase (e.g. Blaisun phase of *Froitzheim et al.*, 1994) affects the Err nappe by north and south directed thrust splays and kilometre-scale, upright east west striking open folds.
- The D4 and D5 phases of Froitzheim et al. (1994) are manifested in the study area by late east-west directed high-angle faults already mapped by Cornelius (1932). Handy (1996) suggested that these faults are related to the Engadine fault that post-date the Bergell intrusion (30myr).

Due to the position of the Austroalpine nappe stack in the hanging wall of the Alpine subduction, the Err nappe largely preserved the inherited structures of the Jurassic rifted margin (*Cornelius*, 1932; *Stöcklin*, 1949; *Handy et al.*, 1993; *Froitzheim et al.*, 1994; *Handy*, 1996; *Handy et al.*, 1996; *Manatschal and Nievergelt*, 1997; *Manatschal and Bernoulli*, 1999; *Masini et al.*, 2011; *Masini et al.*, 2012). These prominent and well described rift structures belong to an extensional detachment system that is exposed over more than 200km² within one single thrust sheet (*Froitzheim and Eberli*, 1990; *Manatschal and Nievergelt*, 1997; *Manatschal and Bernoulli*, 1999; *Masini et al.*, 2012; *Epin et al.*, 2017). In this paper we show that the extensional detachment system consists of at least three fault branches that formed by in-sequence faulting. Although previous studies recognized the existence of two detachment faults (e.g. Err and Jenatsch detachments of *Manatschal*, 1999; *Masini et al.*, 2012; *Manatschal et al.*, 2015), the way they interacted during extension remained unclear.

3. Extensional detachment systems in hyper-extended rifted margins

3.1 Extensional detachment systems

Rift models explaining crustal thinning and mantle exhumation often include extensional detachment systems. The Iberia and Galicia margins are at present the best-studied magma-poor rifted margins, where hyperextension and mantle exhumation have been proven by drill hole data. Fossil analogues are the Alpine Tethys margins, where remnants of the former distal margin including hyperextended crust and exhumed mantle are exposed. These examples, supported by dynamic modelling, show that final extension at magma-poor rifted margins is accommodated along extensional detachment faults (*Manatschal et al.*, 2001; *Perez-Gussinye and Reston*, 2001; *Péron-Pinvidic and Manatschal*, 2010; *Duretz et al.*, 2016). When the crust is thinned to less than 10 kilometres, first faults can penetrate the subcontinental mantle and lead to its exhumation at the seafloor (*Perez-Gussinye and Reston*, 2001; *Reston et al.*, 2004; *Manatschal*, 2004; *Péron-Pinvidic et al.*, 2007). How the different detachments evolve and progressively thin and exhume the crust during final rifting remains yet unclear.

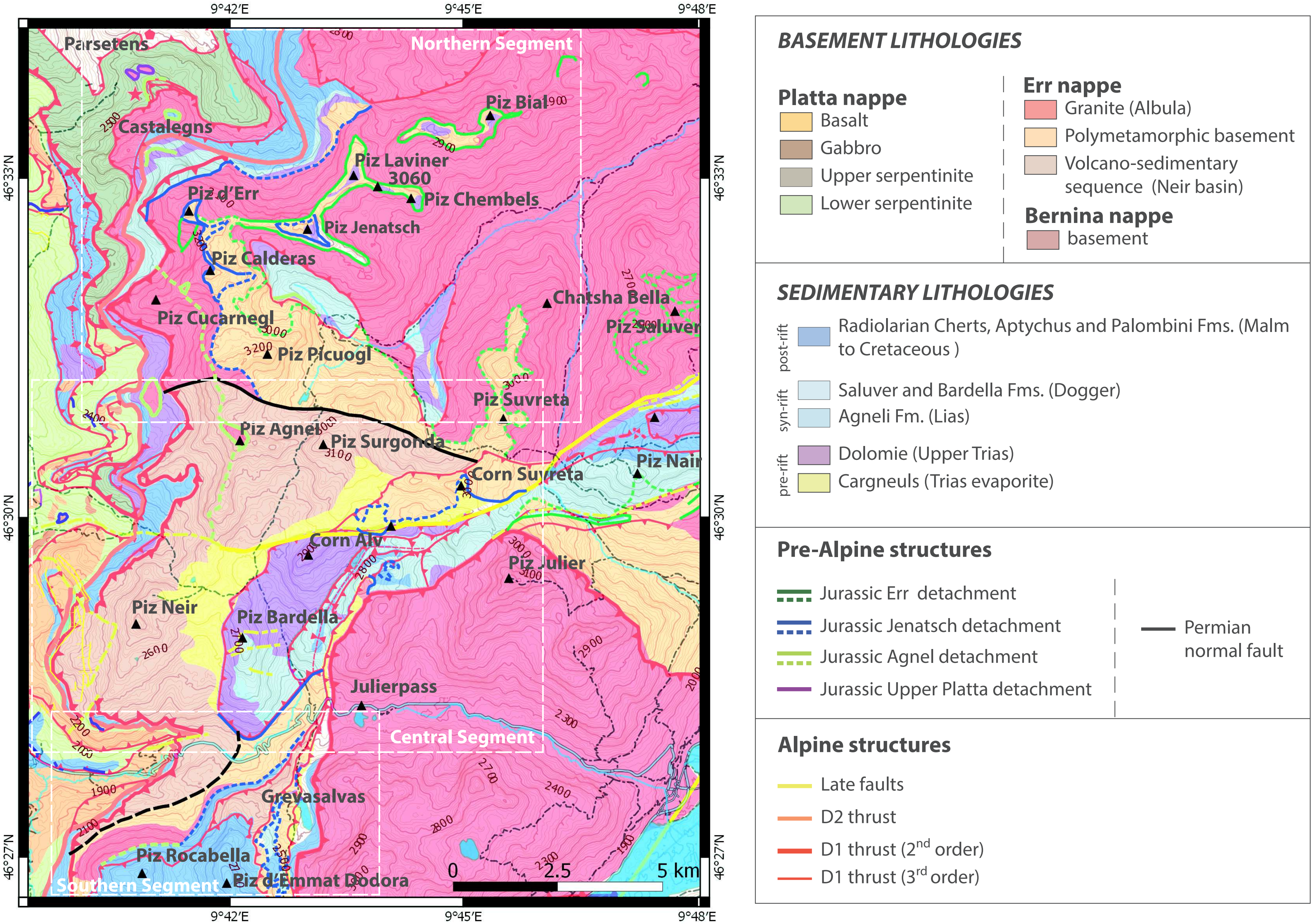
3.2 Characteristics of the Err detachment system

The Err detachment system is formed by a brittle damage zone that is made of characteristic fault rocks including green cataclasites and black gouges (*Manatschal and Bernoulli*, 1999). Manatschal and Nievergelt (1997) and Masini et al. (2012) mapped the detachment in the Err nappe and studied the structures and kinematics of the detachment system in the area between Piz Err and Piz Bial in the north and Piz Nair and Piz Bardella in the south of the Err nappe (see Fig. P2-2 for locations). Based on the analysis of s-c fabrics, shear bands and sigma clasts within the fault gouges, a top to the west transport direction was determined (*Froitzheim and Eberli*, 1990; *Manatschal and Nievergelt*, 1997). The detachment system separates hanging wall blocks from a massive and continuous footwall. Locally, Triassic pre-rift evaporates occur along the detachment fault. Their importance and role during the formation of the extensional detachment system, as well as the occurrence of a Permian basin will be discussed in this paper.

3.3 Geometry of the detachment fault and relation to basement rocks and sediments

Former studies discussed mainly the 2D rift structures along E-W striking dip lines, i.e. parallel to the transport direction across the area between Piz Err and Piz Bial (e.g. northern

Fig. P2-3: *Tectonic map of the Err nappe showing the location of the different Jurassic detachment faults and Alpine thrusts (based on new observations and a compiled map of Masini et al. (2011)).*


9°42′E
9°45′E
9°48′E
46°33′N
46°30′N
46°27′N
Northern Segment
Central Segment
Southern Segment
Parsetens
Castalegns
Piz Bial
Piz Laviner
3060
Piz Chembels
Piz d'Err
Piz Jenatsch
Piz Calderas
Piz Cucarnegl
Piz Picuogl
Chatsha Bella
Piz Saluver
Piz Suvreta
Piz Agnel
Piz Surgonda
Corn Suvreta
Piz Nair
Corn Alv
Piz Julier
Piz Neir
Piz Bardella
Julierpass
Grevasalvas
Piz Rocabella
Piz d'Emmat Dodora
0
2.5
5 km
BASEMENT LITHOLOGIES
Platta nappe
Basalt
Gabbro
Upper serpentinite
Lower serpentinite
Err nappe
Granite (Albula)
Polymetamorphic basement
Volcano-sedimentary sequence (Neir basin)
Bernina nappe
basement
SEDIMENTARY LITHOLOGIES
post-rift
Radiolarian Cherts, Aptychus and Palombini Fms. (Malm to Cretaceous)
syn-rift
Saluver and Bardella Fms. (Dogger)
Agneli Fm. (Lias)
pre-rift
Dolomie (Upper Trias)
Cargneuls (Trias evaporite)
Pre-Alpine structures
Jurassic Err detachment
Jurassic Jenatsch detachment
Jurassic Agnel detachment
Jurassic Upper Platta detachment
Permian normal fault
Alpine structures
Late faults
D2 thrust
D1 thrust (2nd order)
D1 thrust (3rd order)

segment in Figs. P2-2 and 3) (*Manatschal and Nievergelt*, 1997; *Masini et al.*, 2012). In these NS sections two extensional detachment faults (Err and Jenatsch) were identified and mapped. However, the relationship between these two detachment faults remained unclear. North-south striking sections lateral to the transport direction, i.e. strike lines, have been published in Masini et al. (2012) and Manatschal et al. (2015). These sections show a very complex geometry, interpreted as a lateral ramp of a detachment fault that was controlled by the existence of a Permian basin, referred to as the Neir basin (*Manatschal et al.*, 2015). This complexity made it difficult to correlate the well-exposed detachment faults in the north with remnants of exposed detachment faults in the south (Bardella and Grevasalvas area). This is mainly due to the change in composition of the footwall from mainly Carboniferous granites intrusive into poly-metamorphic Paleozoic gneisses and schists in the north, to volcano-sedimentary sequences belonging to a Permian basin in the south. The volcano-sedimentary series are characterized by porphyroids (rhyolites) interleaved with volcano-clastic sequences that grade upward into sub-areal sandstones and conglomerates belonging to the Chazforà and Fuorn Fms. (*Doessegger*, 1974). The Permian extensional to trans-tensional structures resulted in a strong, and for the subsequent rift evolution, important inheritance that will be discussed in this paper. Another important observation is the occurrence of Triassic evaporates that locally coincide with extensional allochthons occurring along the detachment system. Detailed mapping of the along strike changes described in the next chapter enables to better constrain the lateral continuity of the different branches of the detachment system, referred to as the Err, Jenatsch, Agnel and Upper Platta detachment faults.

The “hanging wall”, hereafter defined as consisting of all sequences that overlie the extensional detachment faults, is made of upper crustal rocks and pre-, to post-rift sediments and, on the most distal parts, also of syn-extensional magmatic additions. As discussed in this paper, the middle Triassic evaporates had an important control on the structuration of the hanging wall. This is indicated by the fact that within the hanging wall pre- and post-evaporate sequences are never observed within one continuous sequence, suggesting that the evaporate level was used as a decoupling level during extension. Another important point discussed in this paper is the lateral termination of the extensional allochthones and its implication for the 3D geometry of the extensional detachment system.

In order to understand the timing of the creation of accommodation space and the subsidence history and related depositional environments, it is critical to link the sedimentary evolution to that one of the extensional detachment faults. The syn-extensional sediments can be subdivided into the Agnelli, the Bardella and the Saluver Fms. (for more details see *Masini et al.*, 2011). These formations (Fms.) are pre- to post detachment faulting, despite the fact that at the scale of the entire margin, they formed during rifting (e.g. *Masini et al.*, 2013). Based on the detailed relationship between the detachment system and the syn-rift sediments, Masini et al. (2012) suggested a migration of deformation towards the future ocean. Moreover, the depositional environments also show a deepening of the distal margin during its formation (e.g. *Decarlis et al.*, 2015). The Agnelli Fm. that is pre-detachment faulting shows a plate-form environment, suggesting a shallow bathymetry. The syn-detachment sediments, the Bardella and the Saluver Fms. are made of breccias, turbidites and hemi-pelagic sediments that show a deepening of the future distal margin, which is consistent with the occurrence of deep marine sediments sealing the detachment systems and overlying syn-tectonic sediments. Based on geometrical relationships between sediments and detachment faults maximum and minimum ages of the detachment system can be determined. A maximum age for the onset of detachment faulting is 187 Ma (Early Pliensbachian; *Dommergues et al.*, 2012) which corresponds to a hardground capping the Agnelli Fm. This hard ground is truncated by detachment faults, indicating that the latter has to be younger. A minimum age for the detachment faults is the onset of deposition of the Bathonian-Callovian Radiolarian chert Fm. (*Bill et al.*, 2001), which is the first formation that seals the syn-tectonic sediments in the distal margin, including basalts with a Mid Ocean Ridge signature in the Platta nappe. As we will discuss it later, the lateral distribution of these syn-to post-tectonic sediments is complex and their deposition is intimately related to the 3D evolution of the extensional detachment system. The observation that at some locations syn-tectonic sediments overlie at a low angle directly exhumed detachment faults is in line with the interpretation that these detachment faults were locally exhumed and were at a low angle (<15°) when they reached the seafloor. However, the occurrence of post-rift sediments directly overlying detachment faults (e.g. Roccabella; southern Err nappe) also shows that their 3D structure was complex. In this paper we will discuss the morpho-tectonic evolution and final 3D architecture of the detachment system exposed in the Err nappe.

4. 3D architecture of the extensional detachment system exposed in the middle Err unit

In this chapter we present the key observations made in the field and shown in the maps and in the sections (Figs. P2- 2 to 7 and summarized in Fig. P2-8). We subdivide the study area in three segments, a northern, a central and a southern one and describe E-W and N-S trending sections corresponding to dip and strike sections. Each of the segments preserves different relations between footwall and hanging wall rocks and inherited structures. The northern segment is located along the mountain ridge formed by Piz d'Err, Piz Calderas, Piz Jenatsch, Piz Laviner and Piz Bial. The central segment is located around Piz d'Agnel, Piz Bardella and the Fuorcla Cotschna area, and the southern segment is located at the south of the Julier road around Grevasalvas, Piz d'Emmat Dadora and Piz Rocabella (Fig. P2-2). It is important to note that all segments are in one and the same Alpine tectonic unit, which is the Middle Err unit.

4.1 The northern segment

In the northern segment (Fig. P2-3), between Piz d'Err and Piz Bial, the detachment system is best exposed. This area corresponds also to the location where the Err detachment system has been first described (*Froitzheim and Eberli*, 1990). This zone preserves the Jurassic detachment structures with no Alpine tectonic overprint (*Froitzheim and Eberli*, 1990). Detailed mapping enables to follow the detachment system over 200 km^2. It is important to note that the relation between the rift related detachment faults and the Alpine D1 thrust fault, forming the base of the Middle Err unit, can be mapped in 3D (Fig. P2-3A). The intersection between the two structures is E-W directed, i.e. parallel to the sense of shear in the two structures. In the area of Piz Jenatsch and Piz Calderas (Fig. P2-3), two detachment faults are observed. These detachment faults have been described previously and referred to as the Err and Jenatsch detachments faults (*Manatschal and Nievergelt*, 1997).

The Err detachment fault (green line, Fig. P2-3) is well exposed in the area of Piz Bial and Piz Laviner. It is characterized by a footwall that is made of a massive granitic basement (Albula Granite) that becomes more deformed and cemented by silica towards its top, i.e. the detachment surface. In sections perpendicular to the detachment, one can see a gradual transition from massive granites to green, silica rich cataclasits with sharp contacts to black, indurated gouges that define the detachment surface. The transition can occur through hundreds of meters but can also be, locally, less than 50m.

The hanging wall of the Err detachment fault is made of gneisses and schists belonging to the poly-metamorphic Variscan basement. Since these rocks preserve primary contacts to Permian extrusive rocks elsewhere and can be found reworked in Permian sediments, these rocks had to be in the upper crust before detachment faulting started. The contact between the basement and the overlying Permian to Lower Jurassic pre-rift sediments is complex and will be described below. The stratigraphic successions are often reduced and incomplete, however, stratigraphic repetitions are never observed. Detailed observations show that the sedimentary successions are affected by polyphase normal faulting that affect in particular the

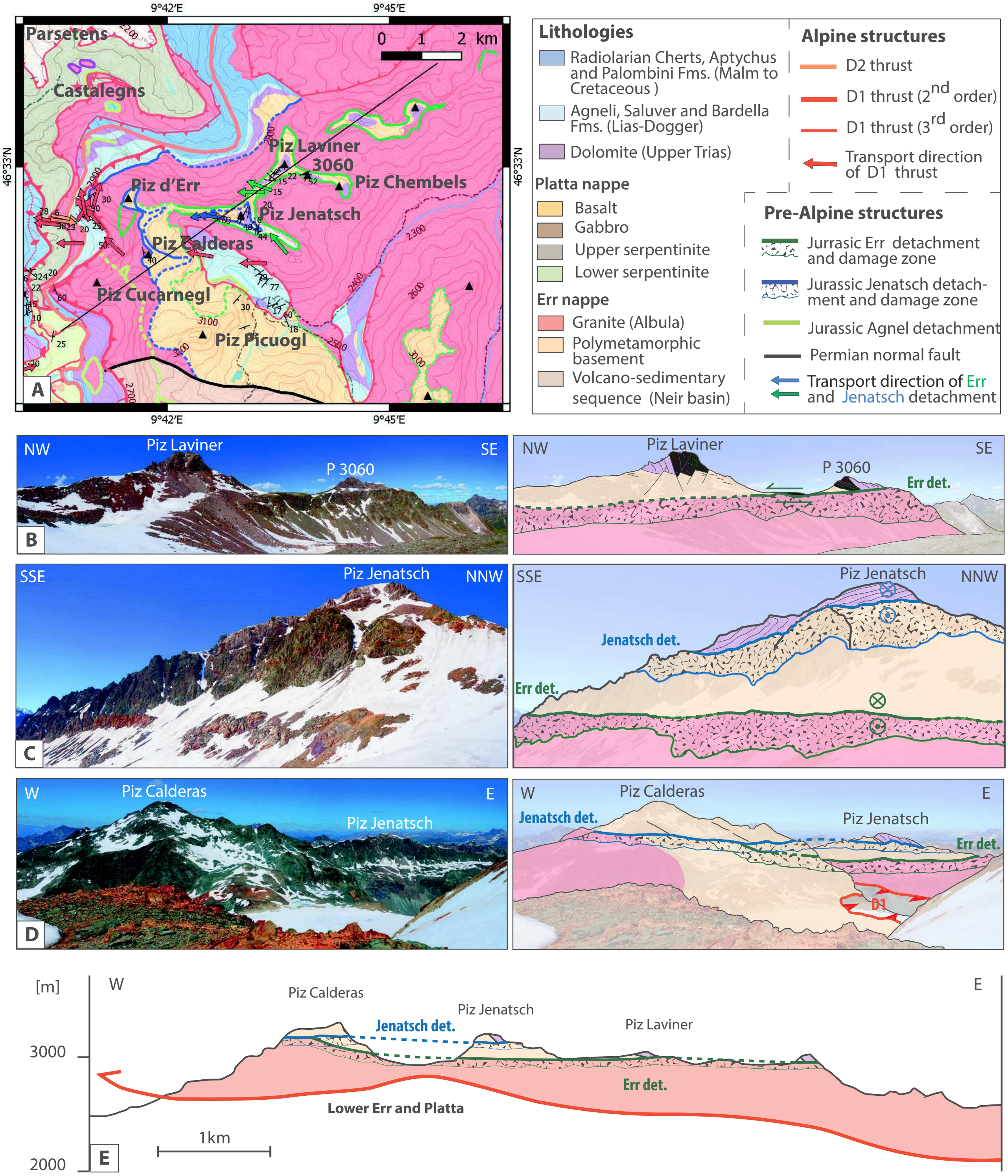


Fig. P2-4: Tectonic map and section of the northern segment. **A:** *Tectonic and structural map of the northern segment.* **B:** *Panoramic view of the Piz Laviner and P 3060 showing the Err detachment fault.* **C:** *Panoramic view of the Piz Jenatsch showing the Jenatsch and Err detachment faults (view in transport directon).* **D:** *Panoramic view of Piz Calderas and Piz Jenatsch showing the Jenatsch detachment truncating the Err detachment.* **E:** *Section parallel to transport direction across the northern segment of the Err nappe.*

Triassic evaporates. Locally, as for instance at Piz Lavinèr, normal faults are associated with the formation of neptunian dykes filled with the surrounding material in the presence of a sedimentary, calacareous matrix. This suggests that the hanging wall underwent extension near or at the surface before being uncomfortably overlain by mid Jurassic to lower Cretaceous syn- to post-rift sediments (*Manatschal and Nievergelt*, 1997). Along the mountain ridge between Piz Lavinèr and Piz d'Alp Val and Piz Bial, both tilting to the east and to the west can be observed in the hanging wall blocks. It is important to note that the faults that accommodate the tilting are truncated by the Err detachment fault, with the exception of one fault, which is east of P.3060. This structure truncates the detachment fault. At Piz Jenatsch, the polarity in the sediments indicates an east side down tilting of the hanging wall (Fig. P2-3). Between Piz Laviner and Piz Bial, tilting of the blocks is more complex and occurs in all directions. Kinematic and structural analyses show a top to the west transport direction. The intersections between stratigraphic layers in the Triassic dolomites and high angle normal faults strike predominantly SW-NE, indicate that they are slightly oblige to the movement direction documented along the detachment fault, which is E-W directed (see compiled transport direction on Fig. P2-3A; *Manatschal and Nievergelt*, 1997; *Masini et al.*, 2012 and own observations).

The Jenatsch detachment fault (blue line, Fig. P2-3) is well exposed at Piz Jenatsch and Piz Calderas. At Piz Jenatsch, the footwall of the Jenatsch detachment corresponds to the hanging wall of the Err detachment. It contains a characteristic, reddish K-feldspar bearing granite, with phenocrysts up to 4 cm long (*Manatschal and Nievergelt*, 1997). At Piz Calderas, the footwall of the Jenatsch detachment is composed of granite and gneiss showing intrusive contacts of the former into the latter. Similar to the Err detachment, the basement shows a strong cataclastic overprint that becomes more pronounced towards the detachment surface. The hanging wall of the Jenatsch detachment at Piz Jenatsch is made of a gneissic basement that is overlain along a stratigraphic contact by Permo-Triassic sediments. The bedding of this sequence forms a low-angle (between 15 – 45°) with the detachment surface and dips to the east to southeast. The sediments at Piz Jenatsch are, however, cross cut by several normal faults, some of which are sub-parallel to the bending and some are steeply dipping with a NE-SW trending direction. At Piz Calderas, the hanging wall of the Jenatsch detachment is made of gneiss. The dipping of the foliation in the gneiss is east to southeast, similar to the one observed at the top of Piz Jenatsch.

Since the intersection of the two detachment faults, obscured by the strong cataclastic overprint, were not clearly mapped in the past, the relationship between the two detachment faults remained unclear. A detailed mapping of the area between Piz Agnel, Piz Jenatsch and Piz Err enabled to show that the Err detachment is indeed intersected by the Jenatsch detachment (a previous study; e.g. *Manatschal and Nievergelt*, 1997, suggested the opposite) and enabled to identify and map a new detachment surface, referred to as the Agnel detachment (for details see below). On the panoramic views shown in (Fig. P2-3C), and the section shown in (Fig. P2-3D), the cross cutting relation between the Err and the Jenatsch detachment faults is shown. In the area of Piz Laviner and further east, only the Err detachment fault is present and overlain by small allochthones constituted of basement and pre-rift sediments. At Piz Jenatsch, it can be observed that the Jenatsch detachment occurs in the hanging wall of the Err detachment. Further south, at Piz Calderas it can be observed that the Err detachment is indeed overprinted by the cataclastic damage zone belonging to the footwall of the Jenatsch detachment. Detail mapping allows following the Jenatsch detachment westwards towards Piz d'Err, where it truncates the underlying Err detachment. The cross cutting relationships can be best observed in an east-west tending section (Fig. P2-3E), indicating that the two structures intersected at an angle of about 20°.

4.2 The central segment

In the central segment of the Err unit, in the area of Piz Neir, Piz d'Agnel, Piz Bardella and Piz Surgonda (Fig. P2-4), the rift structures are partly reactivated during Alpine convergence. However, this reactivation is minor and displacements are in the order of <1km, as indicated by the mapping of cut off points.

In the central segment, two detachment faults are identified: the Jenatsch detachment (blue line, Fig. P2-4) and the Agnel detachment (olive green line, Fig. P2-4). Previous studies suggested that Piz Bardella, the western Samedan basin including Fuorcla Cotschna were underlain by the Err detachment (*Masini et al.*, 2012). However, detailed mapping shows that the detachment underlying these areas corresponds to the Jenatsch detachment (blue line, Fig. P2-4). The north-south correlation between these detachment faults and between the different segments will be discussed in paragraph 4.4.

At Piz d'Agnel (Fig. P2-4B), which lies in the hanging wall of the Jenatsch detachment, another detachment surface, referred to as the Agnel detachment can be observed. It can be identified by the occurrence of characteristic silica rich green cataclasites. The hanging wall of the Agnel detachment is only exposed at Piz Agnel and is made of gneissic basement. The footwall of the Agnel detachment consists of a thick Permian volcano-sedimentary sequence

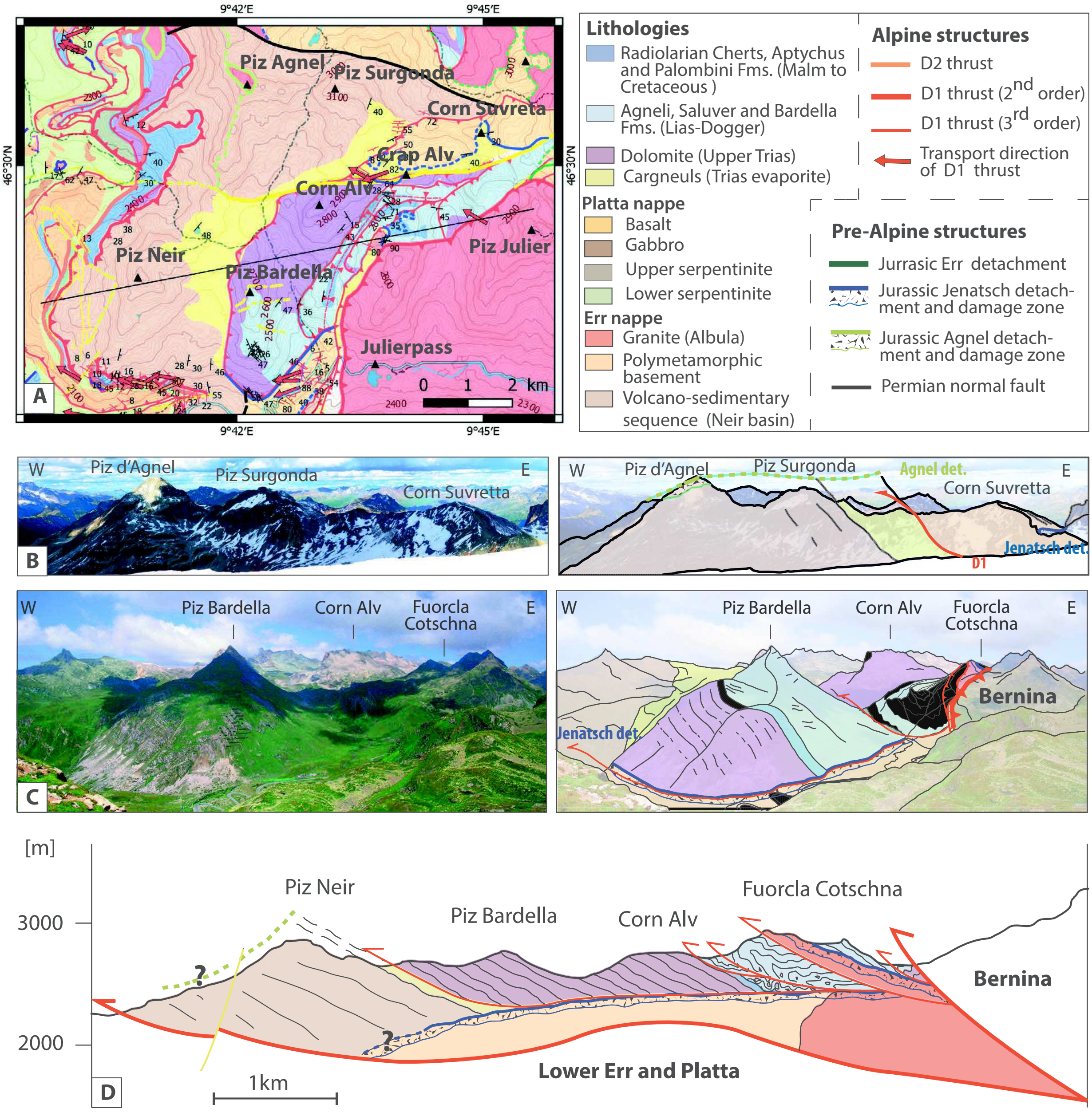


Fig. P2-5: *Tectonic map and section of the central segment.* **A:** *Tectonic and structural map of the central segment.* **B:** *Panoramic view of the Piz d'Agnel, Piz Surgonda and Corn Alv showing the Agnel detachment fault and the tilting of the basement and its pre-rift cover.* **C:** *Panoramic view of the Piz Bardella and Fuorcla Cotschna area showing the tilting of the pre-rift Triassic dolomite and the stratigraphic unconformity with the syn-rift sediments.* **D:** *Section in transport direction (Jurassic and Alpine D1) across the central segment.*

that is well exposed south of Piz d'Agnel and Piz Surgonda at Piz Neir. Further north, the basement is made of granite and gneiss. As shown on the map (Fig. P2-4), the Agnel detachment (olive green line) truncates the east-west striking contact separating the thick Permian volcano-sedimentary sequence in the south from the granitic and gneissic basement to the north. This contact corresponds, as we will discuss it later, to an inherited, east-west striking Permian normal fault that controls the local architecture of the Jurassic detachment fault (see paragraph

4.4). On the panoramic view shown in figure P2-4B, we can see that the footwall, made of a Permo-Triassic volcano-sedimentary sequence, is over tilted and dips with an angle between 30 to 50° to the east.

The top of the Piz Neir is the lateral continuity of the Piz d'Agnel - Piz Surgonda tilted block and as a consequence part of the footwall of the Agnel detachment. The detachment is not preserved, due to erosion.

In the panoramic view shown in figure P2-4C (view perpendicular to the transport direction), it can be seen that the Bardella block is rotated eastwards and truncated at the base by the Jenatsch detachment fault. The base of the Triassic dolomites at Piz Bardella are made of cargneules (reworked dolomites with evaporates). The cargneules can be mapped towards the Piz Neir separating the massive Permian volcano-sedimentary sequence in its footwall from the dolomites forming the Bardella block. The layering within this sequence shows a general tilting to the east with an angle of 30-48°, similar to what can be observed in the area of Piz Surgonda. As a consequence, the Bardella block lies also in the footwall of the Agnel detachment and is floored by the Jenatsch detachment. The occurrence of cargneules (i.e. Triassic evaporates) at the base of the Bardella block played, as discussed below, an important role during extension and subsequent convergence.

The area between Piz Bardella and Fuorcla Cotschna is affected by third order D1 thrusts with displacements of hundreds of meters that have been accommodated along thrust faults that are mapped and discussed in Epin et al. (2017). In their reconstruction, the eastward continuation of the Jenatsch detachment flooring the Bardella block can be found at Fuorcla Cotschna (Fig. P2-4C), where it separates strongly deformed basement rocks in the footwall from syn-rift sediments in the hanging wall (*Handy et al.*, 1993; *Manatschal and Nievergelt*, 1997; *Masini et al.*, 2012). The detachment surface is made of green cataclasites that are transected by anastomosing black gouges. The syn-rift sediments are made of sandstones belonging to the Saluver Fm. that overlies the Jenatsch detachment fault with an angle of 20-30°.

The syn-rift Saluver Fm. shows an evolution from bottom to top initiating with breccias made mostly of basement clasts, interleaved with black claystones showing a similar chemical composition to the black gouges (*Manatschal*, 1995). These breccias grade up section into sandstones that are interleaved by carbonate rich breccias and olistoliths. Epin et al. (2017) showed this in the sub-units lying between the Bardella block and Fuorcla Cotschna, (Fig. P2-4C). The syn-tectonic Bardella Fm. shows an angular discordance of about 15° with the underlying Triassic dolomites and Agnelli limestone at Piz Bardella that are tilted to the east with an angle between 22° and 43°. It is also important to note that the syn-tectonic sediments show major lateral changes in the composition of the clasts. While at Fuorcla Cotschna the breccias are dominated by footwall as well as hanging wall derived clasts, at Piz Bardella the breccias contain mainly hanging wall derived dolomite clasts (for more detail see *Masini et al.*, 2011 and reference therein). The syn-tectonic sedimentary sequence preserves its transition into the post-rift sediments that contain strongly folded red cherts and shales of the Radiolarian Chert Fm.

4.3 The southern segment

The southern segment of the Middle Err unit, around Piz Rocabella, Piz d'Emmat Dadora and Grevasalvas is the most affected by Alpine reactivation. It corresponds to a stacking of different sub-units that preserve internally pre-Alpine rift related contacts (*Epin et al.*, 2017). Between Piz Bardella and Piz d'Emmat Dadora (Figs. P2- 2 and 5), there is a remnant of a Jurassic detachment that can be correlated across the valley with the Jenatsch detachment flooring the Bardella block (blue line). The detachment surface is marked by the diagnostic, silica-rich green cataclasites. Black gouges can also be observed locally. It overlies granitic basement and a Permian volcano-sedimentary sequence (see sub-unit 1 on section

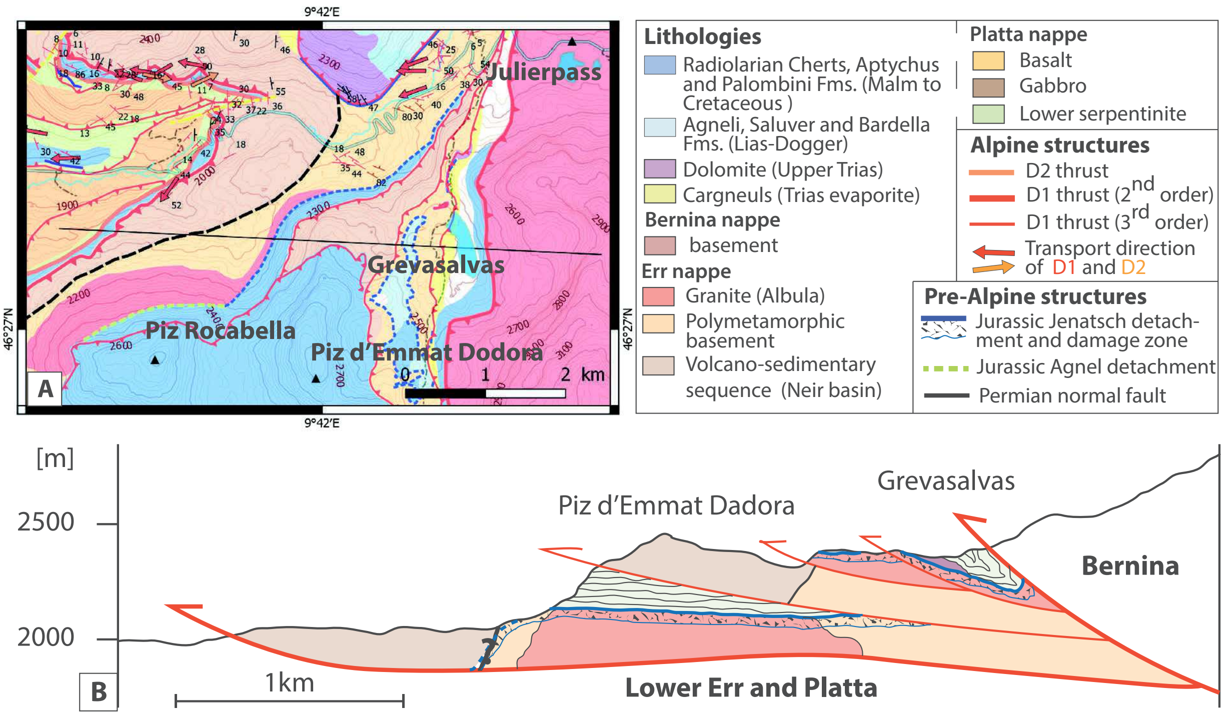


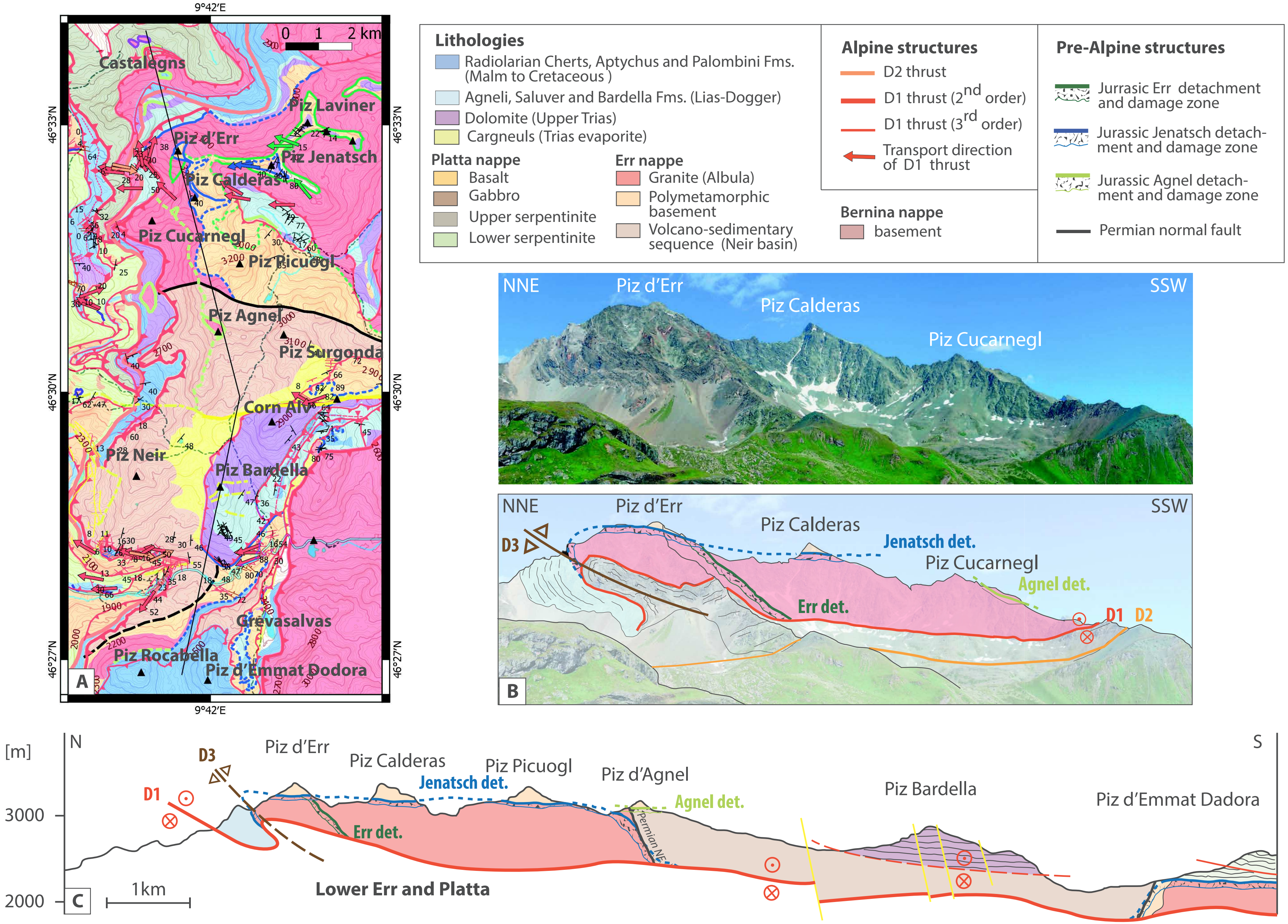
Fig. P2-6: *Tectonic map and section of the southern segment.* **A:** *Tectonic and structural map of the southern segment.* **B:** *Section in transport direction (Jurassic and Alpine D1) across the southern segment.*

Fig. P2-5B) and is overlain by olistoliths of dolomites that are overlain by Radiolarian Cherts and Calpionella and Aptychus limestones forming the post-rift sequence. Piz Roccabella is the only place in the Err nappe where post-rift sediments directly overlie exhumed basement. In a sub-unit overlying this unit (i.e. derived from further eastwards; sub-unit 3 on Fig. P2-5B) and located between Grevasalvas and Piz d'Emmat Dadora, another piece of the Jenatsch detachment fault is preserved. The footwall is made of granite and gneiss, and the detachment surface is made of green cataclasites. The hanging wall is made of syn-tectonic sedimentary breccias that consist of reworked dolomites. These sediments, that belong to the Bardella Fm., grade up section into Saluver type sediments and are sealed by post-rift sediments.

4.3.1 Nord-south correlations (strike section)

A comparison of the Jurassic structures preserved in the different segments in the Middle Err unit shows important along strike variations of the detachment system. The Jurassic rift structures observed along a north-south section shown in figure P2-6 are within one and the same Alpine tectonic unit. They are little affected, apart from 3rd order D1 structures and D3 folds by Alpine deformation. Exceptions are major Alpine structures in the most northern part of the area (e.g. D3 structure north of Piz d'Err; Fig. P2-6) and in the southern segment south of Piz Rocabella.

The north-south section shown in figure P2-6 shows the distribution and cross cutting relationships between the three detachment faults presented before. In the northern part (Fig. P2-6) a sub-horizontal detachment fault can be found at an altitude of 3000m. It can be mapped from Piz d'Err, to Piz Caldera to Piz Picuogl. This corresponds to the Jenatsch detachment fault (blue line, Fig. P2-6). After Piz Picuogl this detachment fault plunges towards the south under Piz d'Agnel. In the lateral continuity, it reappears further south under Piz Bardella and Piz d'Emmat Dadora. Westward thrusting of the Piz Bardella along a thrust that reactivates the former detachment fault, explains the repetition of the detachment fault in the section. Along the north-south directed section, the Jenatsch detachment is overlain by basement (gneiss and schists) in the north. In the central part it is overlain by the volcano-sedimentary Permian section and further south directly by post-rift sediments. The footwall is made of granite in the southern and northern parts of the section, while in the central part of the section it is truncated/ reactivated by an Alpine D1 thrust fault. Thus, where the Jenatsch detachment hits the edges of the Permian basin (at Piz d'Agnel in the north and Piz d'Emmat Dadora in the south; black line, Figs. P2- 2 and 6) it forms lateral ramps, i.e. the detachment dip is perpendicular to the transport direction. This suggests that the lateral ramps of the Jenatsch detachment are controlled by



9°42'E
46°33'N
46°30'N
46°27'N
0 1 2 km
Castalegns
Piz Laviner
Piz d'Err
Piz Jenatsch
Piz Calderas
Piz Cucarnegl
Piz Picuogl
Piz Agnel
Piz Surgonda
Corn Alv
Piz Neir
Piz Bardella
Grevasalvas
Piz Rocabella
Piz d'Emmat Dodora
A
Lithologies
Radiolarian Cherts, Aptychus and Palombini Fms. (Malm to Cretaceous)
Agneli, Saluver and Bardella Fms. (Lias-Dogger)
Dolomite (Upper Trias)
Cargneuls (Trias evaporite)
Platta nappe
Basalt
Gabbro
Upper serpentinite
Lower serpentinite
Err nappe
Granite (Albula)
Polymetamorphic basement
Volcano-sedimentary sequence (Neir basin)
Alpine structures
D2 thrust
D1 thrust (2nd order)
D1 thrust (3rd order)
Transport direction of D1 thrust
Bernina nappe
basement
Pre-Alpine structures
Jurrasic Err detachment and damage zone
Jurassic Jenatsch detachment and damage zone
Jurassic Agnel detachment and damage zone
Permian normal fault
NNE
SSW
Piz d'Err
Piz Calderas
Piz Cucarnegl
D3
Jenatsch det.
Agnel det.
Err det.
D1
D2
B
[m]
N
S
3000
2000
Piz d'Err
Piz Calderas
Piz Picuogl
Piz d'Agnel
Piz Bardella
Piz d'Emmat Dadora
Jenatsch det.
Agnel det.
Err det.
Permian NF
Lower Err and Platta
1km
C

***Fig. P2-7:** Tectonic map and section of the north-south correlation (on a strike view, perpendicular to the Jurassic and main Alpine (D1) transport direction).* **A:** *Tectonic and structural map of the western Err nappe.* **B:** *Panoramic view of the Piz d'Err and Piz Calderas area showing lateral variations of the detachment geometry.* **C:** *N-S section showing the lateral ramps of the Jenatsch detachment controlled by the presence of the Permian basin.*

the boundaries of the Permian basin and that the Permian basin is inverted during Jurassic extension. The east-west directed strike of the lateral ramp is compatible with the transport direction determined within the fault rocks of the detachment system.

The Err detachment fault (green line, Fig. P2-6) is only visible on the most northern part of the section. In north-south sections further east, it can be traced further southwards due to the fact that it becomes the dominant structure east of the breakaway of the Jenatsch detachment at Piz Jenatsch. The base of the Err detachment is cross cut by the same D1 thrust fault that is also truncating the Jenatsch detachment further to the west.

The third detachment described in this paper, the Agnel detachment, is only visible at Piz d'Agnel on the north-south directed section, where the Jenatsch detachment is inverting the Permian basin (Fig. P2-6). Its footwall is made of the Permian volcano-sedimentary sequence. Its hanging wall is only observable at Piz d'Agnel, where it is made of gneiss.

5. Detachment structures in the Lower Err and Upper Platta units

The Lower Err and Upper Platta units preserve relics of a former transition from exhumed continental to mantle rocks, similar to the Tasna nappe (*Florineth and Froitzheim*, 1994; *Froitzheim and Rubatto*, 1998; *Manatschal et al.*, 2006). While these units are omitted along an Alpine D2 normal fault in the southern part of the study area, north of Piz Calderas these units are well preserved (Figs. P2- 2 and 7). The Lower Err unit consists in this area of porphiric granite that shows towards its top brittle anastomosing fault zones comprising characteristic silicified green cataclasites and black gouges that define a detachment surface, which is overlain by crystalline breccias (*Manatschal*, 1995). To the southeast (Fig. P2-7B), the detachment is overlain by polymictic crystalline and carbonate sedimentary breccias. Further to the northwest, the detachment is overlain by Permian volcanic rocks and Triassic dolomites (location of the detachment shown by the green line in Fig. P2-7). We interpret this transition as the one of a detachment fault that is exhumed at the surface and overlain by syn-tectonic sedimentary breccias (southeast), to a position where the detachment is covered by a small allochthonous block (northwest; see section Fig. P2-7B, and schematic restoration Fig. P2-7C).

Further to the northwest, the detachment overlies exhumed mantle and is overlain by a continent derived basement that is strongly deformed and locally injected by syn-tectonic sediments.

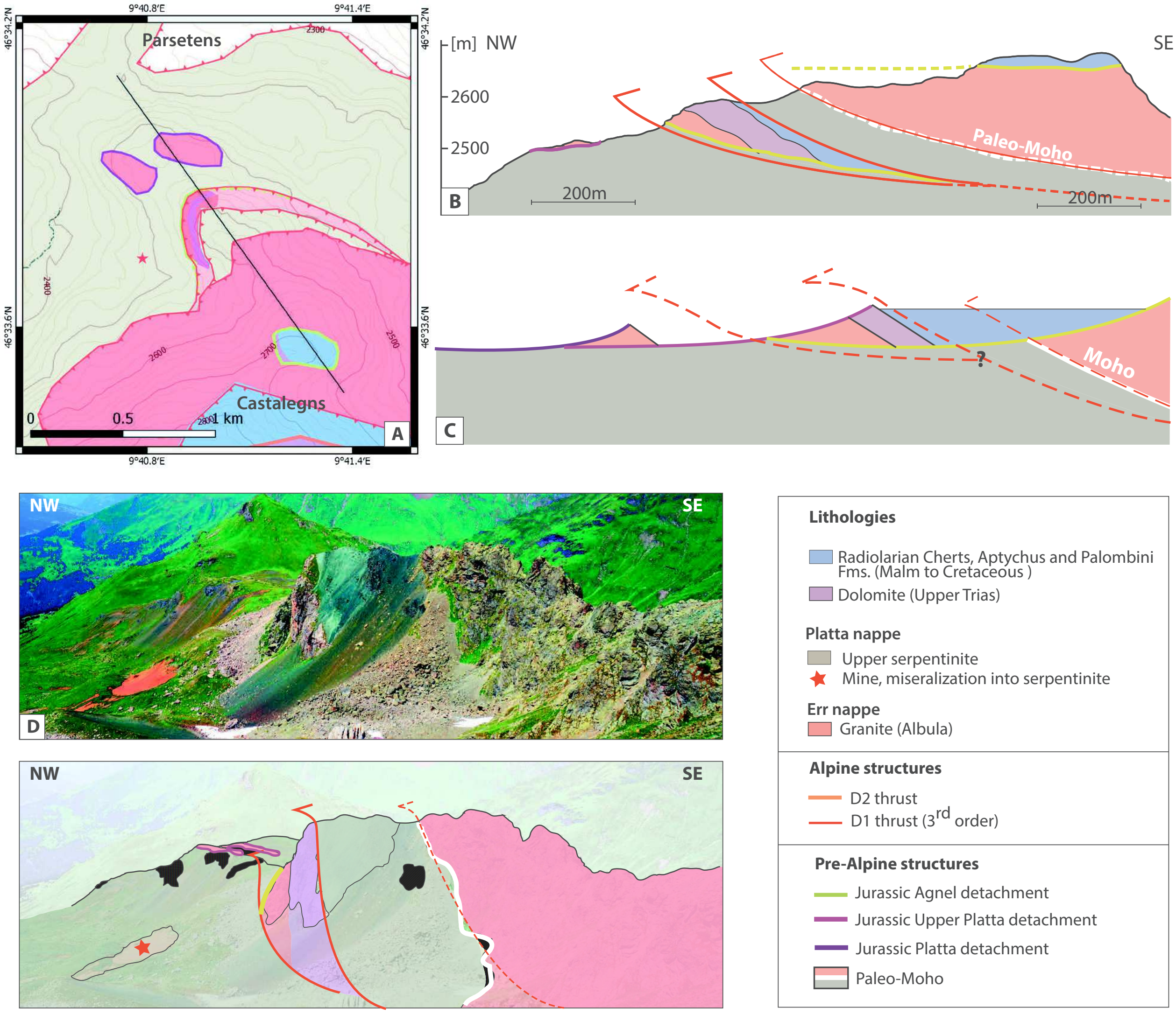


Fig. P2-8: *Tectonic map and section of the northeaster part of the Err nappe corresponding to the Lower Err and Upper Platta unit.* **A:** *Tectonic map of the Castalegns area.* **B:** *Section of the Castalegns area, modified after Manatschal 1995.* **C:** *Schematic restoration of the Castalegns area showing the occurrence of allochthones blocks of continental basement onto exhumed subcontinental mantle.* **D:** *Panoramic view of the Castalegns area.*

6. Discussion

6.1 3D restoration of an extensional detachment system

A detailed analysis of the detachment system exposed in the Err nappe allows proposing a 3D model of its architecture in the former hyper-extended margin. In figures P2- 8A and 8B, we present a simplified 3D restoration of the area shown in the map in figure P2-2. The general extensional direction along the detachment system is E-W, with the eastern part corresponding to the continent ward part and the western part corresponding to the ocean ward part.

The extreme western part (exposed in the northwest of the studied area between Castalegns and Parsettens, north of Piz d'Err, Figs. P2- 2, 7and 8B) is characterised by the exhumation of the sub-continental mantle (i.e. the Upper Platta unit). This exhumation is due to the action of the olive green and violet detachment faults (Fig. P2-8), referred to as the Agnel and the Upper Platta detachment faults respectively. The footwall of the Agnel and Upper Platta detachment faults is made of granite on its continent ward side and sub-continental mantle on its oceanward side (Fig. P2-7). We interpret these detachment faults to be the first to exhume sub-continental mantle and consequently the petrologic Moho. This contact is reactivated by a third order D1 Alpine thrust that defines the contact between the Lower Err unit and the Upper Platta unit (Fig. P2-2).

The Agnel detachment (olive green, Fig. P2-8A) shows an important lateral variability of the geometry of its fault plain from north to south along a strike section. In the northern segment only the footwall of the Agnel detachment is visible, forming the top of the Piz Calderas (Fig. P2-3). In the central segment, the Agnel detachment fault is preserved at the Piz d'Agnel and Piz Neir where the footwall is composed of gneiss, granite and a volcano-sedimentary sequence belonging to the Permian Neir basin. In the southern segment, direct evidence of the Agnel detachment fault doesn't exist. However, at Piz Rocabella and Piz d'Emmat Dadorat, an exhumation fault separates tectonized granitic and gneissic basement from the post-rift sediments. We propose that the southward termination of the extensional allochthone observed at Piz Bardella and the drastic thinning of the syn-tectonic sediments may be explained, as discussed below, by the interaction of two detachment faults.

The Jenatsch detachment (blue, Fig. P2-8) lies in the footwall of the Agnel detachment and is truncated by the latter. The Jenatsch detachment shows a lateral complexity (Fig. P2-6)

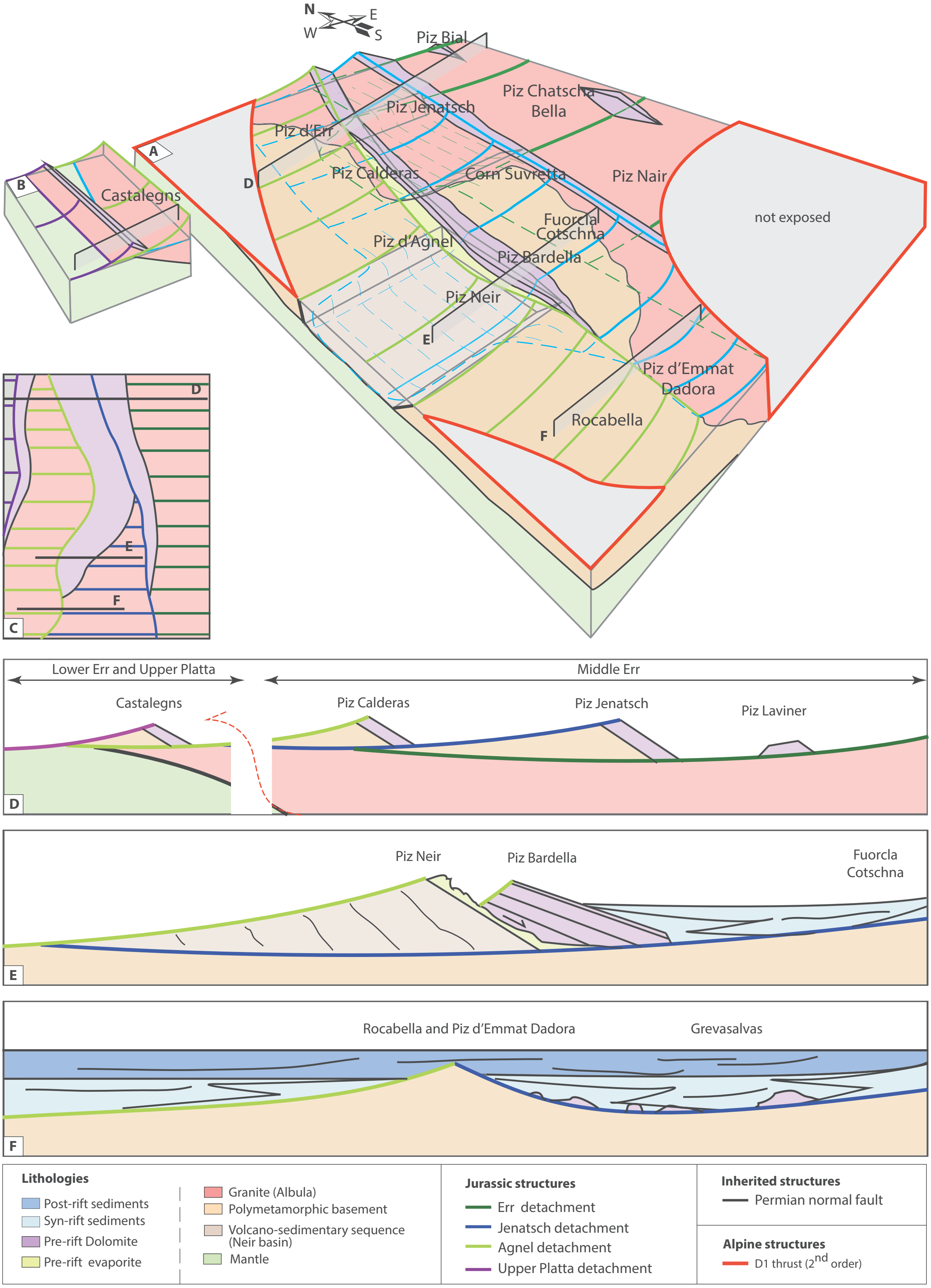


Fig. P2-9: *Restoration of the Err nappe.* **A:** *Restored block of the Err nappe showing the location of different detachment faults.* **B:** *Restored block of the Lower Err and Upper Platta unit showing the transition from the hyper-extended domain to the exhumed mantle domain.* **C:** *Schematic map of the Err domain showing distribution of detachment faults and the lateral termination of allochthonous blocks.* **D:** *Simplified restored section through the northern Err and Upper Platta domains.* **E:** *Simplified restored section through the Piz Neir, Piz Bardella, Fuorcla Cotschna domain showing local complexities due to the presence of salt.* **F:** *Simplified restored section through the southern segment* with the occurrence of a lateral ramp. This ramp coincides with a change in the composition of the basement from granitic and gneissic in the north to a volcano-sedimentary sequences to the south. Therefore we interpret that the ramp may be controlled by the occurrence of the Permian Neir basin. The entire hanging wall of the Jenatsch detachment is tilted to the east, and preserves a complete stratigraphic section including a Permo-Triassic section made of a thick volcano-sedimentary sequence and dolomites, overlain by evaporates of Carnian age, and massive dolomites and limestones of upper Triassic to Lower Jurassic age. This hanging wall block, which can be mapped from the north towards Piz Bardella (Fig. P2-2-4), abruptly terminates in the Julier valley. Since the footwall of the Jenatsch detachment continues south of the Julier valley together with remnants of the hanging wall block and syn-rift sediments, the direct disappearance of the block cannot be explained by Alpine tectonics. We propose therefore that the southern termination of the extensional allochthone and the occurrence of a basement high at Piz Rocabella (see discussion above) results from the interference of the Jenatsch and the Agnel detachment faults. In figure P2-8 one can see that in strike view, the two detachment faults can be followed from north to south separated by an allochthonous block. South of Piz Bardella, we interpret that the Agnel fault incises backwards and truncates directly the Jenatsch detachment. As a consequence, there is no allochthonous block and the new fault (Agnel, olive green, Fig. P2-8) truncates directly the detachment (Jenatsch, blue, Fig. P2-8). The basement high observed at Piz Rocabella where post-rift sediments directly overlie an exhumation surface is explained by the over-tilting of the pre-existing Jenatsch detachment in the footwall of the Agnel detachment (for more discussion see paragraph 6.3.2; Fig. P2-8E). Thus, to be coherent in our colour code, at Piz Rocabella we change the colour of the detachment fault from blue (Jenatsch) to olive green (Agnel) (Fig. P2-8).

The Err detachment (dark green Fig. P2-8) corresponds to the most continent ward structure in the 3D block (Fig. P2-8). It is overlain by little allochthonous blocks of Triassic dolomite (e.g. Piz Laviner area), which are in contrast to the breakaway blocks (e.g. Bardella block) much smaller and do not represent the breakaway of a new detachment fault (for further discussion see paragraph 6.3.1.)

6.2 In-sequence detachment fault evolution

In figure P2-9, we present a conceptual model to explain the evolution of the detachment faults observed in the Bernina, Err and upper Platta units. The crosscutting relationships of the different detachment faults observed in the field led us to propose an in-sequence evolutionary model, where each new fault exhume, tilt and truncate an older detachment fault. In fact, this

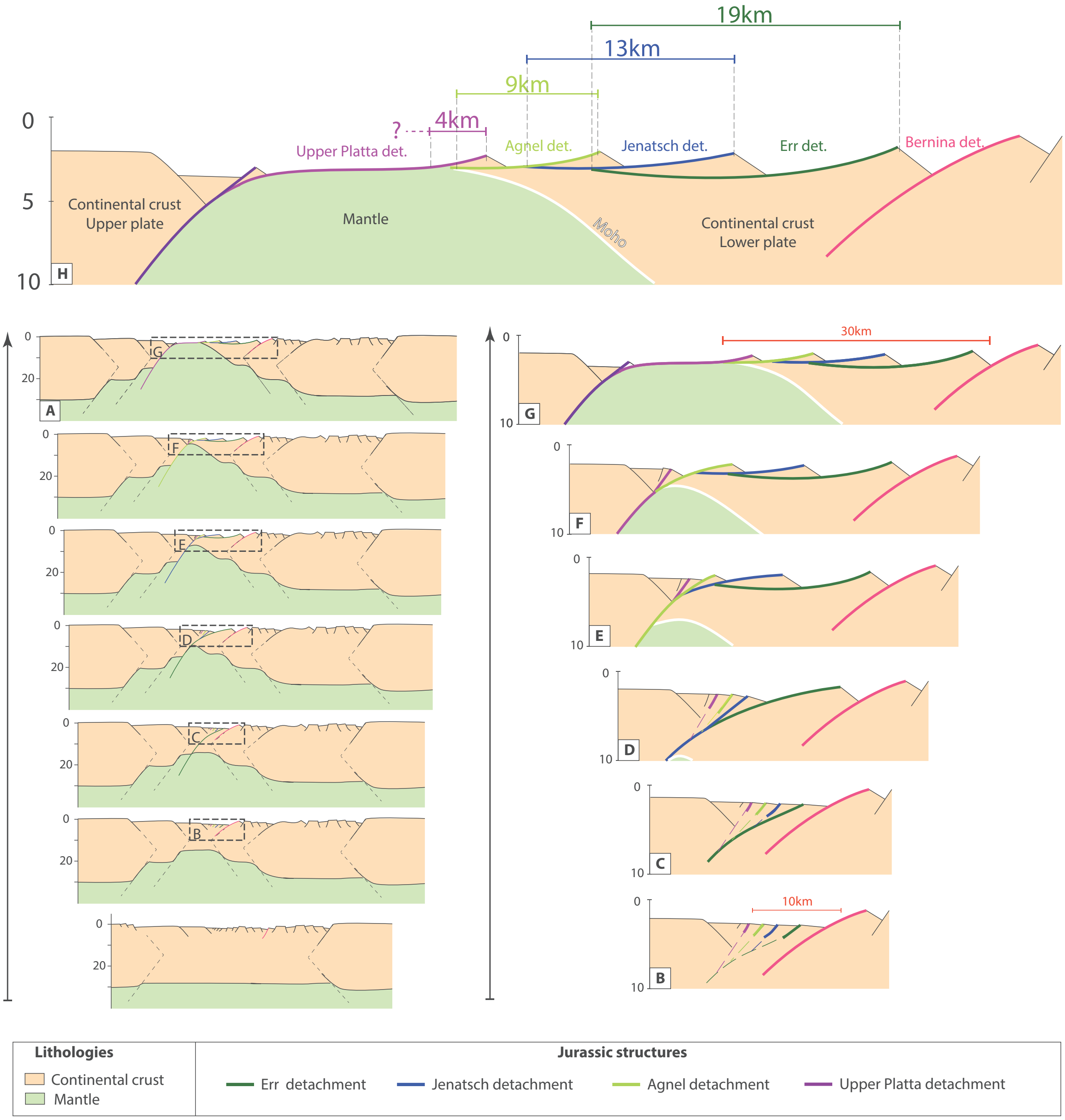


Fig. P2-10: *Schematic model showing the evolution of the hyperextended system.* **A:** *Large-scale evolution of the rift system from the stretching phase to the exhumation of subcontinental mantle.* **B and C:** *Zooms on the initial stages of the hyperextension phase at the end of the necking phase and at the stage of decoupling.* **D:** *Zoom on the development of the Err detachment fault and the initiation of the Jenatsch detachment fault.* **E:** *Zoom on the evolution to the Agnel detachment fault.* **F:** *Zoom on last stage before first exhumation of sub-continental mantle.* **G:** *Zoom on the final exhumation phase, with the exhumation of mantle in the footwall of the Upper Platta.* **H:** *Restored section through the Err domain with minimum values for the restored size of detachment faults.*

evolution corresponds to the classical rolling hinge model proposed by Wernicke and Axen (1988) and Buck (1988). Within the Austroalpine units in Grisons, detachment faults have been described in the Bernina, Err and Platta nappes and have been interpreted to be formed during Jurassic hyper-extension. Mohn et al. (2011) showed that the Bernina detachment was the first to be activated after crustal necking. The conditions at onset of activity of the Bernina detachment fault, i.e. crustal thickness and bathymetry are not constrained. In our model, we assume that the Bernina fault formed at a stage when the crust was already thinned to less than 20km (Pink line, Fig. P2-9B). Because of the lack of evidence of mantle derived fluids along the Bernina detachment fault, we suggest that this fault was not yet couplet to the mantle (see *Pinto et al.*, 2013; *Pinto et al.*, 2015; *Incerpi et al.*, 2017a).

The Err detachment fault is the first detachment fault that is couplet to the mantle (Fig. P2-9C), as indicated by the occurrence of mantle derived fluids along this fault (e.g. *Pinto et al.*, 2015; *Incerpi et al.*, 2017a). We assume that the Err detachment corresponds to the upward continuation of a major fault zone that was formed at depth and penetrated into the mantle. This fault system formed a proto-plate boundary that accommodated all deformation between the two future conjugate margins, i.e. the lower plate Adriatic margin and the upper plate European margin (Fig. P2- 9C to D). Near to the surface, in a wedge shaped domain directly overlaying the lower plate, new faults localized ahead of the active exhumation fault, led to the creation of breakaway blocks. These new faults (Jenatsch, Agnel and Upper Platta faults) formed in-sequence, and as high-angle faults, while the older faults locked and were exhumed and rotated in the footwall of the new, active fault. This processes results in the delamination of hanging wall derived blocks (e.g. breakaway blocks) that becomes part of the footwall when the fault in its footwall rotates and becomes inactive. Due to the fact that all shallow faults root in one and the same fault at depth, the final structure is the one of hanging wall derived, upper crustal blocks that formed while the footwall containing the Moho rotates and eventually mantle get exhumed at the seafloor (Figs. P2- 9C to 9E). The field observations show a progressive decrease of the length of the detachment fault from 19 km to 13km to 9km. The lengths refer to the distance between the breakaway point and the location where the fault is truncated by the new fault in its hanging wall. Our conceptual model can explain the evolution from a crust thinned from the stage when the first fault penetrates the mantle (e.g. Err detachment) to the onset of mantle exhumation (Upper Platta detachment). It can, however, not explain how the crust thins from initial crustal thickness to 10km and how lithospheric breakup is finally achieved.

6.3 Importance of inherited structures

Detail mapping of the Err unit enables to show a complex 3D architecture of the detachment system and its hanging wall blocks. Two major factors seem to control the architecture of the detachment surfaces and the architecture of the breakaway blocks: 1) weak layers (evaporates) in the pre-rift sedimentary succession, and 2) inherited structures in the basement.

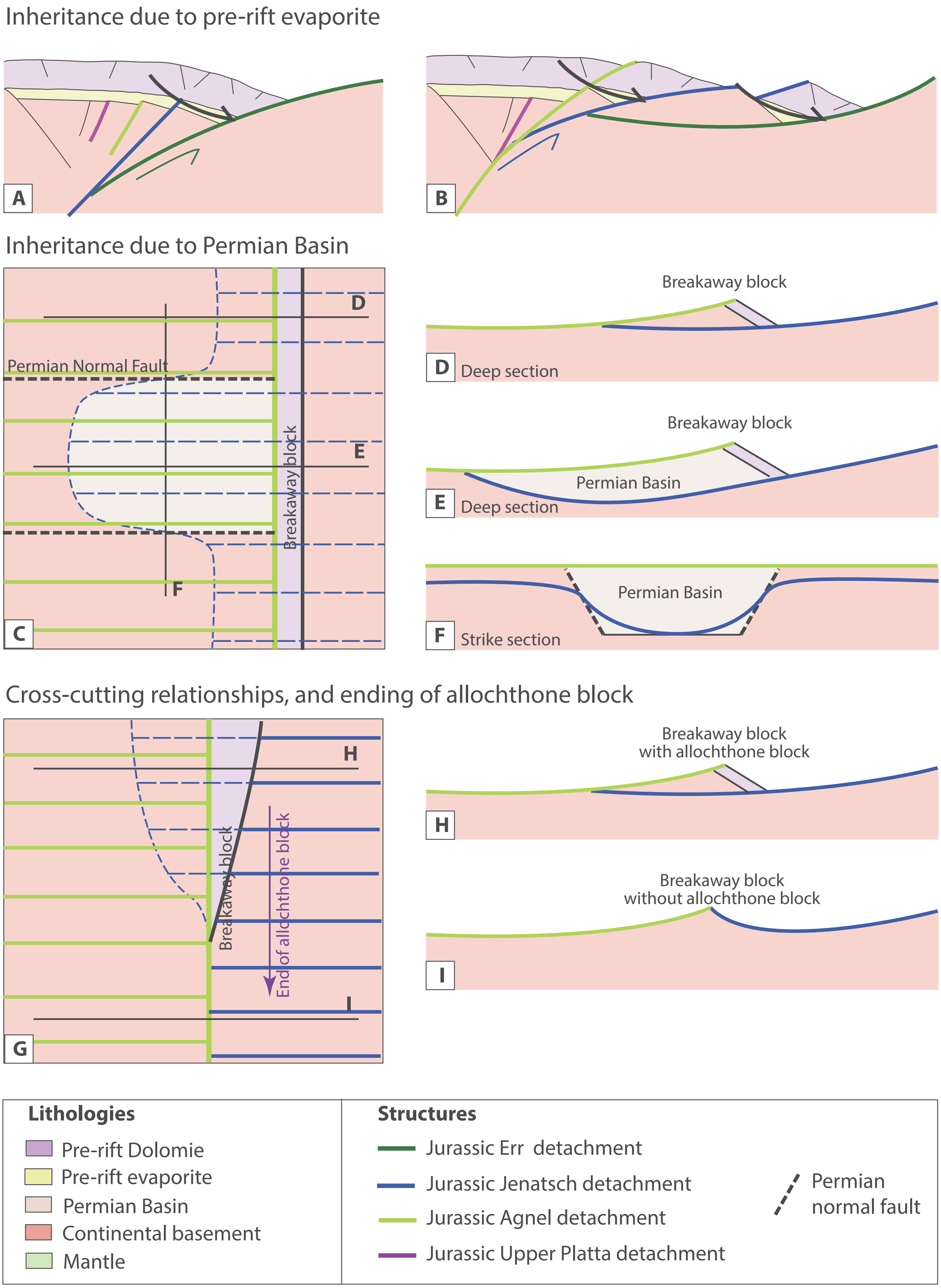


Fig. P2-11: Complexities due to inherited structures and weak layers. **A and B:** *Gravitational gliding over evaporate layers of the pre-rift dolomite during the formation of allochthonous blocks.* **C:** *Schematic map view of the Permian basin and its influence on the location of the detachment fault (see sections D, E, and F).* **D, E, and F:** *Sections showing the influence of pre-existing Permian basin on the location of the detachment fault in deep and strike view.* **G:** *Schematic map view representing the lateral ending of allochthon block due to the cross cutting relationships between the Agnel and Jenatsch detachment faults.* **H and I:** *Sections illustrating the lateral termination of allochthonous blocks across the Julier valley.*

6.3.1 Inherited "weak" layers in the pre-rift sediments controlling hanging wall structures

The role of "weak" layers, i.e. of Triassic evaporates, during the formation of extensional allochthons is best observed at Piz Neir - Piz Bardella in the central segment of the Err domain. Piz Neir and Piz Bardella present a succession of Permian volcano-sedimentary rocks and pre-rift sediments.

As shown in the section in figure P2-4E the Permian volcano-sedimentary sequence is separated from Upper Triassic dolomites and Lower Jurassic limestones along evaporates made of cargneules (evaporate residue) of Carnian age. The Permo-Triassic section is tilted at present to the east to 30-50° while the basal Err detachment is still subhorizontal. In the section in figure P2-4E it can be seen that the dolomites overlying the evaporitic layer and forming the Piz Bardella, are offset relative to the Permian volcano-sedimentary succession present at Piz Neir. We interpret this offset as the result of gravitational gliding associated to tilting and transfer to activity from the Jenatsch to the Agnel detachment (see Figs. P2- 8E and 10A and B). The gliding of the upper Triassic dolomites over the evaporitic layer can explain the complex structures in the breakaway and allochthonous blocks overlying the detachment faults (Fig. P2-8). Indeed, in these blocks the pre- and post-evaporate sequences are decoupled to never form a complete stratigraphic section throughout the pre-rift sequence. Moreover, during the Alpine reactivation, the weak evaporite layers have been in many places reactivated as thrusts, leading to even more complex structures that have been discussed in Epin et al. (2017, see their Fig. P2- 4 and 5).

6.3.2 Inherited basement structures controlling architecture of detachment faults

The major inherited structure in the basement in the Err unit corresponds to the Permian Neir basin that is bounded by E-W striking normal faults (see Figs. P2- 2, 8, and 10C to F). We previously described the lateral ramp of the Jenatsch detachment and discussed its interference with pre-existing Permian normal fault. The Jenatsch detachment inverted the Neir basin, however, the bounding normal fault was too steep to be reactivated completely (Fig. P2-10F). As a consequence, the breakaway of the Permian normal fault has not been reactivated and is preserved at the Piz d'Agnel – Corn Suvretta area (see Fig. P2-6C). The lateral ramp of the Jenatsch detachment is consequently controlled by the inherited Permian Neir basin (Figs. P2-6, 8, and 10C to F). The existence of this lateral ramp and its E-W directed strike shows that the transport direction along the Jenatsch detachment had to be E-W directed and parallel to the fault bounding the Neir basin. Although less well exposed, the southern termination of the Permian basin is exposed south of the Julier valley in the area of Piz Rocabella and Piz d'Emmat Dadora. In this area the bounding Permian normal fault is observed to strike E-W and is truncated by the Jenatsch and Agnel detachment faults. The interference of these two detachment faults with the southern termination of the Permian basin may explain the abrupt termination of the breakaway block exposed at Piz Bardella and the occurrence of a basement high capped by detachment faults at Rocabella (Figs. P2-10G to I). Indeed we explain the lateral termination of the Bardella breakaway block as a consequence of the Agnel detachment that intersects and truncates the Jenatsch detachment (see Fig. P2- 10G to 10I). During exhumation along the Agnel detachment, the Jenatsch detachment has been back tilted, which may explain the formation of a topographic high that is at present preserved at Piz Rocabella. This topographic high would correspond to the location where the Jenatsch detachment is truncated by the younger Agnel detachment.

7. Conclusion

The Err nappe preserves remnants of a well preserved detachment system that formed in a hyper-extended domain of a magma-poor rifted margin. It is at present the best place to study, in the field, the 3D architecture and evolution of a detachment system in hyper-extended rifted margin. In this paper we present maps and sections that describe the 3D architecture of this Err detachment system. The Err detachment system is made of several detachment faults evolving in-sequence to continental break-up. Our observations enable to propose a conceptual model that can describe the evolution of this detachment system, which can explain the formation of the hyper-extended domain by an in-sequence evolution of oceanwards stepping faults. Indeed we identify at least four detachment faults evolving in-sequence to forming the hyperextended domain and leading to exhumation of the sub-continental mantle. The length of the faults decreases oceanwards, associated to the decreasing size of the breakaway block. We show that the architecture of the detachment structures and of the overlying breakaway blocks is strongly controlled by inherited structures, which are a Permian basin and pre-rift evaporitic layers. The results of this study enable to explain, based on field observations, the detailed evolution of a detachment system that is related to hyper-extension and exhumation of mantle in the most distal part of a magma-poor rifted margin.

Post face

The systematic mapping of detachment faults in the Err nappe highlights the occurrence of 4 detachments faults, the Err, the Jenatsch, the Agnel and the Upper Platta detachment faults. Based on field observations it can be proposed that they evolved in-sequence and that inherited Permian basins influenced the location and geometry of these detachment faults. The lateral termination of allochthonous blocks and the formation of basement highs are controlled by the interaction between detachment faults and the control of inherited structures. I also show that local structural complexities can be explained by gravitational gliding of pre-rift rafts over evaporate bearing layers.

Key results are:

- Temporal and spatial evolution of a detachment system explaining the formation of the hyper-extended domain by an in-sequence evolution.
- Oceanward decrease in length of the faults, correlated with the decreasing of the block size
- Strong control of inherited structures (Permian basin and pre-rift evaporitic layers) on the locale architecture of detachment systems.
- Inherited structures have an important control in the formation of topographic highs and sedimentary basins and more particularly in the formation and lateral termination of allochthonous blocks.

Questions that remain concerning the evolution and processes related to detachment systems in hyper-extended margins are: How does the complex morpho-tectonic evolution, related to detachment faulting, control the sedimentary architecture? What are the implications of the observation of seismic interpretation of hyper-extended magma-poor rifted margins? How does the transition from the necking to the hyper-extended domain occur, at what moment does the deformation at a crustal scale start to be coupled and when do first faults penetrate directly into the mantle?

It is interesting to note that in the Err nappe only rocks from the pre-rift upper crust are observed. Is this also true for other margins? Are lower crustal rocks exposed at the conjugate upper plate hyper-extended domain?

CHAPTER 8: THE EXHUMED MANTLE DOMAIN AT AN ULTRA-DISTAL, MAGMA-POOR RIFTED MARGIN

Preface

In this chapter, I discuss tectonic, magmatic and hydrothermal processes identified at exhumed mantle domains at ultra-distal, magma-poor rifted margins. Field observations suggest complex interactions between detachment faults, mantle exhumation and magmatic systems that may have some analogies with those observed at slow to ultra-slow spreading ridges. The access to a field analogue enables to investigate the architecture of these domains over a domain of 150 km^2, i.e. a surface that enables to describe first order features of an ultra-distal domain.

The Platta nappe, previously studied by Steinmann (1925), Dietrich (1969), Dürr (1992), Desmurs et al. (2001; 2002), and Müntener (2004; 2009) corresponds to an exhumed mantle domain that includes two units, one formed by exhumed inherited mantle with rare magmatic additions, the second formed by infiltrated mantle that show the development of a magmatic system. More recent studies investigated the petrological and geochemical nature of the mantle and magmatic rocks (*Desmurs et al.*, 2001; 2002; *Müntener et al.*, 2004; 2009; Amann in prep) within the Platta domain. However, a more detailed restoration of this domain, including a detailed study of the architecture of this domain, was never realised. The studies performed prior to my thesis proofed the existence of a detachment system responsible for the exhumation of sub-continental mantle, the occurrence of allochthonous blocks of continent derived materiel overlying the exhumed mantle and an increase of the volume of magma towards the future ocean (Fig. 8-7). The existence of normal faults crosscutting the detachment faults was suggested, but not demonstrated.

In this chapter (Paper 3) I present new maps and observations from the Lower Platta unit that enable to describe the morpho-tectonic and fluid history of an exhumed mantle domain. More specifically, this chapter will focus on the architecture of an exhumed mantle domain and the processes that may explain the complex morphology, the timing of magma emplacement and its relation to exhumation and fluid circulation.

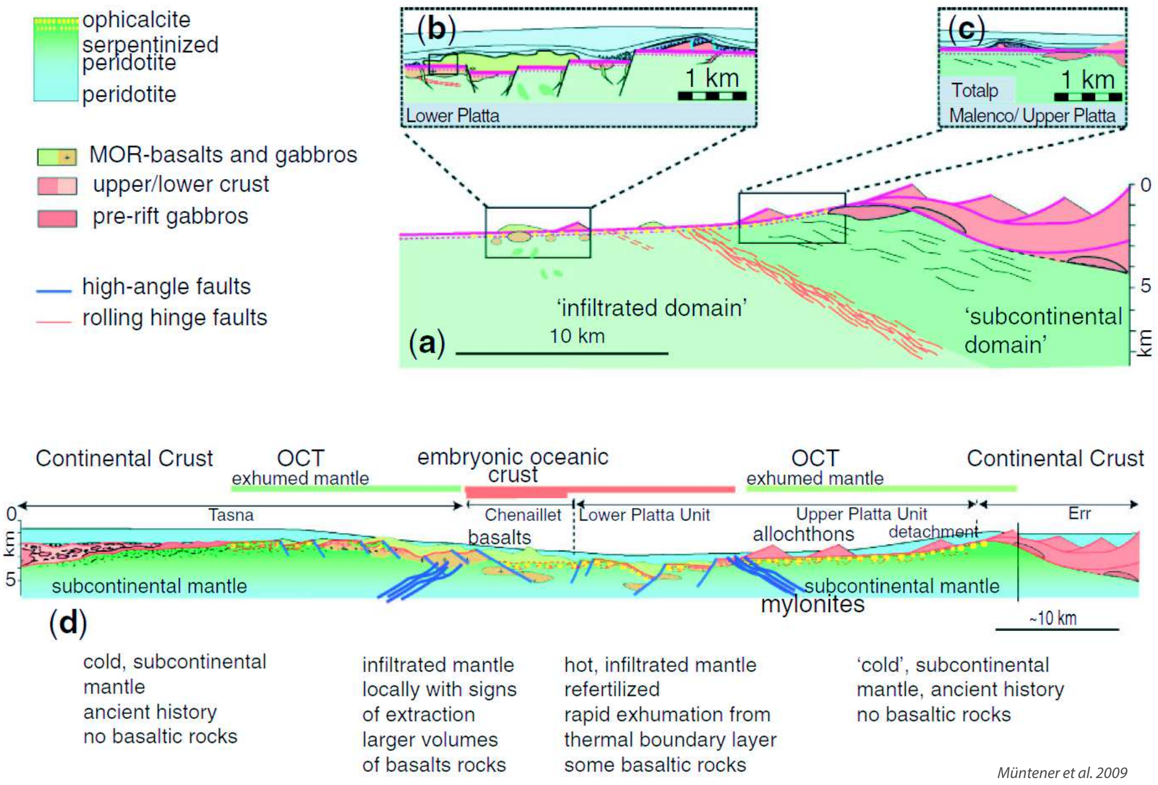


Fig. 8-1: **(a)** *Distribution of sub-continental and infiltrated domains of mantle peridotite within an Ocean-Continent-Transition.* **(b)** *Zoom into the Lower Platta unit and* **(c)** *the Upper Platta unit.* **(d)** *Restored cross-section through a nascent ocean based on the observation made in the Tasna, Chenaillet, Malenco and Platta units (Manatschal and Müntener, 2009; Müntener et al., 2009).*

Paper 3 (in prep. for International Journal of Earth Science)

Polyphase tectono-magmatic and fluid history related to mantle exhumation in an ultra-distal magma-poor rift domain: example of the fossil Platta domain, SE Switzerland

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Abstract

Despite the fact that many studies have investigated mantle exhumation at ultraslow spreading ridges and magma-poor rifted margins, there are still numerous questions concerning the 3D architecture, magmatic, fluid and thermal evolution of these domains that remain unexplained. Indeed, it has been observed in seismic data from ultra-distal magma-poor rifted margins that top basement is heavily structured and complex, however, the processes controlling the morpho-tectonic and magmatic evolution of these domains remain unknown. The aim of this study was to describe the 3D top basement morphology of an exhumed mantle domain, exposed over 200 km^2 in the fossil Platta domain in SE Switzerland, and to define the timing and processes controlling its evolution. Detailed mapping of parts of the Platta nappe enabled to document the top basement architecture of an exhumed mantle domain and to investigate its link to later, rift/oceanic structures, magmatic additions and hydrothermal fluid systems. Our observations show a polyphase and/or complex: 1) deformation history associated with mantle exhumation along low-angle exhumation faults overprinted by later high-angle normal faults, 2) top basement morphology capped by magmato-sedimentary rocks, 3) tectono-magmatic evolution that includes gabbros, emplaced at deeper levels and subsequently exhumed and overlain by younger extrusive magmatic additions, and 4) fluid systems related to serpentinization, calcification, hydrothermal vents, rodingitization and spilitization affecting exhumed mantle and associated magmatic rocks. The overall observations provide important information on the temporal and spatial evolution of the tectonic, magmatic and fluid systems controlling the formation of ultra-distal magma-poor rifted margins as well as the processes controlling lithospheric breakup. In this context, field observations help to better understand the tectono-magmatic processes associated to these, not yet drilled domains.

1. Introduction

Even if exhumation processes at slow to ultra-slow spreading ridges start to be well described, mantle exhumation at Ocean Continent Transitions (OCT) are little investigated, which is mainly due to the difficulty to access directly these structures and the fact that high resolution seismic images through these domains are hardly accessible to the academic community. Therefore we decided to re-investigate the Platta nappe in Grisons (SE Switzerland), which corresponds to a fossil analogue of an ultra-distal magma-poor margin. The detailed study of the Platta nappe enabled to investigate the polyphase tectono-magmatic and fluid history related to mantle exhumation in an ultra-distal part of of a fossil magma-poor rift margin, also referred to as an OCT or Zone of Exhumed Sub-Continental Mantle (ZECM; see *Whitmarsh et al.*, 2001).

Seismic imaging of OCTs reveals a complex architecture with important top-basement topography and drill hole data show occurrence of exhumed mantle rocks at basement highs (Iberia-Newfoundland margin; ODP Sites 637A, 897D-C, 899B, 1068, 1070, and 1277). However, topographic highs can also be associated to continent derived blocks (ODP Site 1069) that exhumed mantle. The evolution and processes associated to the formation of these ultra-distal domains where mantle exhumation is closely linked to the emplacement of magma and fluid systems remain debated. In this study we provided new field observations from the Platta nappe that enable to highlight the polyphase evolution of this fossil ultra-distal domain. The Platta nappe has been intensely studied in the 20th century by Steinman (1905; 1925), Cornelius (1932a), Dietrich (1969) and Desmurs et al. (2001; 2002). Although these studies were able to associate the Platta nappe to a fossil OCT, the detailed Alpine and pre-Alpine architecture of this domain remained little understood. The aim of this paper is to provide a new description of the Platta nappe, which includes a description of the contacts between ultra-mafic and mafic rocks and sediments in order to propose a 3D description of the paleo-architecture and the tectono-magma and fluid evolution of a remnant of an ultra-distal exhumed mantle domain.

2. Geological setting and previous studies

2.1 Geographical and geological overview

The Platta nappe is located in Central Grisons in South-Eastern Switzerland (Fig. P3-1A). It belongs together with the Malenco unit in the south and the Totalp unit in the north to the Upper Penninic units that consist of remnants of the late Middle Jurassic to Early Cretaceous Liguro-Piemonte basin, also referred to as the Alpine Tethys oceanic domain (Fig. P3-1A). These units form the Alpine "suture" zone in Grisons, separating Austroalpine units derived from the Adria microplate in its hanging wall from European derived units in its footwall. The lower contact is made of a late "Eocene" normal fault (e.g. Turba normal fault; *Nievergelt et al.*, 1996, Fig. P3- 1B and C), juxtaposing a Cretaceous nappe stack against Eocene Flysch sediments (e.g. *Ziegler et al.*, 1996). The contact with the overlying Lower Austroalpine units and especially with the Err nappe corresponds to Alpine thrust faults reactivating former Jurassic extensional detachment faults (*Trümpy*, 1975; *Manatschal and Nievergelt*, 1997; *Epin et al.*, 2017). The Platta nappe can be subdivided in two Alpine units, the Upper and the Lower Platta units (Fig. P3-1) (*Desmurs et al.*, 2001). The Platta nappe can be mapped from Tiefencastel in the north to Lej Sgrischus (7 km south of Silvaplana) south of the Engadine over a distance of 30 km (Fig. P3-1A). The core of the Platta nappe, studied in this work, is exposed in the Surses valley between the villages of Sur and Bivio (Fig. P3-1B).

2.2 Historical background

The study of Steinmann (1905;1925) enabled to recognize the intimate link between serpentinites, dolerites and radiolarian cherts along the Alpine chain. He interpreted this sequence (trilogy) of rocks as formed at deep-water conditions in a fossil oceanic domain. This pioneering study was followed by the detailed mapping of the Platta domain by Cornelius (1932) and Dietrich (1969) and the interpretation of this domain as a fossil OCT (Trümpy 1975; for more details on the historical perspective see *Bernoulli et al.*, 2003 and *Bernoulli and Jenkyns*, 2009). The interpretation that the Platta nappe was part of a fossil OCT (*Dietrich*, 1972; *Trümpy*, 1975) was mainly based on three observations: 1) the occurrence of the Upper Jurassic Radiolarian Chert and Aptychus Limestone formations (Fm.) on both oceanic and continental units; 2) the presence of continent derived material in the Platta nappe (at that time interpreted as host rocks into which the magma was intruded; e.g. geosyncline); and 3) the similar metamorphic overprint of the oceanic and continent derived units. Studies in the Apennines (Bracco unit; *Elter*, 1969; *Decandia and Elter*, 1972), in the Western Alps (*Lemoine*, 1961; *Lagabrielle and Cannat*, 1990) and in Totalp (*Peters*, 1968) supported the ideas of Steinmann and lead to the proposition that these units correspond to "oceanic" domains in which the mantle has been exhumed directly to the seafloor.

However, these interpretations were not compatible with the new plate tectonic theory and contradicted the idea that oceanic domains are made of three layers (basalts, sheeted dykes and gabbros; e.g. Penrose Conference in 1972). As a consequence, the Alpine ophiolites have been re-interpreted as either "peculiar" or "incomplete" ophiolites, different from the Penrose sequence observed in Oman or in the Troodos mountains (*Moores and Vine*, 1971) or present-day fast spreading ridges. Alternatively, the Alpine ophiolites have also been re-interpreted as tectonic mélanges or dismembered ophiolites, formed during Alpine subduction (*Hsu*, 1974). Despite of the resistance of the international community, Alpine geologists continued to describe primary relationships between serpentinised mantle rocks, basalts and sediments (e.g. *Dietrich*, 1969; *Lagabrielle and Lemoine*, 1997; Desmurs et al., 2001) suggesting that the Alpine ophiolites had a different origin. With the advent of modern marine geology and the possibility to dredge, drill and directly access the seafloor by submarines, exhumed mantle rocks have been discovered at the seafloor along transform faults (*Bonatti et al.*, 1986), along slow spreading ridges (*Cannat et al.*, 1995) and drilled along OCT (*Boillot et al.*, 1987). This led to reinterpret the Alpine ophiolites as either remnants of former transfer faults (*Weissert and Bernoulli*, 1985), slow spreading mid ocean ridges (*Lagabrielle and Cannat*, 1990; *Lagabrielle and Lemoine*, 1997) or as OCTs (*Lemoine et al.*, 1987; *Piccardo et al.*, 1990; *Florineth and Froitzheim*, 1994; *Froitzheim and Manatschal*, 1996, *Manatschal and Nievergelt*, 1997; *Desmurs et al.*, 2001; for more references and an overview see also *Manatschal and Müntener*, 2009).

At present, it is commonly admitted that the Alpine ophiolites correspond to an ophiolite succession that formed during final rifting and onset of slow seafloor spreading and include the exhumation of subcontinental mantle. The Alpine ophiolites consist predominantly of serpentinised peridotite with minor amounts of gabbros, covered by magmatic rocks and/or deep marine sediments. Weissert and Bernoulli (1985), and Bernoulli and Jenkyns (2009) described the Upper Jurassic Radiolarian Chert and Aptychus Limestone Fms. and compared them with those drilled in the Central Atlantic (DSDP Leg 11). Based on this correlation, they proposed that the Alpine Tethys was linked to the Central Atlantic. Numerous petrological, geochemical and isotopic studies of the mantle rocks show the occurrence of subcontinental mantle that has been refertilized during Jurassic rifting (*Müntener et al.*, 2009; *Picazo et al.*, 2016). However, depleted oceanic mantle rocks, which are genetically linked to the overlying basalts, have not been found yet (*Rampone et al.*, 1995; Müntener et al. 2004, 2009). The existence of pre-rift intrusive contacts welding subcontinental mantle and lower continental crust (*Trommsdorff et al.*, 1993; *Müntener and Hermann*, 1996; *Desmurs et al.*, 2001), the occurrence of extensional continent derived allochthonous blocks and tectono-sedimentary breccias overlying tectonically exhumed subcontinental mantle rocks (*Müntener and Hermann*, 1996; *Manatschal and Nievergelt*, 1997) in the Malenco and Platta units support the idea that they represent fragments of a former OCT. A type sequence through an OCT has been described by Manatschal & Müntener (2009) based on observations made in the Platta - Malenco, Tasna and Chenaillet units. Based on these studies but also based on a comparison with drill hole data from the distal Western Iberia margin (for reviews see *Manatschal*, 2004; *Manatschal et al.*, 2007), we consider the outcrops studied in this work as remnants of an ultra-distal magma-poor rifted margin.

2.3 The Platta nappe

The Platta nappe (previously called "rhätische Decke") has originally been defined by Staub (1916). The main description of the lithologies, structures, metamorphic overprint and sediments forming this nappe was the result of numerous studies that have been performed throughout the last century. Cornelius (1932) produced a first map of the eastern part of the Central Platta nappe, which remains, except for the mislabelling of the Jurassic and Cretaceous sediments, one of the best maps of the area. Staub (1946) mapped the southern part of the Platta nappe that was later investigated by Liniger (1992). The central Platta nappe, which corresponds to the studied area, has been mapped by Dietrich (1969), a work that can be considered as pioneering in its precision, interpretation of the contacts and the description of the rocks. The results of this map have been compiled in the map of Bivio (*Peters*, 2005; 2007).

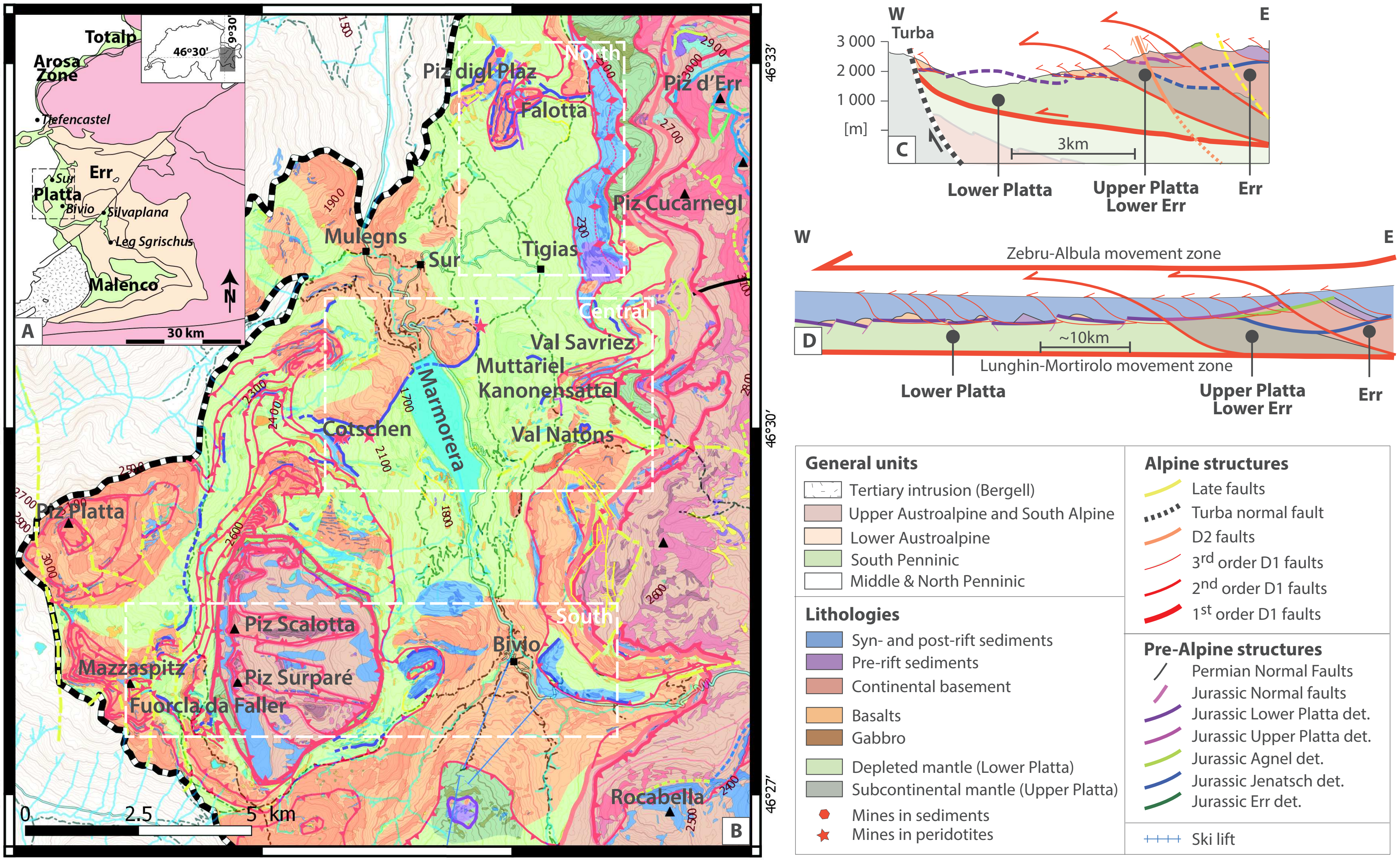
The study of the metamorphic overprint, performed by Dietrich (1976), Trommsdorff et al. (1974; 1983; 1993), Ferreiro-Mählmann (1994; 1996) and Eppel et al. (1997; 1997), showed that the metamorphic overprint in the area north of Bivio never exceeded the Prenite-Pumpellyite facies conditions (< than 300°C). However, the study also showed that the overprint can be very heterogeneous, locally preserving former oceanic hydrothermal metamorphic events.

The relation between the mantle rocks and the magmatic intrusive and extrusive sequences has been studied by Dietrich (1969), Desmurs et al. (2001; 2002) and Müntener et al. (2004; 2009). These studies demonstrated, using major and trace element chemistry and Sm/Nd model ages and U/Pb dating on zircons that the mantle rocks are not genetically linked to the magmatic rocks and that the gabbros and basalts belong to one and the same magmatic sequence.

The hydrothermal activity, including serpentinization, ophicalification, rodingitisation and splitisation has been investigated by Dietrich (1972), Stille et al. (1989), Perseil and Latouche (1989), Früh-Green et al. (1990), Eppel and Abart (1997) and more recently by Pinto et al. (2015) and Incerpi et al. (2017). The results of these studies supported the idea that exhumation of the mantle was related to a penetrative serpentinization that initiated below the thinned crust. Rodingitisation and spilitisation as well as ophicalcitisation of the mantle occurred during and after exhumation of the mantle rocks at the seafloor and the emplacement of basalts and gabbros in an oceanic environment. However, the link between the hydrothermal events and the tectono-magmatic evolution remains ill constrained and will be discussed in this paper.

The sedimentary sequence has been investigated and described by Dietrich (1970), Weissert et al. (1979), Bernoulli and Weissert (1985) and Trümpy (2003). Attempts to date the sedimentary sequence were made using radiolarian cherts (see discussion below) and foraminifera in the Cretaceous sequences. The overall sequence was described as a classical deep marine sequence that consists of Radiolarian cherts, Aptychus Limestones and Pallombini showing strong similarities to sequences found throughout the Alpine domain and drilled in the Central Atlantic (*Weissert and Bernoulli*, 1985). However, the occurrence of locale breccias and detritus, including mantle derived material, and strong geochemical signatures (*Geiger*, 1948; *Perseil and Latouche*, 1989) are likely associated with the tectono-magmatic evolution of the Platta domain (e.g. *Bracciali et al.*, 2014).

The structural description of the Platta nappe was hampered by the interpretation according to which this domain was part of a tectonic mélange that entered into the subduction zone (*Hsu*, 1974; *Dürr*, 1992). However, this idea is at odd with the lack of a high-pressure metamorphic overprint and the continuous stratigraphic succession found in the cover sequences. Froitzheim et al. (1994) and Manatschal and Nievergelt (1997) showed, based on detailed structural analysis that the Platta nappe underwent the same structural evolution as the overlying Austroalpine units. This evolution included a D1 top to the west thrust event that was overprinted by a top to the SE extensional event (D2), and N-S shortening (D3) (Fig. P3-1) (for a summary and a detailed description of the Alpine evolution see *Epin et al.*, 2017). Desmurs et al. (2001) and Schaltegger et al. (2002) proposed, based on mapping of first order structures and mantle domains that the Platta nappe can be subdivided into two units, an Upper and a Lower Platta unit (Fig. P3-1). These authors were able to map two main serpentinite bodies that are limited by a major Alpine D1 thrust throughout the Platta nappe. Based on their mapping, these authors proposed a general increase in magma-production oceanwards. This is in line with the observation of a transition from a T to a N-MORB composition of the magma (*Desmurs et al.*, 2002), and a change in the composition of the mantle from an inherited subcontinental to an infiltrated mantle (type 1 and 2 in *Picazo et al.*, 2016; see also *Müntener et al.*, 2004; 2009). A more detailed mapping and fine-tuned reconstruction of the Platta domain by Epin et al. (2017) enabled to discriminate, using diagnostic criteria, between pre-Alpine and Alpine structures as well as to distinguish between first, second and third order Alpine thrust structures. These authors also demonstrated the importance of inherited rift structures during the subsequent



9°36′
9°39′
46°33′
46°30′
46°27′
Totalp
Arosa Zone
Tiefencastel
Err
Sur
Platta
Bivio
Silvaplana
Leg Sgrischus
Malenco
N
30 km
46°30′
9°30′
A
North
Piz digl Plaz
Falotta
Piz d'Err
Piz Cucarnegl
Mulegns
Sur
Tigias
Central
Val Savriez
Muttariel
Kanonensattel
Cotschen
Marmorera
Val Natons
Piz Platta
South
Piz Scalotta
Piz Surparé
Bivio
Mazzaspitz
Fuorcla da Faller
Rocabella
0
2.5
5 km
B
W
E
Turba
3 000
2 000
1 000
[m]
3km
C
Lower Platta
Upper Platta
Lower Err
Err
Zebru-Albula movement zone
~10km
D
Lunghin-Mortirolo movement zone
Lower Platta
Upper Platta
Lower Err
Err
General units
Tertiary intrusion (Bergell)
Upper Austroalpine and South Alpine
Lower Austroalpine
South Penninic
Middle & North Penninic
Lithologies
Syn- and post-rift sediments
Pre-rift sediments
Continental basement
Basalts
Gabbro
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Mines in sediments
Mines in peridotites
Alpine structures
Late faults
Turba normal fault
D2 faults
3rd order D1 faults
2nd order D1 faults
1st order D1 faults
Pre-Alpine structures
Permian Normal Faults
Jurassic Normal faults
Jurassic Lower Platta det.
Jurassic Upper Platta det.
Jurassic Agnel det.
Jurassic Jenatsch det.
Jurassic Err det.
Ski lift

Fig. P3-1: **A:** *Geologic map of the eastern Grisons showing the distribution of the Austroalpine units and South Penninic ophiolites (modified after Desmurs et al., 2001). Inset in the upper right corner shows location of the map in Switzerland.* **B:** *Geologic map of the Platta nappe (modified after Staub, 1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Peters, 2005; 2007; and own observations).* **C:** *Section through the Platta and Err nappes showing main Alpine units and Alpine D1 structures (modified after Epin et al., 2017).* **D:** *Restored section at Late Jurassic time across the Platta and Err domains. Red lines are location of major Alpine 1st, 2nd and 3rd order D1 faults (modified after Epin et al., 2017).*

Alpine reactivation. In this study, we will focus on the Lower Platta unit exposed between Sur in the north and Bivio in the south. We will describe the relations between lithologies, structures and hydrothermal and magmatic processes, and discuss the tectono-magmatic and morpho-tectonic evolution of this domain and its implication for the sedimentary, magmatic and fluid evolution of the ultra-distal margin during its formation.

2.4 Present-day analogues of exhumed mantle domains

At present, well-described systems of exhumed mantle domains can be found at slow to ultra-slow spreading ridges and along OCT's of magma-poor rifted margins. The only exhumed mantle domain associated with an OCT that has been drilled and which is seismically imaged, correspond to the one of the conjugate Iberia-Newfoundland margins. Along these margins exhumed mantle has been drilled at 5 ODP Sites (Sites 637A, 897D-C, 899B, 1068, 1070, and 1277). Manatschal et al. (2001) showed that these exhumed mantle rocks extend over 160km in the southern Iberia Abyssal Plain and are associated to topographic highs. The top basement in these domains is capped by an exhumation surface as indicated by the occurrence of cataclasites, gouges and ophicalcites. Wilson et al. (2001) showed that the mantle highs are overlain by diagnostic tectono-sedimentary breccias reworking basement and are passively onlapped by younger sediments. This explains the major hiatus that has been drilled on the basement highs. Müntener and Manatschal (2006) showed that the mantle rocks exhumed along the margin are either inherited, depleted subcontinental mantle (ODP Site 1277), or infiltrated subcontinental mantle, corresponding to mantle type 2 of Picazo et al. (2016). Magma occurs at these margins either as infiltrated magma, as theoliites (MORB; Mid Oceanic Ridge Basalt) that are either intrusives or extrusives, or as late alkaline intrusives and extrusives that are post-breakup (*Müntener and Manatschal*, 2006; *Peron-Pinvidic et al.*, 2010). Jagoutz et al. (2007) dated some of these magmatic rocks indicating that mantle exhumation was associated with the emplacement of poly-phase magmatic additions. Dean et al. (2015) and Guillard et al. (2016a) showed, using seismic sections from the Iberian and Newfoundland margins, the polyphase nature of the ultra-distal margin, which is also in line with the potential field methods (gravity and magnetics) described from the same margins (*Stanton et al.*, 2016). All these observations show some similarities with the exhumed mantle domain exposed in the Platta nappe (for a comparison of the two domains see *Manatschal et al.*, 2007).

The best studied and understood examples of exhumed mantle are at slow to ultra-slow mid-oceanic ridges (e.g. South West Indian Ridge (SWIR); *Cannat et al.*, 2003; *Sauter et al.*, 2013, Gakkel Ridge; *Michael et al.*, 2003, several segments in the Mid Atlantic Ridge; *Cannat et al.*, 1995; *Cannat et al.*, 1997; *MacLeod et al.*, 2002; *deMartin et al.*, 2007; *Escartín et al.*, 2015).

Dredging of the top of the basement demonstrated the occurrence of exhumation surfaces made of serpentinite peridotites and rare gabbros, locally covered by patchy basaltic flows and sediments. Poly-phase detachment faults are interacting with high-angle faults and transfer faults, which are at the origin of a complex top basement 3D architecture. Cannat et al. (2006) proposed, based on observations from the SWIR, 3 types of seafloor morphologies that are "smooth", "corrugated" or "volcanic". These morphologies point out different expressions of the seafloor due to different budgets of magma and relation to fault activity. Cannat et al. (1997), Tucholke et al. (1998), Schroeder and John (2004) and MacLeod et al. (2009) described so-called Oceanic Core Complex (OCC), also referred to as megamullions, defined as dome shape highs that are capped by an exhumation surface and made of exhumed magmatic (gabbros) or mantle (serpentinised peridotites) rocks. These structures show downward concave fault surfaces. Single faults are limited by breakaways, which correspond to the initiation of a detachment fault. The rooting level of such faults remains disputed. On a strike section across an OCC, these faults show often corrugated surfaces. The offset along the major detachment faults, which indeed corresponds to a cumulated offset along several faults, vary between few kilometres to several tens of kilometres. Single faults can be active over a time of up to 1 myr (*Blackman et al.*, 2009). The dip angle of these detachment faults changes along a dip section, however, based on seismic data and distribution of earthquakes, the dip at depth of the active fault is 40° to 70° (*deMartin et al.*, 2007; *Reston and Ranero*, 2011). The angle of the fault at the cut-off point with the seafloor is in the order of 10° to 35° (*Cann et al.*, 1997; *Smith et al.*, 2008). Typically the breakaway angle at the break away point (angle between pre-existing top basement and fault) is between 40° and 70°. This geometry is consistent with the rolling-hinge model (*Buck*, 1988; *Wernicke and Axen*, 1988; *Lavier et al.*, 1999; *Buck et al.*, 2005; *Tucholke et al.*, 2008). The morphology of such ultraslow spreading ridges can be modelled in numerical models in which the magmatic budget is less than 20% (*Tucholke et al.*, 2008). It is, however, important to note that despite of the exhumation of mantle rocks along asymmetric structures, the overall accretion along these ridges remains symmetric (*Sauter et al.*, 2013), this has been explained by the occurrence of out of sequence faulting (*Gillard et al.*, 2016a). The concept of out of sequence normal faulting is important, since it allows to explain the emplacement of magmatic rocks onto previously exhumed surfaces as well as to explain polyphase tectonic and magmatic processes at exhumed mantle domains. Even if exhumation processes at slow to ultra-slow spreading ridges start to be well described, mantle exhumation in OCT's are yet little investigated, which is mainly due to the difficulty to access directly these structures and the fact that high resolution seismic images hardly accessible to the academic community.

3. Geological and structural organisation of the Platta nappe

3.1 Lithologies of the Platta nappe

The "ophiolites" preserved in the Upper Penninic units along the boundary with the Austroalpine units in Graubünden are characterized by the predominance of serpentinised lherzolites and harzburgites over magmatic rocks. According to the geochemical and petrological analysis (*Dietrich*, 1969; *Evans and Trommsdorff*, 1974; *Burkhard and O'Neil*, 1988; *Desmurs et al.*, 2002), the peridotites preserve the geochemical and petrographical characteristics of subcontinental mantle (*Trommsdorff et al.*, 1993; *Müntener and Hermann*, 1996). Associated to serpentinised mantle we find small volumes of gabbros and basalts, but there is no evidence for the existence of a sheeted dike complex. Deep marine sediments made of the Radiolarian Chert, the Aptychus Limestone and Palombini Fms. form the main sediments in the Platta nappe. Furthermore, continent-derived crustal blocks occur directly onto exhumed mantle (*Froitzheim and Manatschal*, 1996; *Manatschal and Nievergelt*, 1997). All these observations are consistent with an exhumed mantle domain in an OCT.

3.1.1 Mantle rocks

The mantle rocks constitute two separate tectonic units; the Upper Serpentinite unit and the Lower Serpentinite unit (*Manatschal et al.*, 2003) referred to as the Upper and Lower Platta units (Fig. P3-1) in this study. The Upper Platta unit is located between the Lower Platta unit and an unit made of continental basement and pre-, syn- and post-rift sediments, referred to as the Lower Err unit (*Manatschal et al.*, 2003) (Fig. P3-1). Although in the past the contact between the Lower Err unit (continent) and the Upper Platta unit (subcontinental mantle) was considered to be a major thrust contact, recent studies suggest indeed that this contact was of minor importance and that these two units were already juxtaposed before onset of convergence (Fig. P3-1C and D) (*Epin et al.*, 2017; and this study).

The serpentinised peridotites of the Upper Platta unit preserve a spinel foliation and contain pyroxenite bands that are in most cases parallel to the spinel foliation, indicating that they equilibrated in the spinel stability field (*Desmurs et al.*, 2001). The mantle rocks forming the Upper Platta unit correspond to mantle type 1a described in Picazo et al. (2016).

The peridotites of the Lower Platta unit appear less deformed and are generally free of pyroxenite bands. Several mylonitic shear zones occur within these peridotites. They are commonly found at the top of the mantle (e.g. Muttariel; paragraph 4.2.3; Fig. P3-6; Log 10). These peridotite mylonites show crystal plastic recrystallization of olivines that are associated with ultra-mylonites, suggesting that they formed at 700 to 900°C and fast cooling/exhumation, in order to explain the lack of thermal induce annealing of the microstructures. These mylonites are not dated and therefore cannot be attributed to a particular evolutionary stage of the mantle exhumation at this stage.

The major deformation in the mantle rocks formed under greenschist-facies to seafloor conditions, and is related to a foliation defined by the assemblage of chlorite, serpentine and rare talc (*Desmurs et al.*, 2002) that is overprinted by ophicalcites. This foliation is found at the top to the exhumed mantle, and grades downwards into massive, serpentinised mantle peridotites. The associated fault zones show a top-to-the west, i.e. top to the future ocean, sense of shear, and are cut by undeformed basaltic dykes, demonstrating their pre-Alpine age (describe at the East of Falotta by *Desmurs et al.*, 2001). Structural data in the Platta nappe (top-to-the-west, i.e. top-to-the-ocean after *Bernoulli et al.*, 2003, and top-to-the-east, i.e. top-to-the-continent after *Desmurs et al.*, 2001) are coherent to an east-west extension, however, the exact sense of shear remains debated and may be explained by polyphase activity. Since the Alpine metamorphic overprint never exceeded 300°C, it can be excluded that these mylonites are related to Alpine events.

3.1.2 Magmatic rocks

The magmatic rocks present in the Platta nappe can be subdivided in three groups: 1) infiltrated into hot, depleted subcontinental mantle rocks, 2) intrusives at shallower levels in exhuming mantle or extrusives onto already exhumed mantle, and 3) late dykes/sills in post-rift sequences. In the Upper Platta unit, the magmatic additions are almost inexistent except for few dykes and extrusive rocks. In contrast in the Lower Platta unit, all three types of magmatic additions can be found and represent a significant part of the present lithologies. The mantle rocks forming the Lower Platta unit correspond to refertilized mantle (after *Müntener et al.*, 2004; *Müntener et al.*, 2009; Type 1b and 2 in *Picazo et al.*, 2016). The refertilization of the mantle is not directly dated in the Platta nappe. However, Müntener et al. (2004) were able, using Sm/Nb model ages, to show that the mantle was depleted during the Permian post-orogenic collapse and was intruded by gabbros that have been dated using U/Pb on zircons as 161±1Myr (*Schaltegger et al.*, 2002). Therefore, the mantle refertilization has been assumed to be related to lithospheric thinning (e.g. *Müntener et al.*, 2004). The depth location of the gabbros is difficult to determine in detail. Desmurs et al. (2002) suggested, based on petrological arguments (recrystallization of plagioclase as first phase) and structural arguments (syn-magmatic emplacement and fast cooling) a shallow emplacement depth of less than 6km (for more discussion see below). The dykes, also not very numerous, appear to be mainly localized along faults and to be strongly rodingitized, which suggests that mantle rocks were serpentinizing or were already serpentinised when these rocks were emplaced. Most of the basalts are, as described in this study, emplaced in a syn- to post-tectonic setting and their almost complete spilitization suggests the presence of hydrothermal fluids.

Although the magmatic budget is difficult to estimate in detail, a key observation is that the Upper Platta unit is almost devoid of magmatic additions, while the underling Lower Platta unit has a much higher magmatic budget. Gabbros and dykes of the Lower Platta unit form less than 5% of the total observed volume of the basement (*Manatschal et al.*, 2003), and basalts cover less than 40% of the total observed exhumed surface. Extrusives can be subdivided into massive basalts, pillow lavas, pillow breccias and hyaloclastites (*Dietrich*, 1969) that occur in patches of variable thickness and size, which appear to become more important and continuous oceanwards. A compositional variation from T- to N-MORB seems to by correlated with the spatial distribution of the mafic rocks (*Frisch et al.*, 1994). Desmurs et al. (2002) showed that throughout the Platta domain the mafic rocks with T-MORB signatures occurred close to the continental margin, whereas N-MORB signatures are more frequently found further oceanwards. In addition to gabbros and basalts, rodingitized mafic dykes intruded the serpentinised peridotites at different places in the Platta nappe. Last but not least, the observation of dykes that intruded the Cretaceous sediments suggest a post-exhumation, magmatic activity, similar to what has been drilled along the deep Newfoundland margin or the Gulf of Aden (*Leroy et al.*, 2010; *Peron-Pinvidic et al.*, 2010).

3.1.3 Sedimentary rocks

The first sediments deposited over exhumed mantle or basalts are, apart from tectono-sedimentary breccias, red and green Radiolarian Cherts dated as late Middle to early Upper Jurassic (Calovian/Bathonian to Kimmerigian/Oxfordian; *Bill et al.*, 2001). These sediments are composed of thin bedded, siliceous shales and cherts (*Baumgartner*, 1987; *Manatschal and Nievergelt*, 1997; *Bill et al.*, 2001). In the past, pelagic radiolarian oozes, red clays and chemically precipitated siliceous cherts have been grouped in the Radiolarian Chert Fm. Indeed, the macroscopic distinction between biogenic and chemically precipitated silica is difficult and asks for geochemical analysis. The Radiolarian Chert Fm. is a generic term that we will use in this paper to describe an assemblage that is more complex in reality and that will be discussed below. Red claystones originating from the alteration of basalts in hyaloclastites are often assigned to the Radiolarian Chert Fm. In our study we use the generic term Radiolarian Chert Fm. to describe all reddish sediments that could be either associated with the red claystones, cherts, and radiolarites. The Radiolarian Chert Fm. is overlain by the Aptychus Limestone Fm. also referred to as the Calpionella limestone Fm. This formation is Thitonian to Beriasian in age (*Weissert and Bernoulli*, 1985). It corresponds to light-coloured micritic limestones with intercalations of shales (*Manatschal and Nievergelt*, 1997). This succession is overlain by calcareous slates, dark siliceous shales and calcarenites alternating with dark grey limestones that are grouped in the Palombini Fm. (other commonly used terms are Argille a Palombini or Emmat Series for *Finger*, 1978, Neocomschiefer for *Stöcklin*, 1949 or Roccabella-Schiefer for *Dietrich*, 1970). This formation has been dated to the Cretaceous (approximately Valanginian-Barremian to Aptian-Albian for the youngest dated rocks in the Platta nappe, *Dietrich*, 1970; *Weissert and Bernoulli*, 1985). These sedimentary formations can locally contain clasts of continental basement (gneiss, meta-sediments, granite and pre-rift dolomites), syn-rift sediment (Saluver Group) or serpentinite and magmatic rocks.

3.1.4 Hydration reaction, hydrothermal systems and ore mineralization

The products of hydrothermal activity are widespread in the Platta nappe. Indeed, fresh, not hydrated/altered mantle and magmatic rocks are rare. Since the same hydration events can be observed in Alpine tectonic units that show different ranges of metamorphic overprint, and clasts of the altered material can be found reworked in Jurassic sediments, the bulk of the hydration had to be related to the exhumation and/or their formation prior to convergence. Thus, hydration reactions are intimately associated with the tectonic and magmatic evolution of the rocks during their formation at the OCT.

The major hydration reactions include serpentinization of the mantle rocks (including the formation of minor amounts of chlorite, talk …), rodingitization and spilitization of dykes and basalts, and calcification of the exhumed mantle. Moreover, hydrothermal reactions result also in the formation of mineralizations and ore mineralization that have been mined in the past. While the different reactions and the distribution of the rocks have been described by Dietrich (1972), (*Perseil and Latouche*, 1989; *Stille et al.*, 1989), in this study we will try to link the different hydration/hydrothermal systems to the tectono-magmatic evolution of the OCT.

3.2 Structural organisation of the Platta nappe

The map and the general section shown in figure P3-1 include remnants of the hyperextended crust (Err domain), of the transition between continental crust and first exhumed subcontinental mantle (Lower Err - Upper Platta units), and of the infiltrated exhumed mantle (Lower Platta unit). The section is truncated to the west by the Oligocene Turba normal fault (thick black dotted line, Fig. P3-1) (*Nievergelt et al.*, 1996) that juxtaposes the eo-Alpine D1 thrust stack in the hanging wall against the Eocene flysch (Arblatsch flysch; *Ziegler*, 1956) in the footwall.

3.2.1 Alpine deformation

Detailed structural descriptions of the Platta nappe have been published in Ring et al. (1990), Dürr (1992), Manatschal and Nievergelt (1997) and Epin et al. (2017). Froitzheim et al. (1994) subdivided the Alpine structural evolution into 5 deformation phases referred to as D1 to D5. They correspond to a sequence of Late Cretaceous W to NW-vergent nappe stacking (D1) that are overprinted by extensional, top to the SE normal faults (D2), a subsequent N–S shortening (D3) and two very localized, brittle fault events. The most important structures visible on the geological map of the Platta nappe are by far the D1 structures (red line, Fig. P3-1), which are manifested by the emplacement of a top to the west to northwest thrust system. This major thrust event (thick red line, Fig. P3-1) resulted in a stacking of different rift domains, including the proximal, necking, hyperextended and exhumed mantle domains (*Mohn et al.*, 2011). Second order D1 structures (moderately thick red line, Fig. P3-1) described by Epin et al., (2017) juxtaposed different rift domains. In the fossil OCT these domains correspond to the hyperextended crust (Err and Bernina domains) and the zone of exhumed mantle including magmatic additions (Platta domain). The occurrence of extensional allochthones and interleaved supra-detachment rift basins resulted in a strongly non-cylindrical and non-layer cake pre-Alpine rift architecture that controlled the later reactivation and final orogenic architecture (for a discussion see *Epin et al.*, 2017). Third order D1 thrusts (thin red line, Fig. P3-1) juxtapose units derived from one and the same rift domains that are controlled by local buttresses and decoupling levels. Epin et al., (2017) showed that the local complexity observed in the Lower Platta unit is the result of these third order D1 thrusts that create duplex structures in between major thrust sheets. These duplexes preferentially reactivated the cover of the exhumed detachment system and preserved the underlying basement. Thus, the reactivation of the former OCT occurred in a thin-skin tectonic setting.

The D2 structures are mainly expressed by top-to-the-SE normal faults that formed during an extensional event predating the onset of N–S shortening (D3). It can be interpreted that they have formed after the location of the units in an external part of the eo-Alpine orogen (D1 structures), during the south vergent subduction of the Piemonte basin underneath the Adriatic micro-continent (*Mohn et al.*, 2012). In the Platta unit, a major D2 normal fault (orange line, Fig. P3-1) has been mapped that truncates the previously formed D1 nappe stack. From north to south, it cuts from the Err nappe into the Platta nappe. This normal fault is responsible for the omission of the Upper Platta unit and the direct juxtaposition of units of the Err nappe against the Lower Platta unit south of Val Natons (see map Fig. P3-1). The displacement along this fault has been estimated to less than 3 km, based on the mapping of cut off points in the Err nappe (*Manatschal and Nievergelt*, 1997).

The D3 structures correspond to Cenozoic north–south directed shortening (*Froitzheim et al.*, 1994). D3 structures correspond to E-W trending folds with long wavelengths (> 10km) and amplitudes (> 1km), and subvertical E–W striking fold axial planes. In the north of the Platta nappe (north of Piz d'Err, Fig. P3-1), D3 fold axial planes dip southward, while to the south they dip north- to northwest wards showing a large fan like structure. In detail, however, these folds are related to steep to subvertical thrust faults that have N-S directed displacements in the order of hundreds of meters. At the central part of the Platta nappe between Sur and Bivio, the long wavelength D3 folds are gently expressed and make that the major D1 thrust faults are only gently folded. On an outcrop scale, D3 structures are often linked to a subvertical crenulation cleavage that folds the previous D1 foliation.

Younger structures (D4 and D5) are related to late Alpine deformation (e.g. Froitzheim et al. 1994). The D4 is related to the uplift of the Central Alps. Although it is not expressed in the outcrop scale throughout the Platta nappe, it is responsible for the eastward tilting of the whole nappe pile. The D4 and the D5 are responsible for the late uplift of the studied area. D5 structures (yellow line, Fig. P3-1) are expressed by high-angle to subvertical E-W trending faults that are linked to movements along the Engadine fault. This structure is a conjugate fault of the Oligocene to Miocene Periadriatic dextral strike-slip system (for further discussion see

Trümpy, 1977; *Schmid and Froitzheim*, 1993; *Handy et al.*, 1996).

The Alpine metamorphic overprint in the Platta nappe has been described by Trommsdorff (1983), Ferreiro-Mälhmann (1994; 1996) and Eppel (1997). These studies showed that it ranges from prehnite-pumpellyte facies in the north to greenschist facies in the south. North of Bivio ultrabasic rocks are represented by lizardite-chrysotile-serpentinite and antigorite bearing lizardite-chrysotile-serpentinite south of Bivio, indicating an increase in Alpine metamorphism from north to south (*Trommsdorff and Evans*, 1974; *Trommsdorff*, 1983).

3.2.2 First order Alpine restoration

The major reactivation of the inherited rift structures visible in the Err and Platta nappes is localised along second order D1 thrust faults (after *Epin et al.*, 2017). Two principal D1 thrusts can be identified on the geological map and section shown in figure P3-1 (moderately thick red line). The first one is between the Err unit (e.g. Middle and Upper Err after *Manatschal and Nievergelt*, 1997) and the Lower Err/Upper Platta units. The second one is between the Lower Err/Upper Platta unit and the Lower Platta unit. In order to explain the contrasting magmatic history and the mantle characteristics of the Upper and Lower Platta units, the thrust separating the two units may represent a major, second order, D1 thrust fault. A minimum shortening of 11km along this thrust can be estimated by defining the present-day westernmost position of lower Err/Upper Platta unit (e.g. Scalotta – Surparé klippe, Fig. P3-1) over the Lower Platta unit. During the positioning of the Upper Platta unit over the Lower Platta unit, thin-skin duplexes formed in between the two units (third order D1structures, thin red line, Fig. P3-1) that are made of material that derived from to the Lower Platta unit (e.g. *Epin et al.*, 2017).

4. Local relationships between lithologies, structures and hydration in the Lower Platta unit

In order to structure the description of the local relationships between the different lithologies, structures, type of contacts and hydration/hydrothermal processes, we subdivided the area in three segments: a northern one, a central one and a southern one (white dotted square in Fig. P3-1B).

4.1 The Northern Segment

The Northern Segment of the Lower Platta unit is located around the Falotta - Piz digl Plaz - Tigias area (Fig. P3- 1B and 2). An E-W striking section across this area (Fig. P3-3B; location on Fig. 3-2) corresponds to a section that is parallel to the main Alpine transport

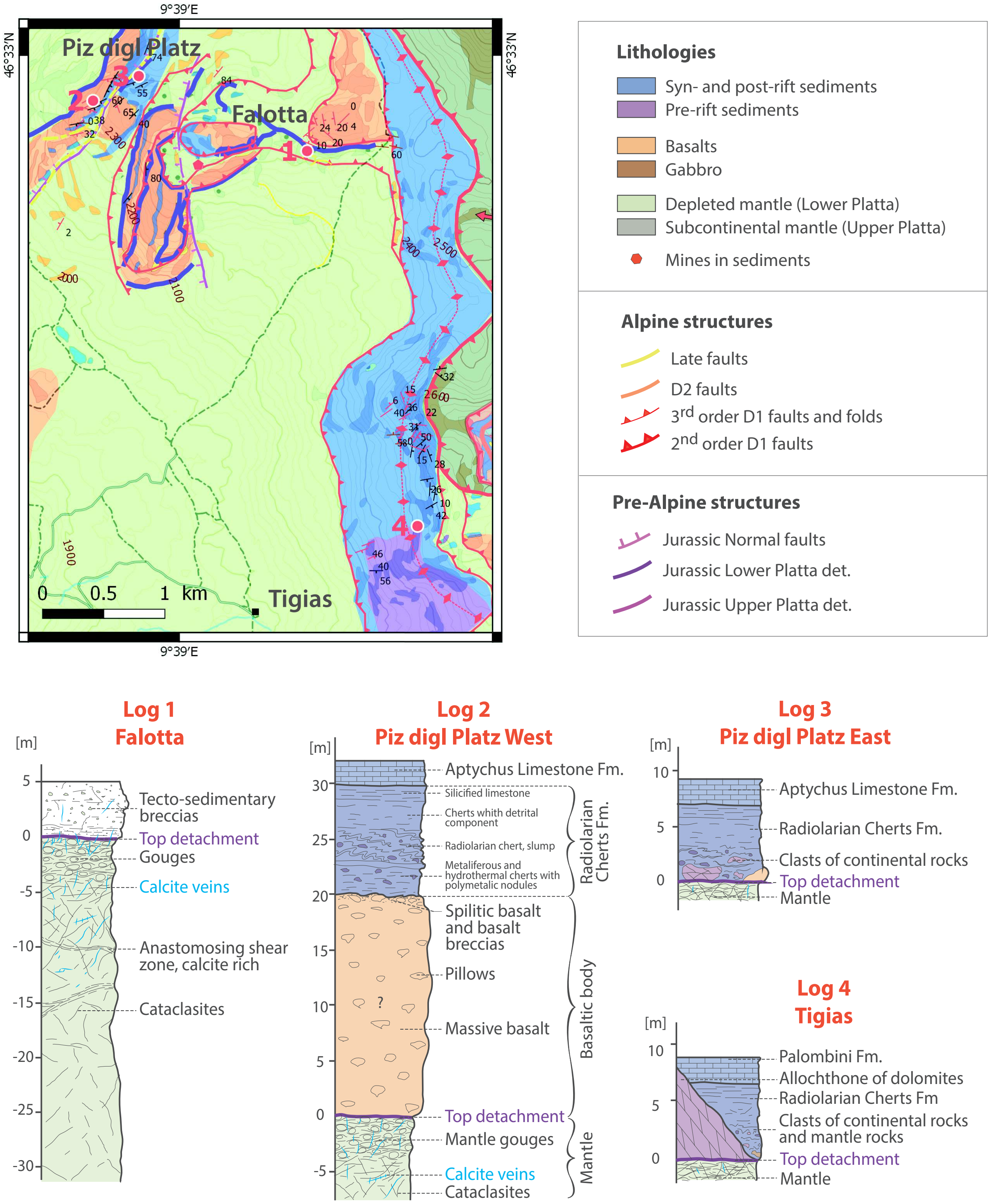


Fig. P3-2: *Geological map of the Northern Segment showing location of Logs 1, 2, 3 and 4 in the Falotta, Piz digl Platz and Tigias area and location of the section present in Fig. 3B.* **Log 1** *presents the champion section through a damage zone of a detachment fault with cataclasites, gouges, ophicalcites and tectono-sedimentary breccias.* **Logs 2 and 3** *show the cover sequence from the footwall and hanging wall of a normal fault that cross cut a detachment surface.* **Log 4** *shows the existence of a continent derived allochthonous block onto the exhumed lower serpentinised mantle.*

direction as well as to a dip line across the former OCT.

4.1.1 Falotta area

The Falotta area, located in the northeastern corner of the map (Fig. P3- 1 and 2), is smoothly reactivated during the D1 phase by third order D1 thrusts, resulting in imbricate duplex structures overlying the top of a massive exhumed mantle body (*Epin et al.*, 2017). In the footwall of a D1 ramp, the top of the mantle and its relation to tectono-sedimentary breccias is locally preserved (Fig. P3-3A). A section from the mantle into the overlying tectono-sedimentary breccias is shown in figure P3-2, Log 1. At the base of the section, a progressive upward transition from a massive serpentinised peridotite to serpentinite cataclasites ranging upwards into foliated cataclasites and gouges can be observed. The transition is gradual and no direct boundaries can be defined between the different fault rocks. The upward transition from the foliated cataclasite to the gouges goes along with: 1) an increase in the ratio between matrix and clasts (transition from a clast to a matrix supported fault rock), 2) the occurrence of increasingly better rounded clasts; and 3) a better developed foliation within the matrix (for more details about the mantle fault rocks see Picazo et al. (2013), who studied similar fault rocks in the Totalp area).

The mantle fault rocks are truncated by calcite veins in the lower part, and in the upper part the foliated cataclasites and gouges are locally replaced by calcite, leading to the formation of so-called ophicalcites. The majority of the calcite veins dip in average with ~60° to the east or to the west (see rose diagram Fig. P3-3C). In the larger veins growth fibers occur. They are orientated sub-horizontal, parallel to the top of the mantle. Observations suggest a syn-kinematic origin of these veins and are coherent to the east-west extension described by Desmurs et al. (2001). Structural data from similar contacts in the Platta nappe show a top-to-the-west, i.e. top-to-the-ocean (*Bernoulli et al.*, 2003), however, top-to-the-east, i.e. top-to-the-continent sense of shear have been described as well (*Desmurs et al.*, 2001). These observations are coherent to an east-west extension as previously shown also for Jurassic detachments in the Err nappe by Froitzheim and Eberli (1990), Manatschal and Nievergelt (1997) and Epin et al. (in prep). The calcification of the exhumed mantle, which includes calcite veins as well as replacement reactions of serpentine by calcite, are commonly referred to as ophicalcitization that results in a large range of rock types with variable proportions of serpentine vs. carbonate material and result from either in-situ fracturation/veining (tectonic), replacing (chemical) or reworking (sedimentary) (*Green*, 1982; *Bernoulli and Weissert*, 1985; *Früh-Green et al.*, 1990, for further references see also *Lemoine et al.*, 1987). The in-situ reworking of tectonized and

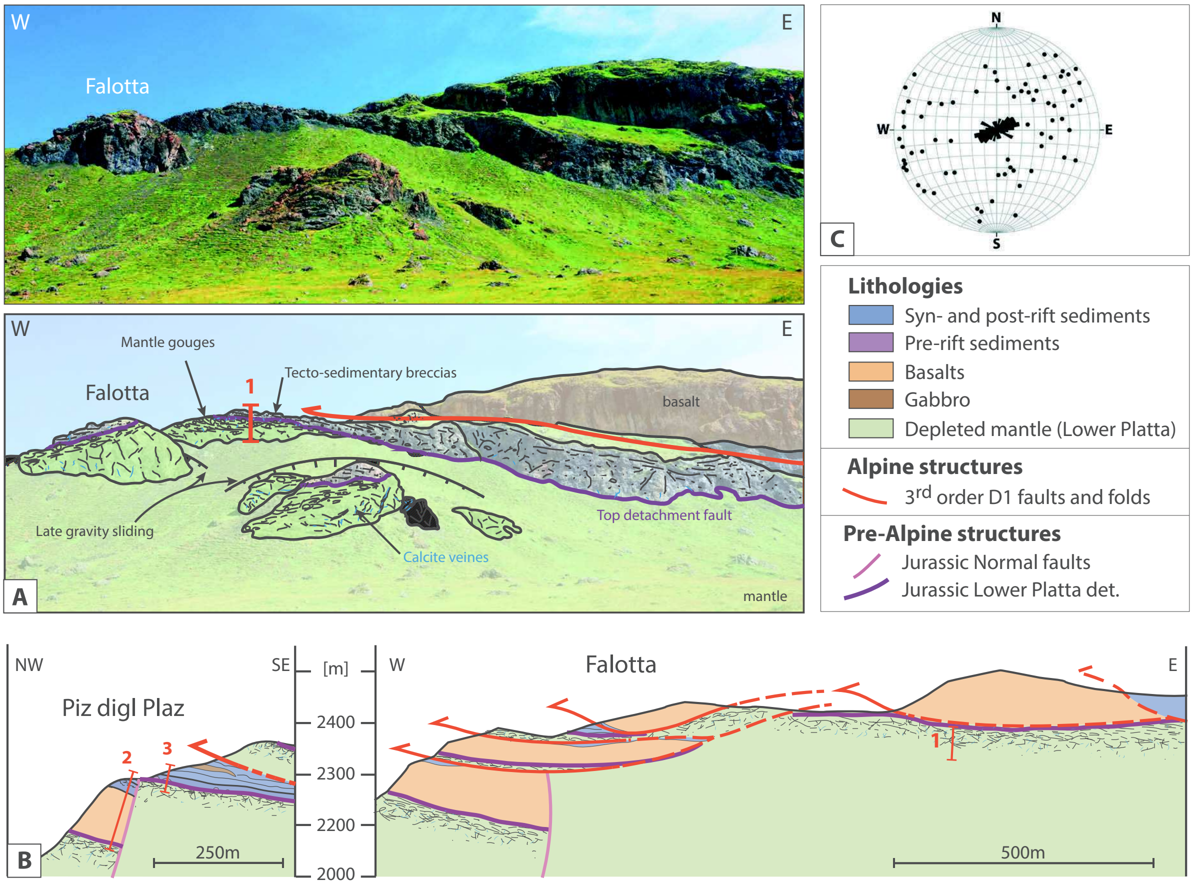


Fig. P3-3: **A:** *Panoramic view of the Falotta ridge showing the trilogy of cataclasites, gouges and ophicalcites that are diagnostic for the occurrence of an extensional detachment faulting that is covered by tectono-sedimentary breccias.* **B:** *Section throughout the northern segment showing the Alpine reactivation and preservation of normal faults cross cutting the extensional detachment fault (see Fig. 2 for the location of the section).* **C:** *Stereo-plot in lower hemisphere showing a rose diagram and poles of calcite veins at Falotta (rose diagram explains the frequency of planes in a given orientation).*

serpentinised mantle along the exhumed detachment surface can result in the formation of clast-supported breccias with different generations of carbonate.

The section at Falotta (Fig. P3-2; Log 1 and Fig. P3-3A) shows a complete transition from massive serpentinised mantle to cataclasites and gouges, overlain by tectono-sedimentary breccias that rework the underlying footwall rocks and include all three types of ophicalcites. Due to the excellent preservation and exposure of this section, we consider this section as the type section across a detachment, including all diagnostic features of extensional detachment faults responsible for the exhumation of mantle rocks at the seafloor. Similar sections, showing similar relationships, but often displaying an Alpine overprint (superposition of a D1 foliation) have been mapped throughout the Platta nappe at the top of the massive mantle bodies. In the map, sections and panoramic views, we represent the top of these extensional detachments by a violet line. The extensional detachment surface is overlain by either tectono-sedimentary breccias (e.g. Falotta area; Fig P3-2; Log 1), basalts (e.g. Falotta and Piz digl Plaz area; Fig P3-2; Logs 2 and 3), pelagic sediments (e.g. Piz digl Plaz area; Fig P3-2; Log 3), or continent-derived extensional allochthons (Tigias area; Fig P3-2; Log 4).

At Falotta, the contact between the basalts and the underlying tectono-sedimentary breccias corresponds to a third order top to the west Alpine D1 thrust (red line Figs. P3- 2 and 3B). This thrust can be mapped westwards, between the basalts and the deformed serpentinised peridotites, and can be observed to cut into sediments. Based on the mapping of cut off points along the section parallel to transport direction (contact mantle/basalts on both sides of the ramp) a displacement of 500m or less can be determined for this Alpine D1 fault (*Desmurs et al.*, 2001). Further to the west, along the Falotta ridge, basalts lie directly on the exhumed detachment fault and are truncated by a normal fault (pink line, Figs. P3- 2 and 3B). This normal fault juxtaposes a thick basaltic sequence in the hanging wall to the west, against mantle rocks overlain by thin basalts in the footwall to the east. The vertical displacement of this fault is in about 100 meters. Along the breakaway of this fault, a mine can be observed within the Radiolarian Chert Fm. (red pentagon, Fig. P3-2). It was principally exploited for copper and manganese mineralisation in the past, and it can be linked to fossil hydrothermal activity.

4.1.2 Piz digl Plaz area

In the Piz digl Platz area, localised at the west of the Falotta ridge, a complete section of the exhumed mantle into its cover is preserved (Fig. P3-2; Logs 2 and 3). The area is separated by a northeast to southwest trending, northwest dipping normal fault (pink line Figs. P3- 2 and 3B). The nature and the timing of the formation of this fault are discussed later, but it is important to note that both hanging wall and footwall are in the same Alpine tectonic subunit.

The hanging wall (Fig. P3-2; Log 2) preserves a succession of mantle, basalts and sediments. The mantle is capped by a similar section like the one described at Falotta (cataclasites and gouges with ophicalcites) that is covered by a massive basaltic body formed by pillows, pillow breccias and hyaloclastite layers that are covered by the Radiolarian Chert and the Calpionella Limestone Fms. The Radiolarian Chert Fm. consists of a succession including silicified sediments of hydrothermal, detritic and biogenic origin (Fig. P3-2; Log 2). Hydrothermal activity is also recorded by manganese concretion within the siliceous metaliferous sediments that may be linked to the alteration of basalts (firstly describe in Oman by *Karpoff et al.*, 1988). The top of the siliceous sequence is made of pelagic radiolarian cherts, including important quantities of diagenetic manganese suggesting sediment starvation in the presence of a mixed hydrothermal and detritic environment. The occurrence of slumps in this sequence can be noted as well. The top of the Radiolarian Chert Fm. is formed by detritic cherts, and finally, silicified limestones that form the contact to the overlying Calpionella Limestone Fm. This section in the Radiolarian Chert Fm. represents the most complete section through post-rift sediments described in the Platta nappe. Therefore we consider this section as the reference section across the post rift sequence and in particular across the Radiolarian Chert Fm. It should be noticed that although the alteration of basalt is observed throughout the Platta nappe, the hydrothermal systems and mineralizations are more punctual and often linked to the paleo-faults (see discussion below).

The eastern part of Piz digl Plaz is represented in figure P3-2, Log 3. It preserves a succession of mantle, and sediments, without the occurrence of a basaltic body. This suggests that the fault defines the lateral limit of the magmatic body. Another major change across the fault is the occurrence of polygenic clasts in the Radiolarian Chert Fm. This formation contains essentially pre-rift Triassic dolomite blocks that range in diameter from centimetre to several meters. Thus, it is important to note that this fault does not represent a simple offset of equivalent lithological packages occurring on both sides of the fault. Since the hanging wall and footwall of the normal fault are within the same Alpine tectonic subunit, the normal fault is interpreted to be of pre-Alpine origin. Moreover, since the fault limits a magmatic addition in the hanging wall from no-magma in the footwall, we consider that the fault was pre- to syn-magmatic (for more discussion about the nature of the fault see below).

4.1.3 Tigias area

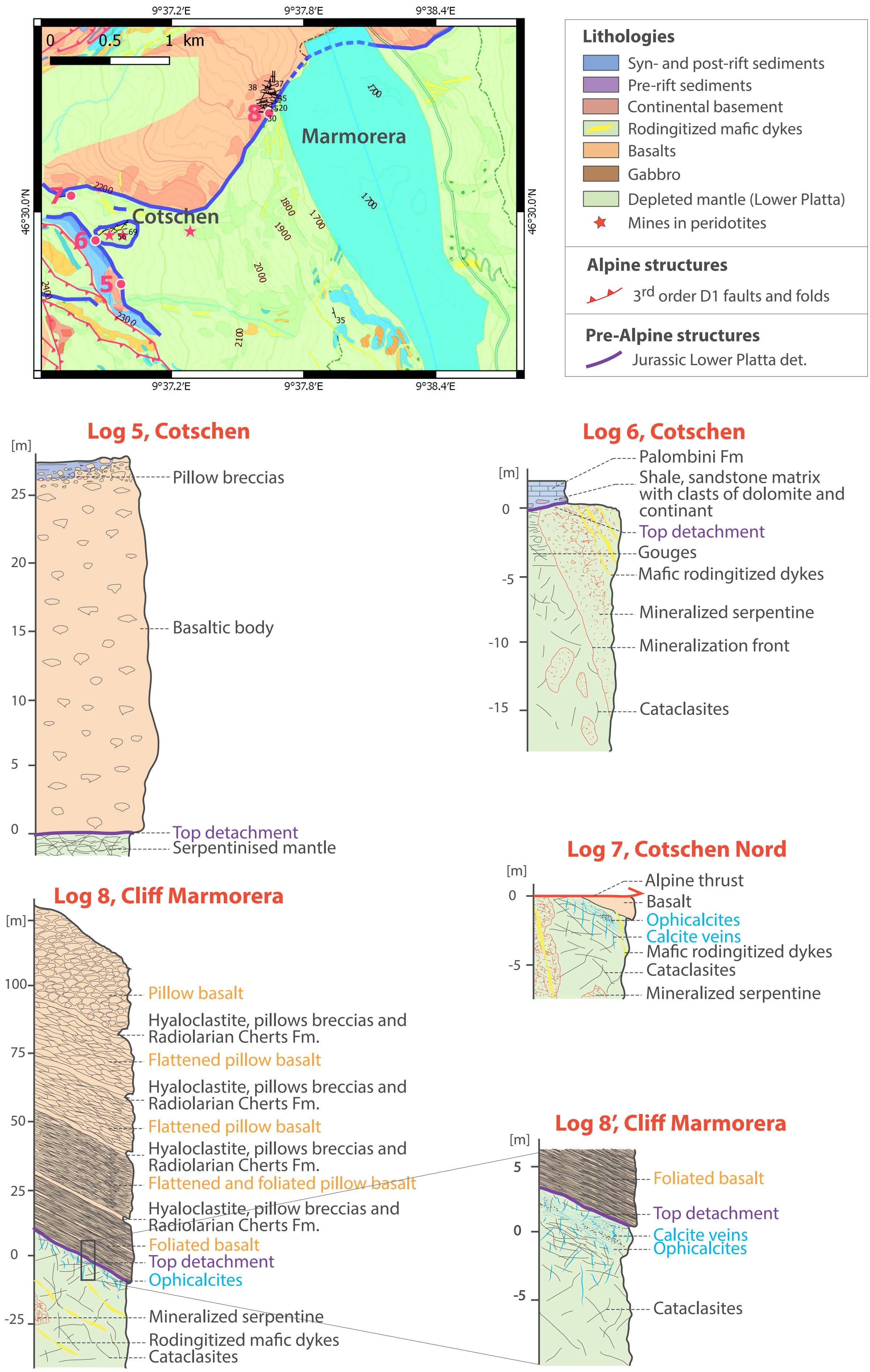
The Tigias area located on the southern part of the map (Fig. P3-2), northeast of Lake Marmorera (Fig. P3-1B) and at the south of the Falotta ridge, presents the best-preserved continent derived extensional allochthon in the Lower Platta unit (Fig. P3-2). The Tigias allochthone block was first described by Cornelius (1932; 1950) and Manatschal and Nievergelt (1997). The Tigias area corresponds to imbricated duplex structures that overlie a massive exhumed mantle body. Third order D1 thrust sheets and large-scale west facing folds can be mapped, sandwiched between the Upper and Lower mantle bodies (for more detail see Figs. 6 and 7 from *Epin et al.*, 2017). In this area, a complete succession from serpentinised mantle to post-rift sediments, interleaved by an allochthon block can be found (Fig. P3-2; Log 4). The mantle shows similar structures at its top (e.g. gouges and cataclasites associated with ophicalcites) as the one described from Falotta; however, these rocks are overprinted by an Alpine D1 foliation. Above this contact zone, a block of pre-rift Triassic dolomites, with a minimum size of ~1km² in a map view, is in contact with sediments of the Upper Jurassic Radiolarian Chert Fm. intercalated with sedimentary breccias containing clasts of gneiss, pillow basalts and grains of spinel (*Manatschal and Nievergelt*, 1997). This sequence is sealed by the Lower Cretaceous Palombini Fm. The stratigraphic contacts of the Triassic dolomites with Upper Jurassic sediments that contain clasts derived from the continent as well as from mantle and basalts clearly show that this block had to be over mantle and not far from the continent and surrounded by basalts before Alpine convergence initiated. Similar blocks, containing continent derived material, are observed throughout the Lower Platta unit, always at the top of the exhumed mantle.

4.2 The Central Segment

The Central Segment in the Lower Platta unit is localized east and west of Lake Marmorera (Fig. P3-1B). Pre-Alpine contacts between mantle, magmatic rocks and sediments are locally preserved. Two areas are described: 1) the western side of Marmorera lake (Figs. P3-4 and 5) with the Cotschen area and cliffs exposed along the western Marmorera lake, and 2) the eastern side of Marmorera lake including the area of Kanonensattel, Muttariel, Val Natons and Val Savriez (Figs. P3- 6 and 7). The major Alpine reactivation structures are top to the west D1 thrust faults and D1 and D3 folds with wave-lengths ranging from the decimetre to the hundred meter scale.

4.2.1 Cotschen area

The Cotschen area is located on the western side of Lake Marmorera, on a grassy plateau 2200 m.a.s (Figs. P3- 4 and 5). The Cotschen area corresponds to a fossil hydrothermal spot formed over a serpentinised peridotite. On the field, it corresponds to a red-brownish patch (~300m², Figs. P3- 4 and 5A) that includes mineralized serpentinites containing pyrite, chalcopyrite and magnetite with secondary transformations in malachite and goethite. Fluids enriched in Fe, Mg, Ca, SiO_2, H_2O, O_2 and CO_2 can also explain the occurrence of ilvait, andradit, actinolite, diopsid, gale-antigorite, greenalith and magnetite. Similarly, mobility of S_2, Fe, Cu, Ni, Co, and Zn of the primary sulfides from the surrounding serpentinites and their basic accompanying rocks were converted into suitable migration zones where they were precipitated as metasomatic sulfides and oxides (*Dietrich*, 1972). The ore mineralization at Cotschen (red stars, Figs. P3- 4 and 5) and in the Platta in general were mined in the past at different occasions especially for copper (*von Regierungsrat Dr et al.*, 1979). Associated with the mineralized patch we can see locally the occurrence of serpentinite gouges (Fig. P3-4; Log 6). The Cotschen area is crosscut by rodingitzed mafic dykes (yellow dykes, Fig. P3-4) that



9°37.2'E
9°37.8'E
9°38.4'E
46°30.0'N
0 0.5 1 km
Marmorera
Cotschen
Lithologies
Syn- and post-rift sediments
Pre-rift sediments
Continental basement
Rodingitized mafic dykes
Basalts
Gabbro
Depleted mantle (Lower Platta)
Mines in peridotites
Alpine structures
3rd order D1 faults and folds
Pre-Alpine structures
Jurassic Lower Platta det.
Log 5, Cotschen
[m]
Pillow breccias
Basaltic body
Top detachment
Serpentinised mantle
Log 6, Cotschen
Palombini Fm
Shale, sandstone matrix with clasts of dolomite and continant
Top detachment
Gouges
Mafic rodingitized dykes
Mineralized serpentine
Mineralization front
Cataclasites
Log 7, Cotschen Nord
Alpine thrust
Basalt
Ophicalcites
Calcite veins
Mafic rodingitized dykes
Cataclasites
Mineralized serpentine
Log 8, Cliff Marmorera
Pillow basalt
Hyaloclastite, pillows breccias and Radiolarian Cherts Fm.
Flattened pillow basalt
Hyaloclastite, pillows breccias and Radiolarian Cherts Fm.
Flattened pillow basalt
Hyaloclastite, pillows breccias and Radiolarian Cherts Fm.
Flattened and foliated pillow basalt
Hyaloclastite, pillow breccias and Radiolarian Cherts Fm.
Foliated basalt
Top detachment
Ophicalcites
Mineralized serpentine
Rodingitized mafic dykes
Cataclasites
Log 8', Cliff Marmorera
Foliated basalt
Top detachment
Calcite veins
Ophicalcites
Cataclasites

Fig. P3-4: *Geological map of the Western Central Segment showing location of Logs 5, 6, 7, and 8 in the Cotschen and Marmorera area.* **Log 5** *shows the occurrence of a basaltic body onto the exhumed mantle.* **Log 6** *shows the exhumed serpentinised peridotite with occurrence of a hydrothermal mineralisation and mafic rodingitized dykes along a mantle damage zone, directly covered by the Palombini Fm.* **Log 7** *is similar to the Log 6, but it is more calcite rich at the top of the mantle damage zone, and it is covered by basalts.* **Logs 8 and 8'** *shows the transition from the serpentinised peridotites and the basalt at the Marmorera cliff. Note the increase in deformation towards the contact with both the mantle and the basalt.*

show sharp contacts to the surrounding of serpentinised or mineralized mantle. These dykes are 0.3m to 3.5m wide and can be traced over up to 100m along strike. All dikes strike southwest to northeast (average of north 63°). 30 to 100 meters west of the mineralized patch, the tectonized serpentinised mantle (contact similar to the one of Falotta (Fig. P3-2; Log 1) is covered by a sedimentary sequence containing blocks of pre-rift Triassic dolomites and continental basement (granite, gneiss and meta-sediments) in a shale to sandstone matrix, covered by the Palombini Limestone Fm. (Fig. P3-4, Log 6). The observed relationships suggest the occurrence of an exhumed detachment fault that forms the top of the mantle onto which sediments and continent derived material has been deposited. Therefore the grassy surface of the plateau at Cotschen corresponds approximatively to a paleo-detachment surface. This surface that overlies a continuous and massive mantle sequence and is overlain by the continent derived material can be mapped throughout large parts of the Central Segment. It is truncated by a D1 thrust fault that is overlain by a serie of third order thrust sheets resulting in the formation of Alpine D1 duplexes made of basalts and sediments of the Radiolarian Chert Fm. About 100 to 400 meters north of the mineralized patch (Fig. P3-3, Log 7) there are ophicalcite veins with a similar orientation as the veins found at Falotta (average of dip direction/dip is 265/72; Fig. P3-5B). The orientation of theses veins is also coherent with a general E-W extension. In the same section, the ophicalcites (veins and replacement) become more common but also more deformed approaching the basalt. Indeed, the calcite constitutes at this site the major component of the fault rocks that form anastomosing shear zones interleaved with rare clasts of serpentinite. We can observe crosscutting relationships with different generations of calcite veins associated to different deformation phases. The calcite precipitation can be associated to a pre-, syn- and post-deformation emplacement. The contact is truncated at its top by a D1 thrust, therefore it is considered as pre-Alpine (Fig. P3- 4; Log 7).

4.2.2 Marmorera area

The Marmorera area is located on the eastern and western side of the Marmorera dam at the northern termination of the lake. The area is essentially constituted of the two cliffs bordering the lake on its two conjugate sides (Fig. P3-4). The area is not affected, apart E-W trending, northward facing Alpine D3 folds, by important Alpine structures. It exposes the top of the Lower Serpentinite body that forms the “backbone” of the Lower Platta unit.

A major contact that strikes about east-west (dip direction/dip: 015/35) separates serpentinised mantle rocks from basalts (Fig. P3-4A). This contact firstly described by Dietrich (1969) as an alpine contact presents a non-classical thrust stacking because it superposes young (basalt) over old (exhumed mantle). Since this contact is within the same Alpine unit and truncated by D1 thrusts, we consider this contact as a pre-Alpine contact. Like most of pre-alpine contact present in the Lower Platta unit, it presents the evidence that is was reworked by alpine deformation. We focus our description on the western side of the lake (Fig. P3-4) since the eastern side is similar but less well exposed. The large cliff that bounds the western slope of the lake (Fig. P3-5A) is made of serpentinised mantle. Close to the dam, mafic, rodingitised dikes can be found in the serpentinites near the contact to basalts. The contact is made of cataclasites and gouges overprinted by ophicalcites and the prolongation of the mineralisation of Cotschens. In contrast to the Cotschen area (Fig. P3-4; Log 6), where the top of the mantle is well defined and overlain by sediments and further south and north by basalts (Fig. P3-4; Logs 5 and 8), at Marmorera, the mantle rocks are in contact with the basalts (Fig. P3-4; Log 8). Key observations are summarized in the figure P3-4, Logs 8 and 8’. The serpentinised peridotite is locally mineralised and forms patches of reddish indurated rocks, similar to the mineralisations described from Cotschens (e.g. S_2, Fe, Cu, Ni, Co, Zn). Indeed patches of mineralised serpentinite can be followed from the Marmorera cliff to the patch exposed at Cotschen. At some locations it can be observed that this mineralisation crosscut the serpentinised gouges or occur into serpentinite cataclasites. Outside the mineralisation, along the contact between serpentinites and basalts, other gouges without mineralisation can be found, but due to the bad quality of the outcrop, they are not as well exposed as those in the Falotta area. Additionally to the mineralisation, similar to Cotschen, the serpentinised peridotites are intruded by rodingitized mafic dykes. Some of these mafic dykes form sigmoidal lenses. The dykes at Lake Marmorera are oriented, like those on the opposite side of the lake, sub-parallel to the contact between the mantle and the basalts (Fig. P3-4; Log 8 and Fig. P3-5A). Close to the contact, the serpentinised peridotites are extremely deformed with a transition from serpentinised cataclasites with ophicalcite veins, to gouges occurring along anastomosing fault zones, and deformed calcite veins that are truncated by undeformed calcite veins. At some places, the fault rocks are foliated and mainly composed of calcite and chlorite with rare clasts of serpentinite up to centimetre in diameter. The rich ophicalcite area marks the transition from the mantle to the basalts, similar to what has been observed north of Cotschen (Fig. 3-4; Log 7) and the foliation is sub-parallel to the contact separating the mantle rocks from the basalts.

The northern part of the Marmorera cliff is made of an important basaltic body (>150m thick). The basalts forming the magmatic body show a strong variation of the texture from strongly deformed to little deformed upsection (Fig. P3-4; Log 8), similar to what has been described by Dietrich (1969) from many places in the Platta nappe. At the base of the section, close to the contact with the mantle rocks, the basalts have the appearance of foliated basalt with intercalations of green, light green, dark green and white layers (Fig. P3-4; Log 8). This kind of layering has been described in detail by Dietrich (1969). In thin section, this layering is made of epidote, actinote, albite, chlorite, calcite, quartz, titanite and hematite indicating that these rocks correspond to meta-basalts that deformed at greenschist facies conditions (*Dietrich*, 1969). It is difficult to know if the protolith of this bended basalt was a massive lava flow, layered lava flow, pillow basalt or a pillow breccia within hyaloclastites. The foliation in the meta-basalt is sub-parallel to the contact limiting the mantle and the basalt. Within the cliff, a vertical evolution from foliated basalts at the bottom to less deformed, layered basalts, to flattened pillows towards the top can be observed, the latter showing a maximum metamorphic overprint at prehnite-pumpellyte facies (*Dietrich*, 1969), (Fig. P3-4; Log 8). The flattering of the pillows is also sub-parallel to the mantle-basalt contact. However, it is important to note that the glassy interface between the pillows is not strongly foliated, suggesting that the pillows can be deformed during their emplacement. It is important to note that centimeter to meter thick layers made of hyaloclastites and pillows breccia are interleaved with reminiscent of the Radiolarian Chert Fm. This layering that is also parallel to the serpentinite-basalt contact is expressed on the outcrop scale by grassy terraces that are interleaved with massive basalt layers (Fig. P3-5A). We interpret the observed layering as the result of cyclic magmatic events that are separated by sediments belonging to the Radiolarian Chert Fm. that represented the background sedimentation. If this interpretation is correct, the four hyaloclastite layers correspond to at least four magmatic events and the layering would define the paleo-seafloor. The pillows at the top of the section are exposed in 3 dimensions. In a NNW-SSE section, perpendicular to the Jurassic and Alpine D1 transport direction, the top of the pillows shows a convex structure while its lower part is more or less sharp and tapers downwards suggesting that it moulded to the underlying pillows during their formation. This suggests that the pillows are in an upward position. On a longitudinal, NW-SE view, perpendicular to the strike of the serpentinite-basalt contact, one can observe tubular, tube like shapes showing a paleo-flow direction that is NE-SW (Fig. P3-5C).

4.2.3 Kanonensattel-Muttariel area

The Kanonensattel-Muttariel area (Figs. P3- 6 and 7) is located at the eastern side of

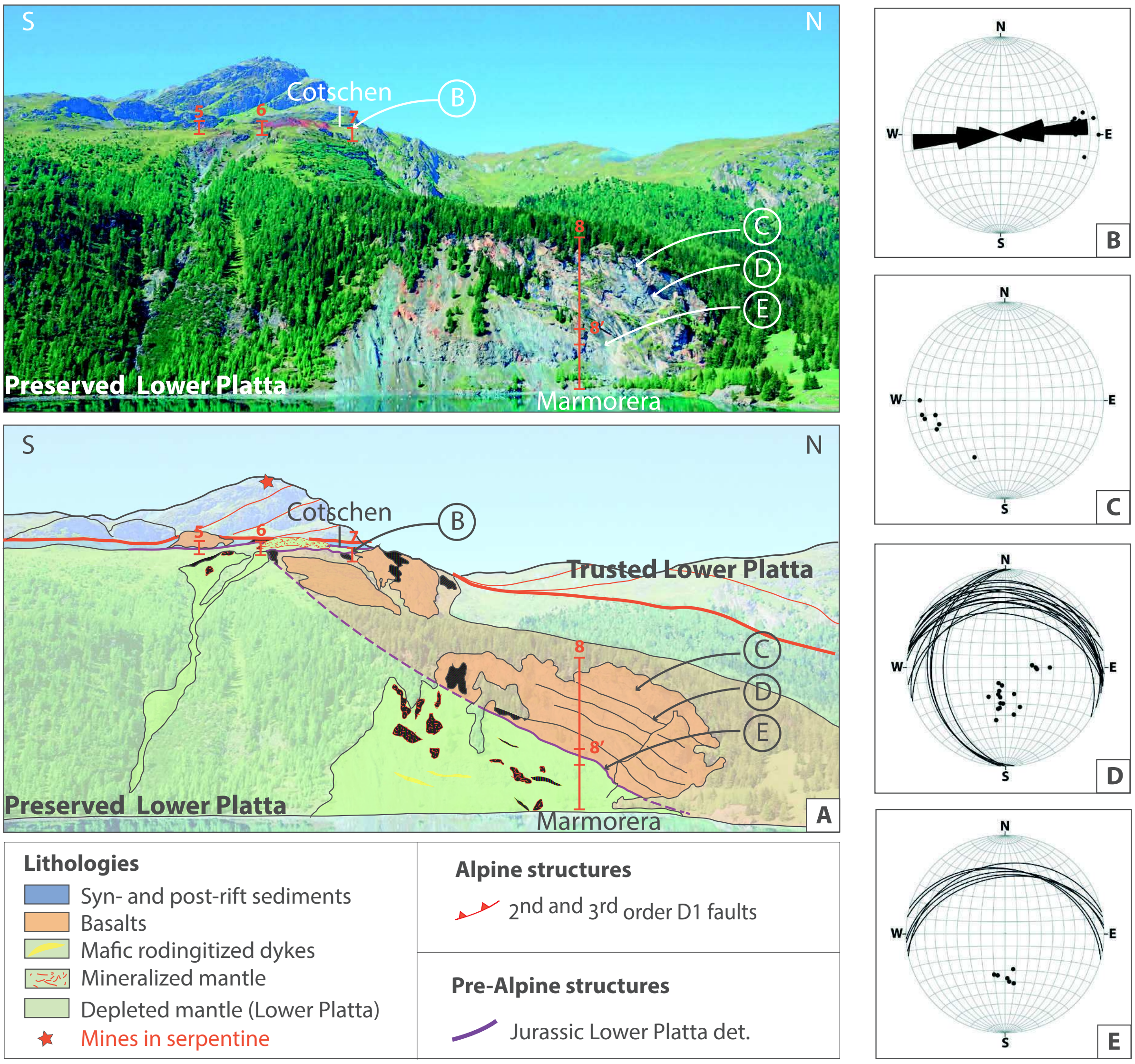


Fig. P3-5: **A:** *Panoramic view of the Marmorera cliff showing the contact between the serpentinised peridotite and the overlying basalt. We can noice the location of mineralisation in the serpentinised peridotites and orientation of mafic rodingitized dykes sub-parallel to the contact, which corresponds to an extensional detachment fault, and also the location of Logs 5, 6, 7, 8 and 8', and stereo-plot.* **B:** *Stereo-plot in lower hemisphere showing a rose diagram and poles of calcite veins at Cotschen (rose diagram explains the frequency of planes in a given orientation).* **C:** *Stereo-plot in lower hemisphere of elongation direction of pillow tube indicating the paleo direction of basaltic flow.* **D:** *Stereo-plot in lower hemisphere showing the orientation of hyaloclastite and the Radiolarian Chert Fm. (plane and pole).* **E:** *Stereo-plot in lower hemisphere showing the extensional detachment fault orientation located at the base of the Marmorera cliff between the serpentinite peridotites and the basalt (plane and pole). We can note the similar orientation of hyaloclastite and the layers in the Radiolarian Chert Fm. to the contact at the base of the cliff, but upsection the dip of the layers decreases.*

Lake Marmorera, at the same altitude as Cotschen (Fig. P3-1B). Similar to Cotschen, the grassy plateau is essentially made of serpentinite. The area is, apart from gentle north-south facing D3 folds, reasonably well preserved from Alpine reactivation. Major Alpine deformation is visible further east at Pare Neira as indicated by Alpine D1 duplexes and tight isoclinal D1 folds.

At Kanonensattel (Fig. 3-6; Log 9), serpentinite cataclasites and gouges, overprinted by ophicalcites, define the top of the mantle. The top is sealed by the Aptychus Limestone Fm. About 500m further north, in the Muttariel area, a similar mantle section is preserved (Fig. P3-6; Log 10). However, at this location the whole section is verticalized due to north-vergent D3 folding. As a consequence, from top (actually to the north) to bottom (actually to the south), a complete section can be observed, including breccias that overlie serpentinite gouges crosscut by ophicalcites. The gouges develop downwards into cataclasites both overprinting older mylonites. These mylonites show extremely stretched orthopyroxene porphyroclasts (with aspect ratios exceeding 10:1 *Peters*, 1963; *Müntener and Hermann*, 1996; *Desmurs et al.*, 2001; *Müntener et al.*, 2009). These mylonites have been described by Müntener et al. (2009) as remnants of a high temperature shear zone. These peridotite mylonites show crystal plastic recrystallization of olivines that are associated with ultra-mylonites, suggesting that the deformation had to occurred between 700 to 900°C and that the exhumation had to be fast in order to explain the lack of thermal induced annealing of the microstructure.

The significance of this shear zone and its age are unknown, but from the field observations it can be demonstrated that the mylonitic shear zone is truncated by the brittle detachment that is marked by the gouges and the cataclasites.

4.2.4 Val Natons area

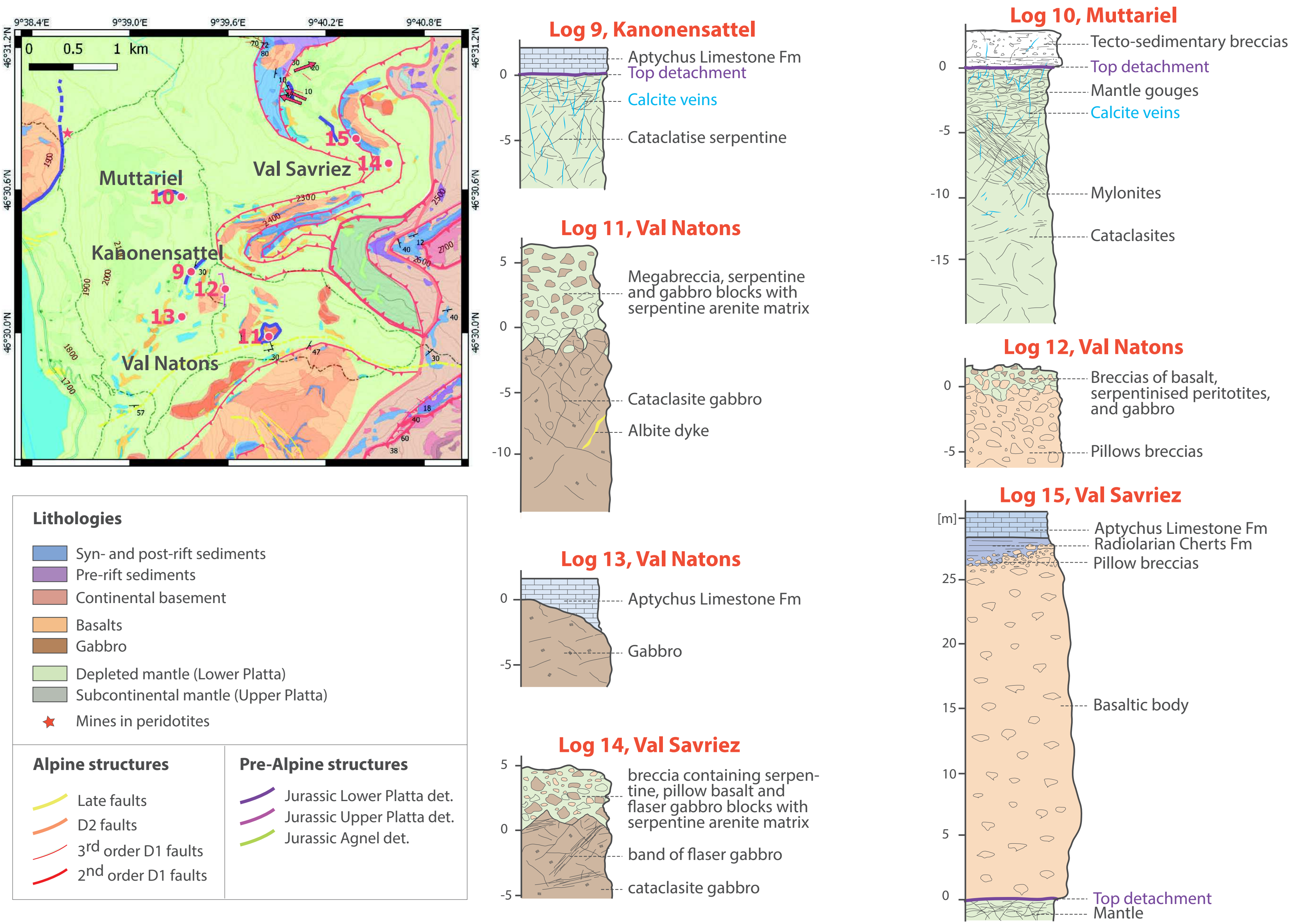
The Val Natons area is located south of the Muttariel-Kanonensattel area (Fig. P3-6). It is fairly well exposed and not too strongly overprinted by major Alpine deformation. The most important Alpine structures are D1 and D3 folds that locally explain the observed reversed section. A late Alpine vertical fault (D5 structure) can also be mapped through Val Natons, showing an offset (southern side down) of about hundred meters. Between the exhumed tectonized mantle and the extrusive magmatic rocks and sediments, intrusive gabbros can be found. Indeed, Desmurs et al. (2001) described gabbros that were exhumed on the seafloor. In Val Natons, several gabbro bodies can be observed (brownish bodies, Fig. P3-6), the biggest occupying a surface of 0.23 km^2 in the map (500m long and 50m thick). Along the northern slope of Val Natons, intrusive bodies are well exposed due to differential glacial erosion preferentially eroding the serpentinites. These bodies consist of sphere shape magmatic intrusive bodies some tens of meters in diameters that are intrusive into the serpentinised mantle (Fig. P3-6). Desmurs et al. (2001; 2002) showed that the smaller, sphere shaped bodies (north of Val Natons, Fig. P3-6) are formed by Mg-gabbros showing an increase in grain size from the rim to the core of the body. These bodies have been interpreted to represent very small magma chambers that crystallised in-situ without undergoing differentiation. In contrast, the bigger bodies exposed south of Val Natons (Fig. P3-6) show differentiation and the occurrence of small diorite dykes that represent the last liquids that recrystallized after differentiation (*Desmurs et al.*, 2002). Both, the smaller and bigger bodies show evidence for emplacement of the gabbroic bodies in a domain that underwent extension. In the larger bodies, Desmurs et al. (2002) showed that deformation initiated in the presence of magma, i.e. at solidus conditions. In all bodies, deformation occurred at retrograde metamorphic conditions from amphibolite to greenschist facies (after *Desmurs et al.*, 2002).

Some of these bodies have been exhumed on the seafloor during Jurassic extension, as indicated by the occurrence of clasts of gabbros in breccias. In some outcrops the magmatic bodies are affected by severe cataclastic deformation and clasts are reworked into tecto- and/or tectono-sedimentary-breccias. Locally, (Fig. P3-6; Log 11) meter-sized blocks of serpentinite and blocks of gabbro occur in a matrix of serpentinite arenite (after *Desmurs et al.*, 2001). At the north-west (Fig. P3-6; Log 12), a polymictic breccia made of clasts of pillow basalts, serpentinite and gabbros occurs onto pillows breccias (Fig. P3-6; Log 12). Further southeast (Fig. P3-6; Log 13), small gabbro bodies are directly overlain by the Aptychus Limestone Fm. Sediments of the Radiolarian Chert Fm. are not observed at this location and the basal contact is not visible. Therefore it cannot be excluded that these small bodies intruded the Aptychus Limestone Fm., as seen elsewhere in the Lower Platta unit (see paragraph 4.3.1; Fig. P3-8; Log 18). This stratigraphic sequence (absence of the Radiolarian Chert Fm.) is consistent with the occurrence of a hiatus in the area of the Kanonensattel that is commonly observed elsewhere in the Central Segment of the Lower Platta unit (Fig. P3-6; Log 9).

4.2.5 Val Savriez area

The Val Savriez area is located to the northeast of the Muttariel-Kanonensattel area (Figs. P3- 6 and 7). It is the southern prolongation of the Tigias area (Fig. P3-1B) belonging to the Northern Segment. It presents a similar Alpine reactivation as observed in the Tigias area, i.e. duplexes of third order D1 thrusts associated with kilometre scale west facing D1 folds. These folds explain the occurrence of reverse sections.

Fig. P3-6: *Geological map of the Eastern Central Segment showing location of Logs 9, 10, 11, 12, 13, 14, and 15 in the Kanonensattel, Muttariel, Val Natons and Val Savriez area.* **Log 9** *shows a stratigraphic contact between exhumed mantle and the Aptychus Limestone Fm.* **Log 10** *shows the occurrence of mylonites that are overprinted by a damage zone and truncated by a detachment fault. L***ogs 11, 12 and 14** *show tectono-sedimentary breccias reworking gabbros, basalt and serpentinites.* **Log 13** *shows a gabbro body in contact with the Aptychus Limestone Fm., the outcrop conditions do not enable to define if this gabbro corresponds to an exhumed gabbro or to an intrusive gabbro into the Aptychus limestone Fm.* **Log 15** *shows a well preserved succession from pillow breccias to the Radiolarian Chert and Aptychus Limestone Fms. We can note the hiatus of the Radiolarian Chert Fm. at some places.*



9°38.4'E
9°39.0'E
9°39.6'E
9°40.2'E
9°40.8'E
46°31.2'N
46°30.6'N
46°30.0'N
0 0.5 1 km
Muttariel
10
Val Savriez
15
14
Kanonensattel
9
12
13
11
Val Natons
Lithologies
Syn- and post-rift sediments
Pre-rift sediments
Continental basement
Basalts
Gabbro
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Mines in peridotites
Alpine structures
Late faults
D2 faults
3rd order D1 faults
2nd order D1 faults
Pre-Alpine structures
Jurassic Lower Platta det.
Jurassic Upper Platta det.
Jurassic Agnel det.
Log 9, Kanonensattel
Aptychus Limestone Fm
Top detachment
Calcite veins
Cataclatise serpentine
Log 11, Val Natons
Megabreccia, serpentine and gabbro blocks with serpentine arenite matrix
Cataclasite gabbro
Albite dyke
Log 13, Val Natons
Aptychus Limestone Fm
Gabbro
Log 14, Val Savriez
breccia containing serpentine, pillow basalt and flaser gabbro blocks with serpentine arenite matrix
band of flaser gabbro
cataclasite gabbro
Log 10, Muttariel
Tecto-sedimentary breccias
Top detachment
Mantle gouges
Calcite veins
Mylonites
Cataclasites
Log 12, Val Natons
Breccias of basalt, serpentinised peritotites, and gabbro
Pillows breccias
Log 15, Val Savriez
[m]
Aptychus Limestone Fm
Radiolarian Cherts Fm
Pillow breccias
Basaltic body
Top detachment
Mantle

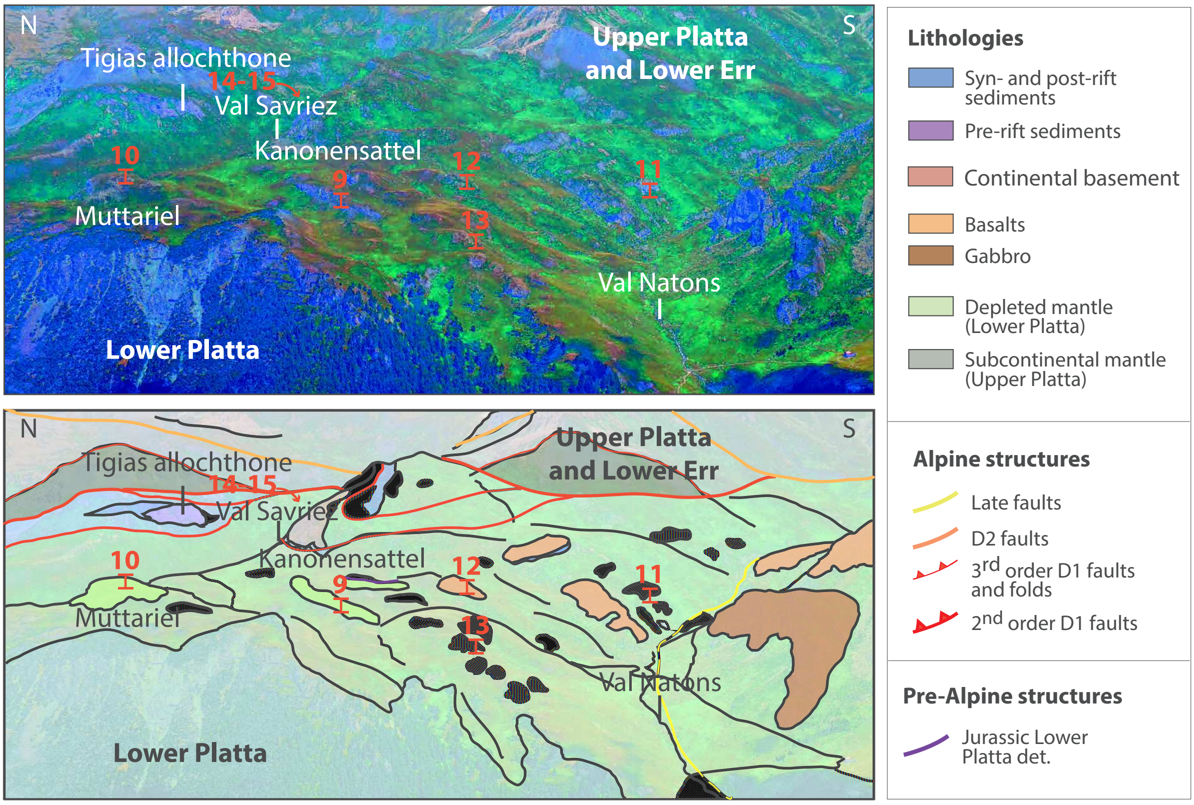


Fig. P3-7: *Panoramic view showing the distribution of gabbroic bodies at the eastern Central Segment and the location of Logs 9, 10, 11, 12, 13, 14, and 15.*

At Val Savriez, a complete succession ranging from serpentinised mantle to sediment including intrusive and extrusive magmatic rocks is present (Fig. P3-6; Logs 14 and 15). The gabbro body (Fig. P3-6; Log 14) shows localized bands of flaser gabbro, overprinted by cataclastic deformation and overlain by breccias. These breccias contain from bottom to the top, clasts of flaser gabbros, serpentinite, and abundant pillow basalt fragments embedded in a matrix of serpentine arenite (after *Desmurs et al.*, 2001). A basaltic body of approximatively 30 meters (Fig. P3-6; Log 15) preserves a beautiful contact between the pillow basalt breccias and the Radiolarian Chert Fm. The Radiolarian Chert Fm. is extremely homogeneous and has a thickness of 2 meters and is covered by the Aptychus Fm.

The Radiolarian Chert Fm. is typically associated with basalts (pillows, or pillows breccias), while they are rare in sedimentary successions containing polymictic breccias and exhumed mantle. The absence of complete and continuous layers of the Radiolarian Chert Fm. over exhumed mantle sections suggests that the proportion of hyaloclastite and/or chemically altered material of hydrothermal origin may be more important than pelagic sedimentation of radiolarian oozes. Moreover, the occurrence of a hiatus suggests important seafloor topography.

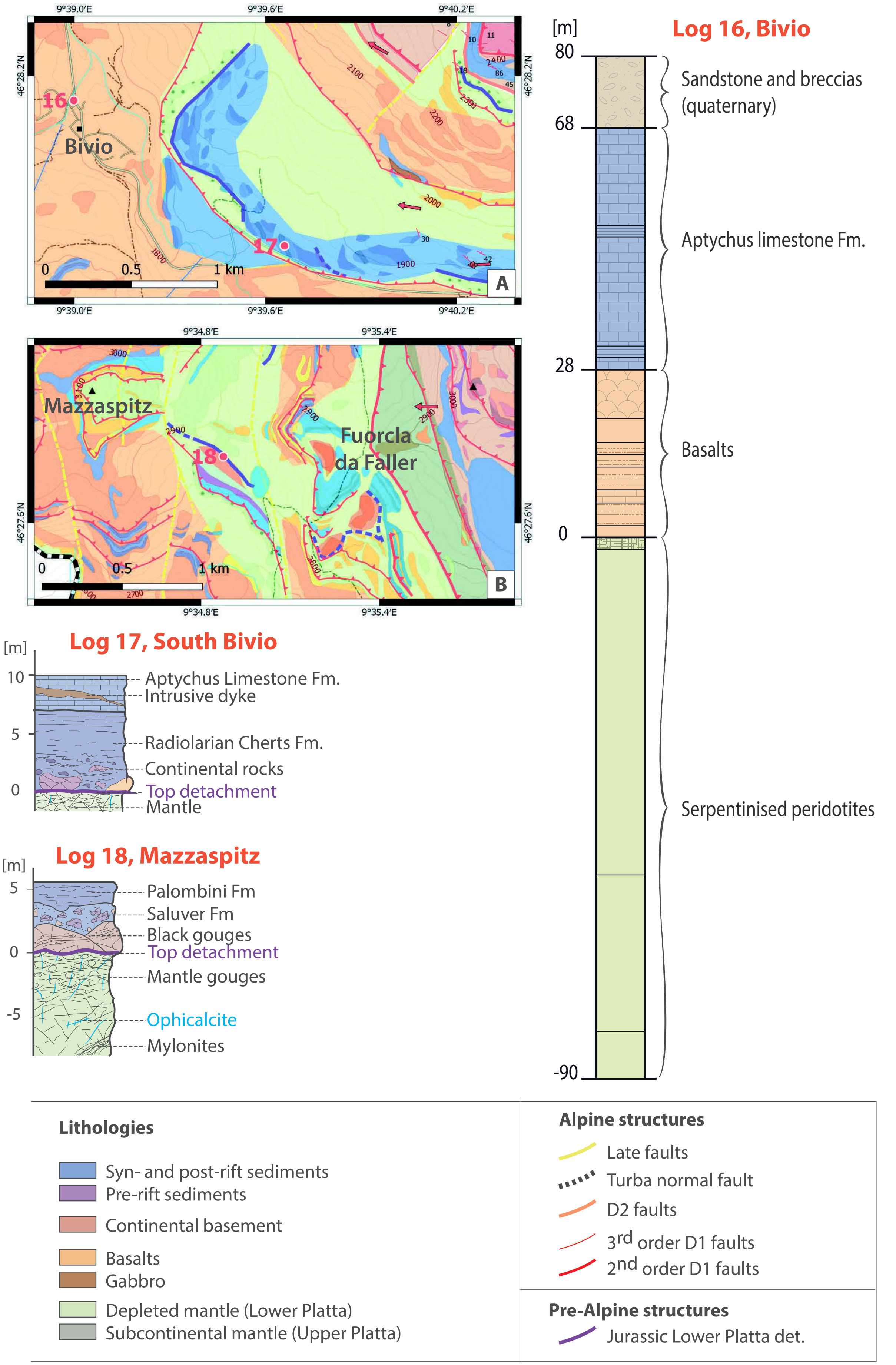
4.3 The Southern Segment

The Southern Segment of the Platta nappe is less well exposed and good contacts are not well preserved. In this study we focus on a drill hole that has been performed in the village of Bivio thanks to geotechnical prospection (thanks to O.Jäger from Bivio for letting me access to this unpublished data) and to three additional locations in the Southern Segment. A first one is located southeast of Bivio, about 40 meters above the Julier road (Figs. P3- 1B and 8A). A second outcrop is exposed west of Bivio in the Mazzaspitz-Fuorcla da Faller area (Figs. P3- 1B and 8B). A third outcrop is exposed south of Bivio, in the Sur al Cant area (Fig. P3-9A; end of ski-lift, not on the map Fig. P3-1B).

4.3.1 Bivio area

In 2015 a drill hole of 170 meters has been performed in the village of Bivio on the property of O. Jäger (House N°40; Julier Strasse) for geotechnical prospection (Bohr Compani: Nicol. Hartmann &Cie. AG St. Moritz; Bohr Master: Pedro Menenzes). The drill hole (Fig. P3-8; Log 16) shows a complete section from the top to the bottom including sediments, basalts and serpentinites. To be coherent with the other Log, we fix the zero, on the depth axes, at the top of the serpentinites and not at the present surface. The drill hole contains: from +80m to +68m sandstones and breccias corresponding to quaternary post and syn-glacial deposits; from +68m to +28m sediments belonging to the Aptychus Limestone Fm. that overlie 28 meters (from +28m to 0m) of basalts, including intercalations of massive basalts and pillows. From 0m to -56m the drill penetrated serpentinised peridotites showing a strong cataclastic overprint with a lot of serpentine veins that overlie, from -56m to -90m (bottom of the drill hole) massive serpentinised peridotites.

Close to the Julier road, southeast of Bivio (see Fig. P3-8A), there is a reverse stratigraphic succession. It starts with serpentinites that show a strong cataclastic overprint at its top, sealed by ophicalcites that are overlain by a dolomite bearing breccia and sediments of the Radiolarian Chert and Aptychus Limestone Fms. (Fig. P3-8; Log 17). This reverse section corresponds to a D1 fold overprinted by a south facing D3 fold. This succession is similar to other successions described before (e.g. Piz digl Plaz; Fig. P3-2; Log 3), with one major difference. The Aptychus Limestone Fm. contains a magmatic sill that is sub-parallel to the stratification. The sill is surrounded by a dark contact aureole. At the outcrop scale, it is difficult to differentiate the sedimentary rocks from the magmatic rocks along the contact. This magmatic sill corresponds to alkaline melts that intruded in the post-rift sedimentary sequence. The study of these magmatic rocks, including the geochemistry and the dating of the rocks, is


9°39.0'E
9°39.6'E
9°40.2'E
46°28.2'N
16
Bivio
17
0
0.5
1 km
A
9°34.8'E
9°35.4'E
46°27.6'N
Mazzaspitz
18
Fuorcla
da Faller
B
Log 17, South Bivio
[m]
10
5
0
Aptychus Limestone Fm.
Intrusive dyke
Radiolarian Cherts Fm.
Continental rocks
Top detachment
Mantle
Log 18, Mazzaspitz
[m]
5
0
-5
Palombini Fm
Saluver Fm
Black gouges
Top detachment
Mantle gouges
Ophicalcite
Mylonites
Log 16, Bivio
[m]
80
68
28
0
-90
Sandstone and breccias (quaternary)
Aptychus limestone Fm.
Basalts
Serpentinised peridotites
Lithologies
Syn- and post-rift sediments
Pre-rift sediments
Continental basement
Basalts
Gabbro
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Alpine structures
Late faults
Turba normal fault
D2 faults
3rd order D1 faults
2nd order D1 faults
Pre-Alpine structures
Jurassic Lower Platta det.

in preparation (e.g. Amann in prep).

4.3.2 Mazzaspitz-Fuorcla da Faller area

The area of Mazzaspitz – Fuorcla da Faller is located west of Bivio and of the Scalotta-Surparé klippe, which is made of the Lower Err and Upper Platta units, thrust along a second order D1 thrust onto the Lower Platta unit (Figs. P3- 1B and 8B).

The Mazzaspitz area (Fig. P3-8; Log 18) is located at the southeast of Mazzaspitz. It preserves a sequence containing a continental allochthone block (*Manatschal and Nievergelt*, 1997). In an outcrop, about 500m large and 200m long, located at the northwestern termination of the Mazzaspitz lake, serpentinised mantle rocks are overlain by black tectonized breccias similar to the black gouges described from the Err nappe, associated to the Jurassic detachment faults (*Manatschal*, 1999). These black gouges separate the serpentinised mantle rocks from pre-rift dolomites and cargneules that are overlain by syn-rift sandstones and sedimentary breccias belonging to the Saluver Group (e.g. *Masini et al.*, 2011) that are sealed by sediments of the Palombini Fm. (*Manatschal and Nievergelt*, 1997). This sequence has been interpreted by Manatschal and Nievergelt (1997) as a continent-derived extensional allochthon block, overlying exhumed mantle. The pre-rift sequence exposed at Mazzaspitz, represents, together with that from Tigias, the two biggest blocks of continent derived material found in the Platta nappe. The continent derived blocks consist of small slivers of continental basement, Triassic dolomites and/or syn-rift breccias of the Saluver Group. These blocks occur in two positions within the Platta nappe. The first position is directly on the mantle or associated with the Radiolarian Chert Fm. These blocks may represent pieces of extensional allochthones or debris flows derived from the former hanging wall of continental origin emplaced during exhumation. The second position is in the Palombini Fm. The origin of these breccias is more controversial, but likely related to gravitational processes along fault scarps and may represent debris flows or olistoliths.

In the Fuorcla da Faller area, located at the east of the Mazzaspitz area (Fig. P3-8B), gabbros are very common and have been described by Desmurs et al. (2002). Apart from Val Natons, it is the second important area in the Platta nappe that preserves gabbro bodies. The

Fig. P3-8: *Geological map of the Southern Segment showing location of Logs 16, 17, and 18 of Bivio and Mazzaspitz area.* **Log 16** *corresponds to a drill hole provided by O. Jäger (House N°40; Julier Strasse; geotechnical prospection made by Bohr Compani: Nicol. Hartmnn &Cie. AG St. Moritz; Bohr Master: Pedro Menenzes).* **Log 17** *shows the occurrence of an intrusive dyke into the Aptychus Limestone Fm.* **Log 18** *shows the occurrence of an allochthonous, continent derived block onto exhumed mantle.*

gabbro bodies show a high diversity in compositions, from primitive olivine-gabbros to highly differentiated Mg-gabbros, Fe-Ti-P-gabbro and diorite (*Desmurs et al.*, 2002). Pegmatitic diorite form patches or dykes that can form boudins or folds within the Mg-gabbro. The most differentiated pockets have been dated using the U-Pb method on zircons. The ages of 161Myrs ± 1Myr after Schaltegger et al. (2002) indicate a syn-exhumation origin of these gabbros. The gabbro bodies are locally cut by basaltic dykes with chilled margins, indicating that emplacement of the dykes took place after cooling of the gabbro (*Desmurs et al.*, 2002).

4.3.3 Sur al Cant area

The Sur al Cant area is located South of Bivio, at the end of the ski lift (Fig.P3- 9). This area is more affected by the Alpine reactivation and metamorphism, and occurred in a succession of many duplexes similar to the Mazzaspitz-Fuorcla da Faller area. In this area, interesting relationships are preserved between mafic dykes, basaltic flows and brittle and ductile deformation in the basement, similar to Muttariel (Fig. P3-6; Log 10). The mylonites are indeed very similar to those at Muttariel and are, like in the latter place, truncated and overprinted by the later brittle deformation.

In addition to the mylonites, in figure P3-9, Log 19, we can see a succession from exhumed mantle to basalts. The serpentinised mantle preserves a succession from bottom to the top similar to the Falotta area. We can follow a gouge level showing irregularities in thickness. Locally, the cataclastically serpentinised mantle is truncated by two gouge layers forming anastomosing fault zones that are sub-parallel to the top of the basement (Fig. P3-9B and Log 19). The gouge layers contain clasts of mafic dykes but are also cross cut by basalt dykes, indicating that these gouges formed in a late stage of exhumation, near to the seafloor and in the presence of magmatic active systems. At the top of the section, gouges are in contact with foliated meta-basalts. This contact is cross cut by mafic dykes. These dykes represent the feeders of the overlying basaltic system. This shows that the extrusive magmatic additions are emplaced onto exhumed mantle surfaces, syn- to post-detachment faulting. These observations show a close link between mantle exhumation and emplacement of magmatic additions.

5. Discussion

5.1 Restoration of an ultra-distal exhumed mantle domain

In previous papers (*Desmurs et al.*, 2001; *Manatschal et al.*, 2007; *Epin et al.*, 2017) the restoration of the distal Adriatic margin preserved in the Bernina, Err and Platta nappes has

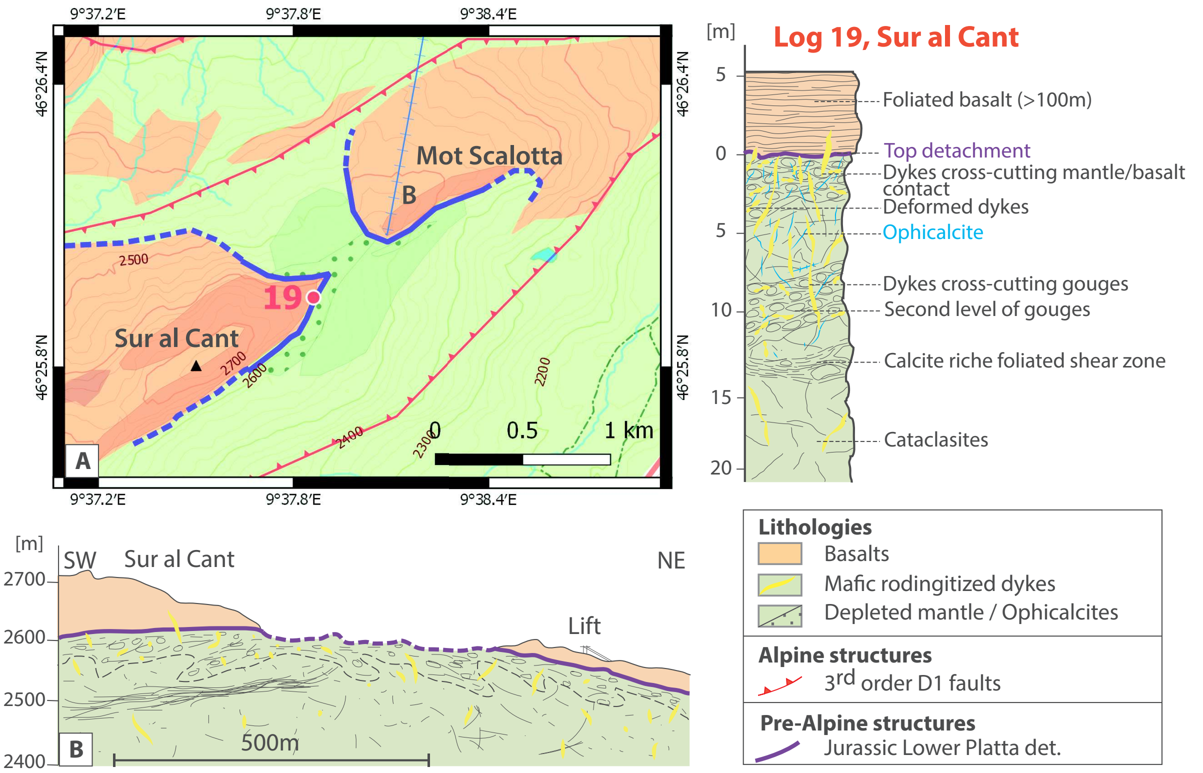


Fig. P3-9: **A:** *Geological map of an outcrop at the southern end of the Southern Segment showing location of Log 19 in the Sur al Cant area located at the end of the Bivio ski lift (Fig. P3-1B).* **B:** *Section of Sur al Cant area showing syn-tectonic (i.e. syn-detachment fault) emplacement of mafic dykes and associated extrusive basalt.* **Log 19** *enhances the relation between tectonic and magma emplacement throughout the mafic dyke deformation.*

been proposed by inverting the D1 thrust faults (for more details see *Epin et al.*, 2017). The aim of this paper is to propose a 3D restoration of the most distal unit, exposed in the Lower Platta unit, back to the pre-Alpine situation (Fig. P3-10, paragraph 5.2). The restoration discussed in this section is based on a detailed mapping, and on the study of the structures, lithologies and contacts within the Lower Platta unit. The major Alpine reactivation visible in the Lower Platta unit is, like in the reminder of the nappe stack, the Late Cretaceous, top to the west D1 event that is responsible for the stacking of the Upper Platta unit over the Lower Platta unit (Figs. P3-1C and D). This major, second order, top to the west D1 thrust structure can be mapped in the northeastern part of study area, from Falotta to Val Natons as well as at the base of the Scalotta Surparré klippe. A minimum displacement of 11 km corresponds to the distance between the westernmost exposed front of Upper Platta unit and the easternmost exposure of the Lower Platta unit. Since this thrust juxtaposes two units with contrasting magmatic histories and different mantle characteristics this thrust has either a major displacement and/or reactivated a former inherited Jurassic structure that separated two different mantle domains (for the nature of this contact see discussion below).

At the base of this second order D1 thrust, minor third order thrust faults result in thin-skin reactivation of inherited rift structures in the Lower Platta unit, which involved mainly the cover sequences (red line, Figs. P3-1C and 1D). The dominant Alpine structures are duplex structures, and in the sedimentary cover kilometre-scale, west-vergent D1 folds. The D1 structures are truncated by a D2 normal fault that can be mapped throughout the study area between the Platta and Err units (orange line, Fig. P3-1B). This structure is responsible for the omission of parts of the former margin going southwards, where the Middle Err unit is directly juxtaposed against the Lower Platta unit. However, since this D2 structure affects the Lower Platta unit only at its southern part, we will not take this structure into account for the restoration. The younger, D3 structures are limited to open folds and do not strongly overprint the Lower Platta unit in the studied area between Falotta and Bivio. Therefore, the restoration of the Lower Platta unit includes mainly the thin-skin local D1 duplexes and reverse large-scale folds. The latter occur mainly along the eastern boundary of the Lower Platta (Falotta, Piz digl Plaz, Tigias, Val Savriez, and Julier Valley east of Bivio, Fig. P3-1B). The formation of theses reverse folds has been attributed to the existence of local buttresses such as extensional allochthons, massive magmatic additions and/or late normal faults (*Epin et al.*, 2017). As illustrated in the 3D restored block (Fig. P3-10), we associate the complex Alpine D1 structures observed along the eastern boundary of the Lower Platta unit to the occurrence of rift inherited normal faults. Indeed, in contrast to the western part that is dominated by magmatic additions, the eastern part preserves exhumed mantle surfaces that are cross cut by several normal faults, some of which are preserved (e.g. Piz digl Plaz and Falotta ridge). While the reverse folds seems to be related to the reactivation of inherited normal faults, the duplex structures occur mainly in the more magma-rich sequences in the western part of the study area (e.g. Piz Platta, Mazzaspitz).

5.2 3D architecture of an ultra-distal OCT

Figure P3-10 shows a restored 3D block of the former Lower Platta domain that corresponds to a restorable surface of about 300 km^2, i.e. 20 km N-S (strike) and 15 km E-W (dip). In the following we place the observations made in the Northern, Central and Southern Segments in the block and discuss the nature of contacts, the 3D architecture of detachment structures, the occurrence of younger high-angle faults and their relation to magmatic additions, fluids and sediments recording the evolution of this ultra-distal domain.

5.2.1 The Northern Segment

The Northern Segment (Figs. P3- 10 and 11A) preserves a detachment fault that is truncated by late normal faults. The detachment surface that is capping the exhumed mantle

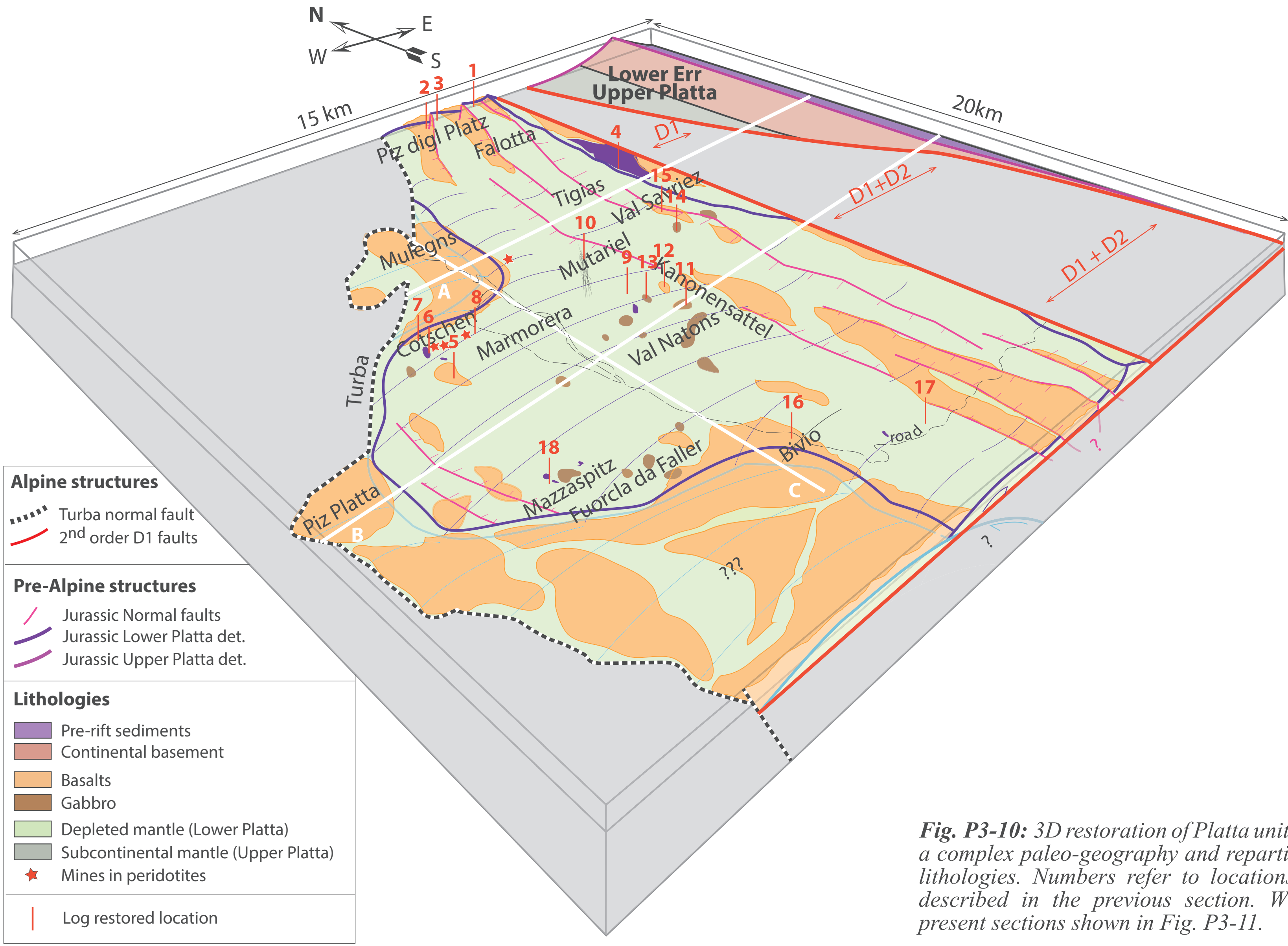


Fig. P3-10: *3D restoration of Platta units showing a complex paleo-geography and repartitioning of lithologies. Numbers refer to locations of Logs described in the previous section. White lines present sections shown in Fig. P3-11.*

is best preserved in the Falotta area. It is characterized by fault rocks, including cataclasites, gouges, and ophicalcites. This trilogy of fault rocks, locally associated with tectono-sedimentary breccias that rework these fault rocks and the underlying basement, are the diagnostic features of extensional detachment faults exhuming mantle rocks. This trilogy can be mapped throughout the Platta nappe. It enables to define the top of the mantle and to determine the locations where it was exhumed at the seafloor, even in locations that have been masked by later magmatic additions or reactivated during Alpine convergence.

At Piz digl Plaz – Falotta, the detachment surface has been truncated by several normal faults (2 faults are identified and mapped; Fig. P3-2). These faults offset the top of the mantle, i.e. an existing detachment surface. As a consequence, they are post exhumation. Although we can map the breakaways of these faults, we do not know at what depth these normal faults root. Throughout the Lower Platta unit, non-serpentinised mantle rocks are not observed and all mantle rocks were already serpentinised and within the uppermost 700 meters of the basement before onset of reactivation. Based on our observations, it appears that these normal faults affect a mantle that was already exhumed and serpentinised. It is unclear if these late normal faults continue into fresh peridotite or if they sole out inside the strongly serpentinised mantle as suggested from seismic observation (e.g. *Gillard et al.*, 2016b). The observed offset along theses normal faults is up to 200 meters, however, we cannot exclude that some faults had higher offsets. At Piz digl Plaz one of these normal faults separates a sequence made of serpentinised peridotites, basalts and sediment in the hanging wall from a sequence where the serpentinised peridotites are directly overlain by sediments in the footwall. This suggests that the emplacement of the magma is directly linked to the presence of the normal fault. Although the breakaway of this fault is not sealed and therefore its age is difficult to estimate exactly, we assume that these normal faults formed during late rifting. The thickening of magmatic bodies across these faults suggests a syn-tectonic emplacement of the basalts. Field observations also show that the basalts get thicker westwards (e.g. Figs. P3- 1B, 10 and 11A).

At Tigias, an allochthone of continent derived material, about 1 km² in size, is preserved and sealed by post-rift sediments that include continent and mantle derived detritus. This allochthone is essentially made of Triassic dolomites, which are a part of the pre-rift sequence. The occurrence of pre-rift dolomites and in general of continent derived materiel onto the mantle, observed in many locations in the Lower Platta unit, is a key observation, since their occurrence is difficult to explain within a spreading environment. Three possible interpretations exist to explain the occurrence of continent-derived material over exhumed mantle (see Fig. P3-

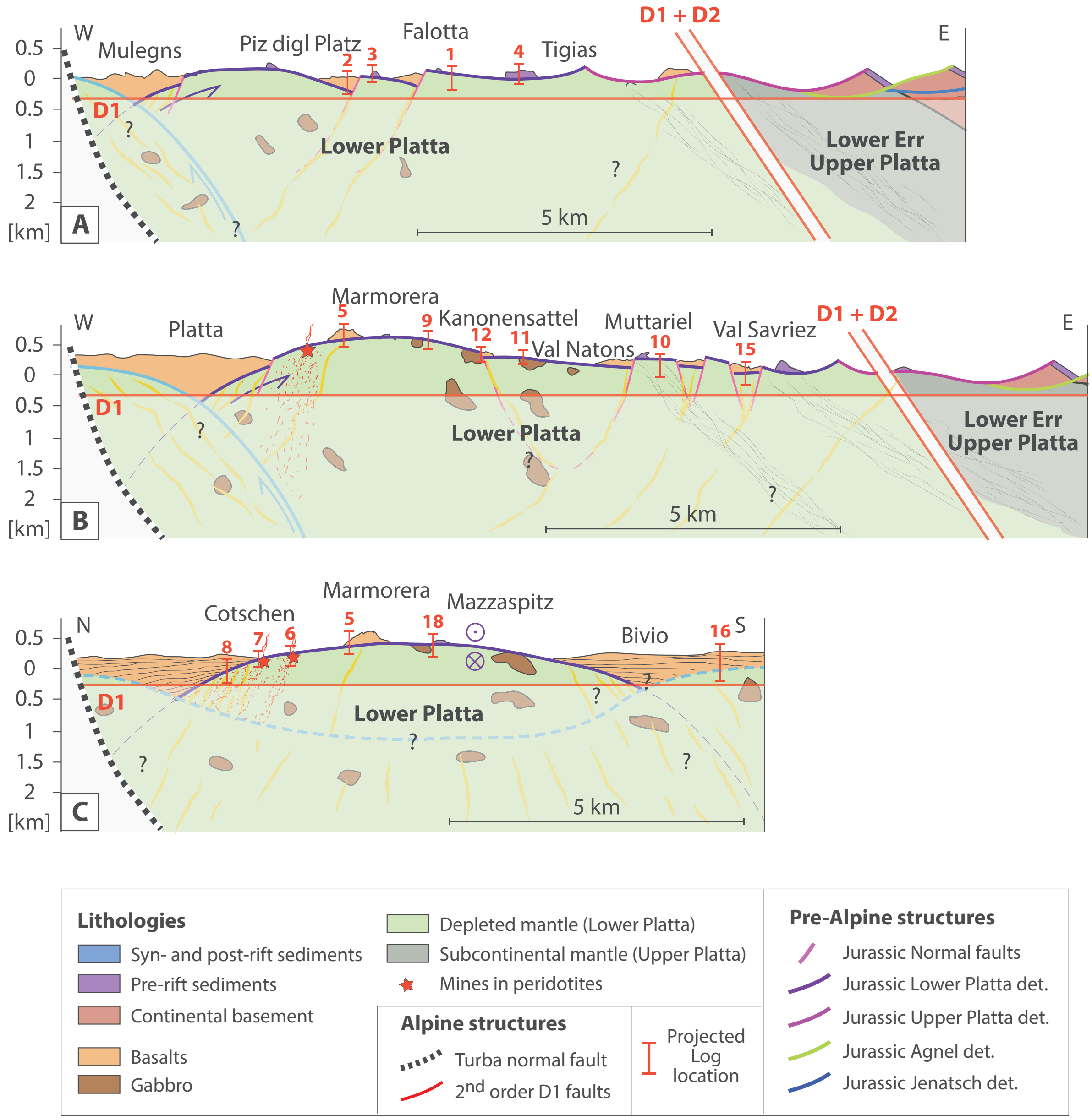


Fig. P3-11: **A:** *Dip and strike sections through of the restore Platta domain, see location on Fig. 10.* **A:** *E-W section corresponding to a dip line across the Northern Segment showing a detachment fault cross cut by late normal faults filled by syn-tectonic basalts.* **B:** *E-W section corresponding to a dip line across the Central Segment showing a topographic high formed by exhumed mantle and topographic lows formed mainly by basalt.* **C:** *N-S section corresponding to a strike line across the Lower Platta domain showing the general organisation of topographic highs and lows across the exhumed mantle domain.*

12): 1) transport by debris flows; 2) gravitational gliding due to presence of evaporitic layers; or 3) tectonic delamination by in-sequence normal faulting. Independent of the mechanism, the occurrence of continent derived material over exhumed mantle asks for a close proximity of continental and mantle derived material. The transport of blocks by debris flows (Fig. P3-12A) asks for the existence of escarpments in the proximity of the zone of exhumation or for a complex topography. This process may explain the occurrence of continent derived blocks in the Palombini Fm. (e.g. Fig. P3- 12A and Fig. 4; Log 6), but necessitates that close proximity of escarpments with continental material even during Cretaceous time. The gravitational gliding of continental derived material over evaporitic levels (Fig. P3- 12B) cannot be excluded, in particular for the emplacement of upper Triassic dolomites that overlie Mid Triassic evaporates. However, this process asks for the occurrence of evaporates and the formation of forces that can support gravitational movements (steepening of the slope or loading by sediments). Since the Adriatic margin is very sediment starved and the evaporates post rift in age, this scenario is unlikely. A possible explanation is that gravitational processes occurred during exhumation, forming a kind of rafted blocks on the exhumed surface (Fig. P3-12B; see also *Lagabrielle et al.*, 2010 and *Epin et al.* in prep). The hypothesis that the continent derived blocks result from the delamination of the upper plate during in-sequence detachment faulting (Fig. P3-12C) is the classical interpretation for the formation of extensional allochthons (see *Nirrengarten et al.*, 2016; *Epin et al. in prep*). This process may explain larger blocks and ask for in-sequence faulting, i.e. detachments that cut in front and remove blocks of the hanging wall and load it on the footwall. In this case, the mantle had to be subcontinental and exhumed from underneath the conjugate margin (Fig. P3-12C).

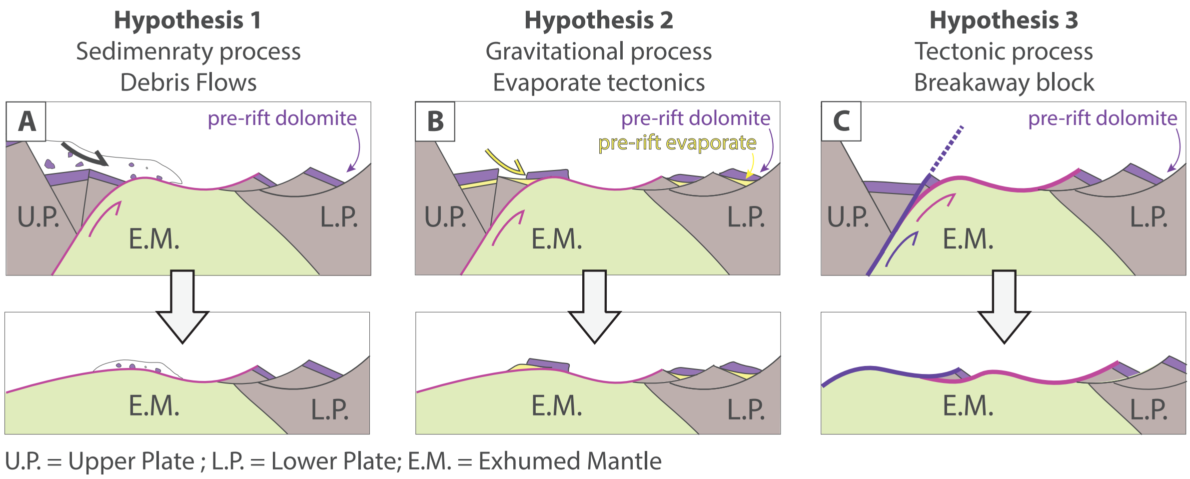


Fig. P3-12: *Conceptual models explaining the occurrence of continent derived blocks and especially dolomites onto the Lower Platta unit. Presentation of 3 hypotheses.* **A:** *Sedimentary process: debris flows.* **B:** *Gravitational process: evaporate tectonics.* **C:** *Tectonic process: in sequence breakaway blocks.*

For the example of the Lower Platta unit, we consider that the two later processes or a combination of the two can explain the occurrence of continent derived material over exhumed mantle. Independent of the mechanism, a paleo-geographic position of the Lower Platta unit not too far from the continent and a subcontinental origin for the mantle need to be envisaged. This is in line with the petrological and geochemical data (*Müntener et al.*, 2009; *Picazo et al.*, 2016).

5.2.2 The Central Segment

In the Central Segment a large area of exhumed mantle can be mapped. In the central part of this domain, i.e. in the area near Cotschens and Kanonensattel, the Lower Cretaceous Aptychus and Palombini Fms. are directly deposited over the exhumed mantle. Thus, the central domain was never covered by thick basalts and the Radiolarian Chert Fm. suggests that it corresponded to a topographic high. North and south of the central domain, i.e. in the areas of Mulegns and Bivio, the mantle rocks are overlain by thick basalts and the Radiolarian Chert and Aptychus/Palombini Limestone Fms.

In the Muttariel area, a well preserved mylonitic shear zone is exposed within the serpentinised peridotites. These mylonites include ultra-mylonties that formed at 700 to 900°C (*Müntener et al.*, 2009). Müntener et al. (2009) interpreted this shear zone as a paleo-boundary between the inherited subcontinental mantle, exposed in Upper Platta unit, and the infiltrated mantle of the Lower Platta unit (*Müntener et al.*, 2009; e.g. mantle types 1a and 2 of *Picazo et al.*, 2016). It is important to note that the mylonitic shear zone is truncated by a brittle detachment fault responsible for the final exhumation of the mantle rocks at the seafloor. Unfortunately the mylonites could not be dated and therefore their significance cannot be conclusively determined. Assuming that Picazo et al. (2017) hypothesis according to which infiltration of the mantle in the lower Platta unit occurred during rifting, i.e. that the mantle reached temperatures as high as 1200°C during Jurassic rifting (*Müntener et al.*, 2009), one would expect that these ultra-mylonites would anneal. On the other hand, the mantle rocks in the Lower Platta unit have been serpentinised and exhumed during mantle exhumation, and during the subsequence Alpine reactivation they never exceeded prehnite-pumpellyte facies conditions. Therefore the ultra-mylonites formed most likely after peak-temperature, during the exhumation but before serpentinization and exhumation at the seafloor. Although this interpretation is not supported by direct data, it suggests that the mylonites may have played an important role in controlling the exhumation of the hotter and deeper infiltrated mantle underneath the colder inherited mantle. A similar situation has been described by Kaczmarek and Müntener (2008) about the Lanzo shear zone (northern Italy) where similar mylonites are found between cold subcontinental and hotter infiltrated mantle. This would suggest that the limit between the lower mantle (infiltrated, preserved in the Lower Platta unit) and the upper mantle (inherited, preserved in the Upper Platta unit) may be a mantle shear zone, suggesting that the mantle rocks of the Upper and Lower Platta units were already juxtaposed prior to their exhumation at the seafloor.

In the Val Natons and Val Savriez area gabbros are exposed. Desmurs et al. (2002)

showed that two types of gabbros can be distinguished, smaller, sphere shaped bodies, some tens of meters in diameter and, larger, elongated bodies that are up to several kilometres long and several tens of meters wide. While the former are intruded into already serpentinised mantle, the latter show a more complex emplacement history. The most differentiated magmas were emplaced at 161±1Myr, most likely at depth of about 6-8 km, or 2 to 3 kbar (*Desmurs et al.*, 2002). Both, the smaller and bigger bodies were emplaced in a syn-tectonic setting. Desmurs et al. (2002) showed that deformation in the larger bodies initiated in the presence of magma, i.e. at solidus conditions, before being exhumed at the seafloor. Local gabbros have been found reworked in tectono-sedimentary breccias. The depth of emplacement of these gabbros, although ill defined, may correspond to an important thermal and rheological boundary as suggested by Gillard et al. (2016a). The fact that these gabbros have been exhumed at the seafloor shows that detachment faults were able to penetrate down to the depth location of the gabbros and to exhume them to the seafloor. The exhumation history is indicated by the retrograde metamorphic path from amphibolite to green-schist facies to seafloor conditions (after *Desmurs et al.*, 2002). Along the northern slope of Val Natons, breccias containing big clasts of serpentinite, gabbros and basalts occur, suggesting the existence of escarpments at the seafloor. This escarpment may be related to normal faults that overprint and displace older exhumation faults (pink line, Figs. P3- 10 and 11B).

At the northern end of Lake Marmorera, primary contacts between serpentinised peridotites and basalts are exposed on both sides of the lake (Fig. P3-11D). The contact dips to the north with an angle of 35°. Along the contact the classical trilogy (cataclasites, gouges and ophicalcites) can be found indicating that this surface was a detachment fault. However, unlike Falotta, the detachment fault is not flat but dips to the north perpendicular to transport direction. In order to understand the nature of the contact, it is important to integrate the structures observed along the contact and in the basalts forming the hanging wall. Indeed, the serpentinised mantle along the contact is cross cut by a dozen of rodingitized mafic dykes oriented sub-parallel to the northward dipping contact. At the Cotschen area, the transition from rodingitised mafic dykes to basalt flows can be observed. The dykes may have served as feeders for the overlying basaltic flows. The dykes are not continuous. They are deformed and cross cut older deformation structures related to the mantle exhumation. This suggests that their emplacement is syn- to post movement along the detachment fault, similar to what has been described also from the Sur al Cant area (see paragraph 4.3.3, Fig. P3-9; Log 19). The massive basalts overlying the contact (i.e. the detachment fault) are formed by at least 5 magmatic flows. Near the contact the basalts are deformed at green schist facies conditions (*Dietrich*, 1969) and form banded meta-basalts and when pillows are present, they are strongly flattened. In contrast, at the top of the basaltic body, the pillows are well preserved and the basalts are in the prehnite-pumpellyte facies. This shows strong metamorphic variations and high thermal gradients across less than 100 to 300 meters, which may be pre-Alpine in origin. Indeed, the general Alpine overprint in the Central Segment is prehnite-pumpellyte (*Dietrich*, 1976; *Trommsdorff and Evans*, 1974; 1983; 1993; *Ferreiro Mählmann*, 1994; 1996; *Eppel*, 1997). It is also important to note that green-schist facies conditions are observed in basalts overlying Oceanic Core Complex (OCC) (e.g. FUJI Dome in the SW Indian Ridge; *Searle et al.*, 2003). Thus, if we consider the metamorphism observed along the contact to be oceanic, this would mean that magma flows, dyke emplacement and rodingitization are syn-tectonic. In contrast, the basalts at the top of the section preserve pillow structures. Paleo-flow directions suggest a SE-NW flow direction, which is consistent with magma growth away from the detachment surface and fed by the dykes that formed along and parallel to the contact between mantle and magmatic rocks using the lateral ramp of the detachment fault.

Evidence for localized hydrothermal circulation is recorded in the Cotschen area and along the contact between the mantle and the basalts within the footwall, up to 100m away from the contact. Mineralizations in the serpentinite (mineralization of Cu, Fe …) can be followed from bottom, at >200 meters below seafloor to the seafloor in the Cotschen area. This mineralization is crosscut by rodingitised mafic dykes. Some dykes also seem to be directly related to the mineralization indicating that the fluid circulation is pre- to syn-magmatic.

5.3 The Southern Segment

The transition from the Central to the Southern segment is related to the occurrence of thick basalts (similar to the transition from the Central to the Northern segment). However, further south the Alpine metamorphic and tectonic overprint gets stronger and the restauration is more difficult. Moreover, the fact that the eastern limit of the Platta unit is truncated by a D2 extensional fault makes that the eastern (continent ward) part of the Platta units is missing. Therefore the southern domain is less well constrained.

An important observation made in the area southeast of Bivio is the occurrence of an alkaline magmatic sill in the Upper Jurassic to Lower Cretaceous Aptychus Limestone Fms. This observation shows that magmatic activity continued after onset of MOR-magmatic activity and onset of mantle exhumation dated at early Late Jurassic time. The geochemistry of this magma is alkaline and contrasts with the intrusive and extrusive magma found in the Lower Platta unit that is tholeiitic. The occurrence of late, post-rift magma can be compared with the alkaline sills drilled along the Newfoundland margin within post-rift sediments (*Peron-Pinvidic et al.*, 2010).

5.3.1 Dip and strike sections across the Lower Platta unit

Figure P3-11 shows two dip sections (Figs. P3-11A and B; E-W, parallel to the extensional direction) and two strike sections (Figs. P3-11C and D; N-S; perpendicular to the extensional direction) through the reconstructed Lower Platta domain. The architecture of the ultra-distal domain is controlled by: 1) a sequence of faults that show complex structures (high-angle vs. low-angle faults, here referred to as detachment faults) and overprinting relationships, 2) magmatic additions, and 3) topographic lows and highs. As observed at different places in the Lower Platta unit, exhumed mantle covered by the Aptychus and Palombini Fms. occurs in the central domain and is associated to a topographic high, whereas exhumed mantle covered by thick basalts and older post-rift sediments occurs at topographic lows.

On the two dip lines (Figs. P3-11A and B) a change in the top basement morphology can be observed (here we include magmatic additions as part of the basement, as it is the case in seismic section where magmatic additions are part of the acoustic basement). In the eastern part of the Lower Platta unit (e.g. Falotta – Tigias in the north, Fig. P3-11A; Val Savriez - Murrariel further south, Fig. P3-11B) the top basement topography can be linked to either secondary normal faults overprinting older detachment faults or to the occurrence of an extensional allochthon (e.g. Tigias) structuring the previously exhumed mantle. Rugosity of the top basement is mainly fault controlled, however, the overall topography is minor (≤ 200m). Further oceanwards, (Fig. P3-11A) the style of deformation does not change, however, magmatic additions (< 100m thick) fill the fault bounded basins and as a consequence, top basement topography gets soother and rugosity less important. In the central section (Fig. P3-11B) top basement forms an about 5 km wide basement high where mantle is exhumed and not covered by later magmatic additions. Post-rift sediments onlap onto this structure as indicated by the hiatus in the sections. Further oceanwards there is an abrupt transition to thick magmatic additions (e.g. Platta area; ≥ 300m).

On the two strike lines (Figs. P3-11C and D) top basement topography is expressed by topographic highs formed by exhumed mantle and gabbros interleaved by thick magmatic additions. Thus, top basement topography is mild and late high-angle faults are not structuring top basement. If one considers the basalts as part of the infill, onother can define basement highs with a wave length in the order of 5 to 10 km and formed by exhumed mantle and capped by a detachment fault. Magmatic additions are mainly in-between the highs and thicken oceanwards to more than 300m. From local observations at Cotschen – and the northern termination of Lake Marmorera, it can be shown that the magmatic additions form syn-to post-exhumation, suggesting that the lows and highs formed already during the exhumation process. Subsequent sediments onlap and passively infill the topography explaining the hiatus observed across the Lower Platta domain.

Our observations show that detachment surfaces are not flat and the magmatic emplacement is directly linked to tectonic activity, i.e. to the emplacement of detachment faults and/or later normal faults. The major structure in the Lower Platta unit is associated to a proto-oceanic core complex, which created: 1) a dome of exhumed mantle (area of Cotschen, Val Natons, Kanonensattel, Muttariel), 2) an area where the detachment surface is cross cut by normal faults, probably in the vicinity of the breakaway zone (eastern area with Piz digl Plaz, Falotta, Tigias), and 3) magma rich domains, where exhumed mantle is covered by basalts, forming topographic lows filled by basalts and early post-rift sediments (e.g. Mulegns, Piz Platta, Bivio).

5.4 Evolution model of an ultra-distal OCT: insights from the Lower Platta unit

Previous studies of the Platta nappe enabled to understand the first order Alpine and pre-Alpine structure of this domain (*Dietrich*, 1969; *Desmurs et al.*, 2001), as well as to understand its first order magmatic and mantle evolution (*Desmurs et al.*, 2002; *Müntener et al.*, 2004 and 2009). The aim of this study is to understand, based on a detailed mapping and study of the field relationships, the 3D architecture and evolution of this ultra-distal domain that may be one of the few areas, were the processes of lithospheric breakup are so well preserved, exposed and documented. While the aim of the previous section was to document the architecture of the Lower Platta domain, in this section we try to propose an evolutionary model to explain the evolution of an ultra-distal OCT based on the observations made in the Platta units.

5.4.1 Detachment system at an ultra-distal exhumed mantle domain

The occurrence of exhumed mantle, capped by fault rocks and overlain by tectono-sedimentary breccias, post-rift sediments, extensional allochthons or basalts, altogether observed in the Lower Platta unit, leads to the question about the processes that control mantle exhumation. More recently Gillard et al. (2016a) discussed different modes of extension, including in-sequence and out of sequence detachment faulting as well as flip-flop faulting, i.e. the change in polarity of exhumation faults in ultra-distal exhumed mantle domains. While in seismic sections the interpretation of deformation modes takes advantage of the scale and the increasing quality of the imaging, the characterization of extensional modes based on field observations is more difficult due to the lack of continuity and the small scale of outcrops. In the following, we will discuss different scenarios that may explain the observations made in the Lower Platta unit.

Mohn et al. (2012) and Epin et al. (in prep) showed, based on a study of the detachment systems in the Grosina/Campo, Bernina and Err units in Graubünden that the last stages before mantle exhumation are controled by a thinning stage (necking process) that is followed by in-sequence detachment faulting and crustal separation. In-sequence detachment faulting is supposed to start when the first major detachment fault penetrates the mantle, i.e. when the crust is thinned to less than 10km and no residual ductile crust is left (*Perez-Gussinye and Reston*, 2001; *Nirrengarten et al.*, 2016). Thus, prior to first mantle exhumation, a sequence of detachment systems thinned the crust (see Fig. P3-13). The detachment fault responsible of the exhumation of the sub-continental mantle, exposed in the Upper Platta unit is referred to as the Upper Platta detachment (light purple, Fig. P3-14). First exhumation of the mantle in the Platta domain is associated to an amagmatic stage. Indeed, the mantle rocks exposed in the Upper Platta unit do not show melt impregnation (*Müntener et al.*, 2009; *Picazo et al.*, 2016) and there is, except for very rare cases, a lack of any type of magmatic additions within the exposed sections. Therefore this initial stage is considered as an amagmatic stage, although it cannot be excluded, that during the exhumation of the first mantle, first magma already formed at depth and interacted with deeper parts of the lithospheric mantle. Therefore, the term "amagmatic" may not be correct, if the process is considered at a lithospheric scale. Indeed, it remains unclear how deformation, lithospheric thinning and associated magmatic processes interacted during final breakup. Before considering the magmatic processes, we therefore investigate possible scenarios that may explain detachment faulting during final rifting recorded in an ultra-distal OCT. Key observations that we consider are: 1) the geometry, kinematics and structural evolution of the exposed detachment faults (this study); 2) nature of exhumed mantle (*Müntener et al.*, 2004; 2009; *Picazo et al.*, 2016), and 3) marker horizons that are exhumed in the footwall of the detachment faults (e.g. petrological Moho, mylonitic shear zones in the mantle (a proxy for an isotherm of ~ 800±100°C); base lithosphere (~1300°C). Unfortunately we cannot directly constrain the age of the mylonites since they are not dated. However, following our discussion, we include them in our argumentation, although we are aware that their age and deformation conditions are not directly constrained. Concerning the base of the lithosphere we do not have direct constraints neither, however we assume that at the end of rifting, i.e. at the moment of lithospheric breakup, the base of the asthenosphere reached its shallowest level, which we consider to be at 15±5km as expected for magma-poor, slow spreading ridges (*Cannat et al.*, 2009).

For the extensional evolution of the Upper and Lower Platta units, the following scenarios can be envisaged:

Scenario 1: There is only one detachment fault responsible for all the exhumation of mantle rocks in the OCT (Fig. P3-13A).

Scenario 2: Mantle rocks in the OCT are exhumed by in-sequence detachment faulting (Fig. 3-13B).

Scenario 3: The mantle in the Lower Platta unit is exhumed by a detachment that is out of sequence compared to the Upper Platta unit (Fig. P3-13C).

Scenario 4: The Lower and Upper Platta units were juxtaposed during Alpine deformation, i.e. they originated from different paleogeographic positions and did not have any direct relationship prior to convergence.

Assuming the existence of one detachment system only (scenario 1; Fig. P3-13A) implies a minimum length of the detachment fault of 30km in transport direction. The 30km are obtained if one calculates the present exposed width of the Lower Platta unit (15km), of the Upper Platta unit (<1km) and the minimum estimation for shortening (11km see discussion above). The occurrence of such long detachment systems is not impossible, and comparable system can be seen at present-day examples. However, Epin et al. (in prep) show that in the Adriatic margin detachment systems get shorter oceanwards. It is not clear if this trend is only valid for the hyper-extended crust or also the exhumed mantle domain? For the exhumation of the mantle at ultra-slow spreading ridges, a flip-flop model has been proposed (*Sauter et al.*, 2013). For the hyper-extended domain, an in-sequence evolution can however better explain the observations (*Ranero and Pérez-Gussinyé*, 2010). An in-sequence scenario can also explain the occurrence of continent-derived material in the exhumed mantle domain, as well as the oceanwards change from inherited to infiltrated mantle linked to the increase of magmatic additions oceanwards. It can also explain the top to the west sense of shear observed along the detachment fault. However, applying this model to the Alpine Tethys margin would suggest that first magmatic additions would be emplaced in the distal European margin. Although we cannot exclude this, since large parts of the distal European margin have been subducted, the few areas that preserve this domain (e.g. Tasna nappe; *Manatschal and Muntener*, 2009) show that both conjugate margins are formed by exhumed subcontinental mantle (*Picazo et al.*, 2016).

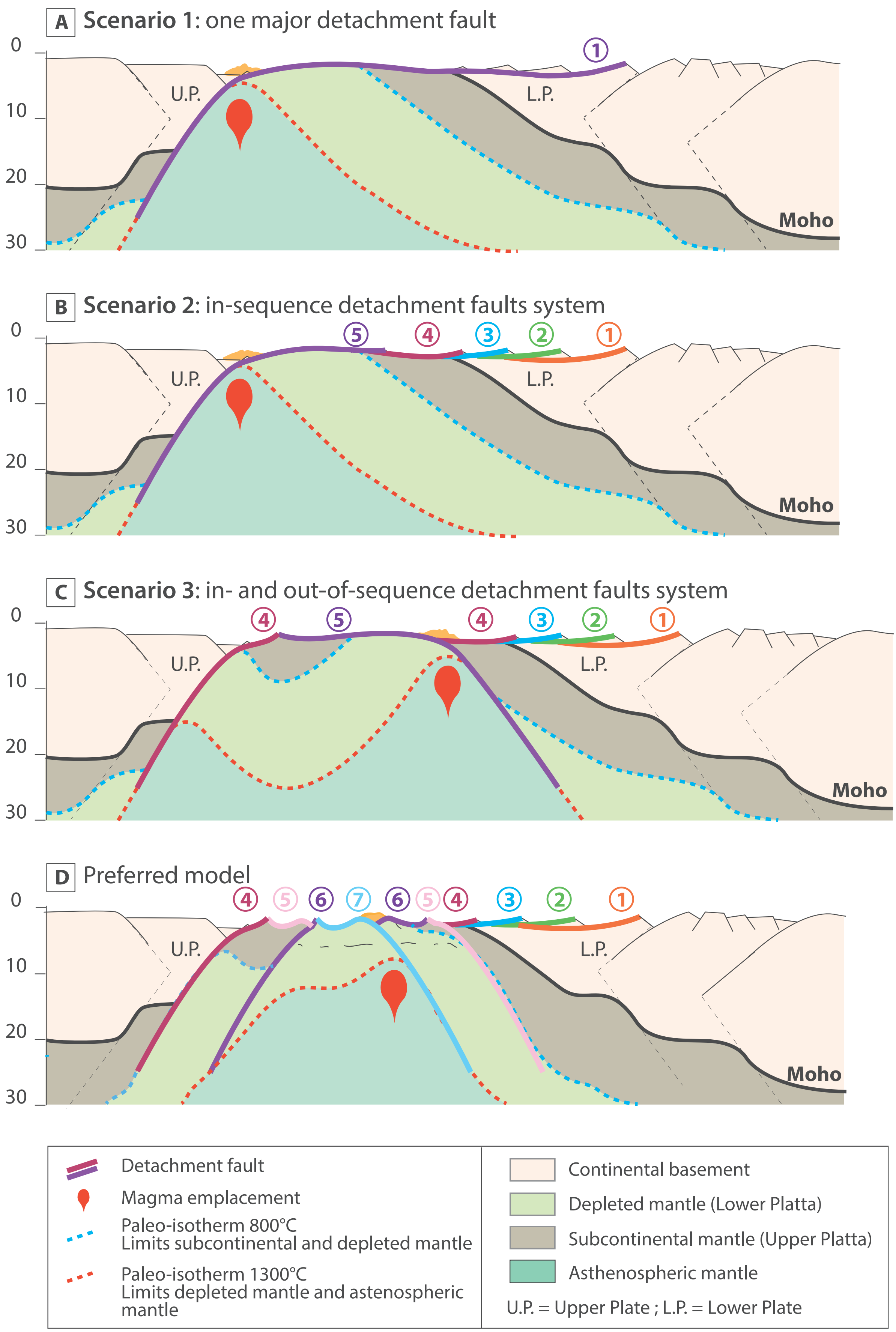

A Scenario 1: one major detachment fault
0
10
20
30
U.P.
L.P.
Moho
1
B Scenario 2: in-sequence detachment faults system
5 4 3 2 1
C Scenario 3: in- and out-of-sequence detachment faults system
4 5 4 3 2 1
D Preferred model
4 5 6 7 6 5 4 3 2 1
Detachment fault
Magma emplacement
Paleo-isotherm 800°C
Limits subcontinental and depleted mantle
Paleo-isotherm 1300°C
Limits depleted mantle and astenospheric mantle
Continental basement
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Asthenospheric mantle
U.P. = Upper Plate ; L.P. = Lower Plate

***Fig. P3-13:** Conceptual model showing the formation of the Upper and Lower Platta units showing the evolution of different detachment faults. Presentation of 4 scenarios:* **A:** *One detachment fault responsible for the exhumation of all the mantle rocks in the OCT,* **B:** *Mantle rocks in the OCT are exhumed by in-sequence detachment faulting,* **C:** *The mantle in the Lower Platta unit is exhumed by a detachment that is out of sequence compared to the Upper Platta unit,* **D:** *The model preferred in this study (for further explanations see paper).*

Assuming an in-sequence evolution of detachment faulting (scenario 2; Fig. P3-13B) would decrease the length of single detachments, which is compatible with the observation made by Epin et al. (in prep) according to which detachments get shorter oceanwards. It can also explain all field observations and result in similar implications for the conjugate margin as scenario 1.

Assuming an out-of-sequence exhumation for the Lower Platta mantle (scenario 2; Fig. P3-13C), would explain a more symmetric OCT with exhumation of subcontinental mantle on the conjugate margin. However, an out-of-sequence detachment faulting cannot explain the occurrence of continent-derived material in the Lower Platta unit since in such a scenario the new detachment fault would have at both hanging wall and footwall only mantle and magmatic rocks, but not continent-derived rocks. Moreover, such a model could also not explain the observed kinematic transport direction.

Scenario 4 (Fig. P3-13D) assumes that the juxtaposition of the Lower and Upper Platta units is due to Alpine convergence and that the two units were not linked and within the same domain prior to Alpine convergence. This would mean that Alpine shortening is much more important. This could be coherent with the transport direction observed on the Lower Platta unit and a flip-flop evolution. Although we cannot exclude this hypothesis, it is important to note that the Upper and Lower Platta units show a similar Alpine metamorphic evolution and an identical stratigraphy. Moreover, the continent derived blocks and the brittle exhumation structures are identical too. Based on these arguments, we consider this latter scenario as unlikely.

With the available data, we cannot favour one single scenario. While scenario one results in very long (too long) detachment faults, the in-sequence scenario can explain all observations made in the Platta nappe. However, it cannot explain the occurrence of exhumed subcontinental mantle on both margins. Therefore we propose a combination of scenario 2 and 3, in which we initiate exhumation by in-sequence faulting before we flip and develop an out of sequence detachment fault that exhumes the deeper lithosphere underneath the Lower Platta domain. This may explain the sudden increase in magmatic production over the distal margin, but more important, it is also compatible with the observation that along the Alpine Tethys margins sub-continental mantle is exhumed at both margins (see *Picazo et al.*, 2016).

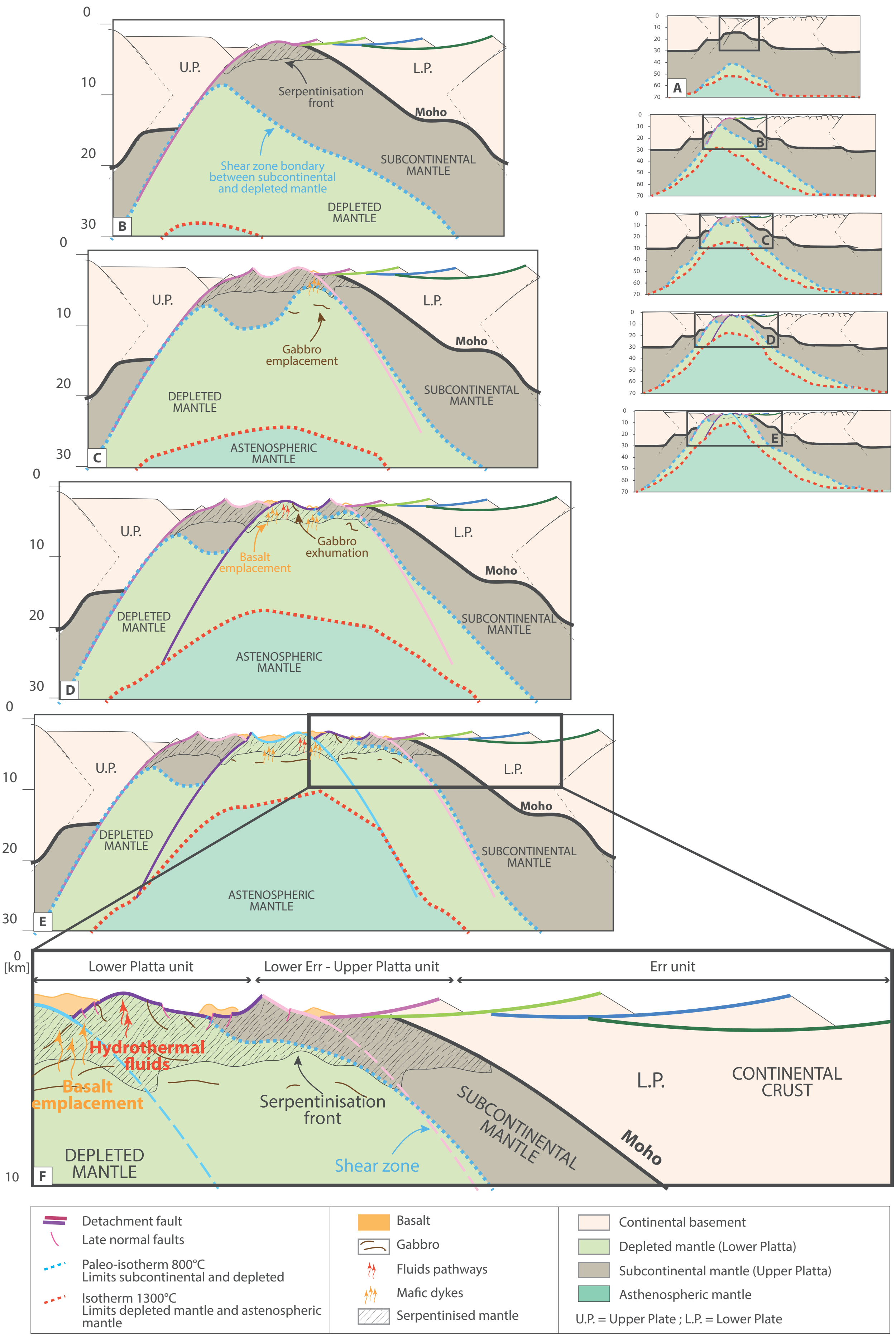
5.4.2 Magmatic and fluid history at the ultra-distal exhumed mantle domain

The Lower Platta unit preserves direct relationships between tectonic, magmatic and hydrothermal fluid systems. The observations show a complex interaction between these processes that are at present little understood. A major problem is that magmatic systems are controlled by different processes and affect different scales. Magmatic production is related to the rise of the asthenosphere and is controlled, on a first order, by extension rates and composition of the mantle lithosphere. The transport and emplacement of magma is far more complex and controlled by many factors that are difficult to estimate. Hydrothermal fluid systems are, in contrast, more simple, since the reservoir is well defined (marine) and the main controlling parameters are permeability and thermal gradients. Therefore, fluid systems are, on a first order, controlled by tectonic and magmatic processes, since they control permeability and thermal state of the extending lithosphere. Therefore, we focus first on the discussion of the tectono-magmatic evolution of the ultra-distal exhumed mantle domain, before we discuss their relation to hydrothermal systems observed in the Lower Platta unit.

5.5 Magmatic system: production, transport and emplacement.

The fact that first mantle exhumation occurs in the Platta domain without any observable magmatic additions indicates that the overall magmatic budget at the beginning of mantle exhumation is very low. This can be explained by the nature of the mantle lithosphere that was depleted prior to rifting during post-Variscan collapse (*Picazo et al.*, 2016). First extraction of magma occurs only after onset of mantle exhumation, most likely due to localized rise of the asthenosphere, either due to active upwelling, or controlled by tectonic processes. Observations in the Lower Platta unit show that there is a strong link between tectonic and magmatic processes. However, if tectonic processes (faulting) controlled the production or only the transport then emplacement of magma is difficult to estimate. Moreover, observations show that the magmatic system is manifested by different emplacement mechanisms and emplacement depth, including infiltration in mantle rocks, intrusion of gabbro bodies, dyking and extrusion

Fig. P3-14: *Conceptual model showing the evolution of the OCT and its implication in the structural, thermal and magmatic evolution.* **A:** *Hyper-extended stage and first coupling fault to the mantle.* **B and C:** *Exhumation of sub-continental mantle.* **D:** *Exhumation of infiltrated mantle, gabbros, and emplacement of basalt.* **E:** *Out of sequence fault evolution and increase of magmatic rocks and ascend of lithosphere-asthenosphere boundary.* **F:** *Conceptual model showing location of fluids and magma mantle along the OCT preserved in the Err and Platta nappe linked to the detachment fault evolution*


U.P.
L.P.
Serpentinisation front
Moho
Shear zone bondary between subcontinental and depleted mantle
SUBCONTINENTAL MANTLE
DEPLETED MANTLE
B
Gabbro emplacement
ASTHENOSPHERIC MANTLE
C
Basalt emplacement
Gabbro exhumation
D
E
A
Lower Platta unit
Lower Err - Upper Platta unit
Err unit
[km]
Hydrothermal fluids
Serpentinisation front
Shear zone
CONTINENTAL CRUST
F
Detachment fault
Late normal faults
Paleo-isotherm 800°C
Limits subcontinental and depleted
Isotherm 1300°C
Limits depleted mantle and astenospheric mantle
Basalt
Gabbro
Fluids pathways
Mafic dykes
Serpentinised mantle
Continental basement
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Asthenospheric mantle
U.P. = Upper Plate ; L.P. = Lower Plate

of magma at the seafloor, either as flows, pillows, pillow breccias or hyalocalsites or as sills in post-rift sediments. The fact that in the Lower Platta unit magmatic rocks can be observed that were emplaced at different parts of the extending lithosphere (infiltrated deep in the mantle, intruded at about 6km and extruded at the seafloor) is due to the fact that magma emplacement occurs simultaneous to tectonic exhumation. As a consequence, magmatic rocks that have been produced at different lithospheric levels and at different time are finally juxtaposed (see Fig. P3-14).

First manifestation of magmatic processes in the Lower Platta unit is the reaction of magma with the lithospheric mantle, resulting in infiltrated plagioclase peridotites (for processes and details see *Müntener et al.*, 2004; *Müntener et al.*, 2009; *Picazo et al.*, 2016). The stability of plagioclase is limited at 10kbar (~30km) and equilibration temperatures of these rocks are at 1200-1300°C (*Piccardo et al.*, 2004). Therefore, the presence of plagioclase peridotites indicates that the base of the lithosphere (isotherm 1300°C) had to be shallower than ~30km in order to form these rocks. The fact that these rocks occur in the Lower Platta unit, but not in the Upper Platta unit suggests therefore that the limit between the upper and lower mantle coincided with an infiltration front (paleo-isotherm of 1200°C). As discussed before, we consider that exhumation of the plagioclase peridotites (lower mantle) to shallower levels occurred along the mylonitic shear zone expose at Muttariel. Final exhumation of both, the upper and lower mantle to the seafloor occurred along a final, brittle detachment fault. In order to explain the continentward tilting of the paleo-isotherm the detachment had to dip oceanwards with a top to the future ocean, i.e. a top-to-the west sense of shear.

Gabbros are exposed only in few locations in the Lower Platta unit. As discussed above, these gabbros were emplacing at 161±1My and have been exhumed subsequently to the seafloor, as indicated by their reworking in tectono-sedimentary breccias (e.g. Val Natons, Fig. P3-6; Log 11). These gabbros had to form before exhumation, however, the emplacement depth is ill defined. Desmurs et al. (2002) suggested 6-8 km, corresponding to 2 to 3 kbars. The gabbros show sigmoidal pockets, include mylonitic shear zones that initiated in the presence of magma. Therefore we consider that the emplacement of these gabbros, at least of the bigger ones, may correspond to an important thermal and rheological boundary that has been exhumed subsequently to the seafloor.

The emplacement of most extrusive magmatic rocks observed in the Lower Platta unit appears to be controlled by tectonic processes and to be syn-tectonic. Two preferential emplacement mechanisms can be observed, either along late, high-angle faults, or associated to exhumation faults. The emplacement along high-angle faults results in small basaltic bodies (<100m thick) (Fig. P3-2; Log 2). These normal faults offset the top of the exhumed serpentinised peridotites, however, it remains unclear at what level these faults are rooting. Since their offset never exceed 200m (at least not in the observed examples), we consider that these normal faults only affected the upper part of the serpentinised peridotite. Nevertheless, these normal faults seem to provide preferential pathways for the magma. The magma emplacement along the fault zone itself is not clearly exposed in the Lower Platta unit, but it may be similar to what has been described at the Chenaillet ophiolite in SE France (for more detail see *Manatschal et al.*, 2011).

More voluminous magma emplacement resulting in >300m thick massive basalt bodies, further westwards (Mulegns, north of Cotschen and Piz Platta), occur in the hanging wall of the active part of a detachment fault (Fig. P3-14). This is best demonstrated at the northern termination of Lake Marmorera. In this area rodingitized mafic dykes are syn- to post-detachment faulting, as clearly shown in the Sur al Cant area (Fig. P3-9). At present, the dykes are sub-parallel of the main slip surface along the detachment faults (Figs. P3- 4 and 5). However, it is unclear if the dykes formed subparallel to the detachment surface or if they have been rotated to this position during exhumation. The dykes preferably occur in the damage zone of the detachment fault which is up to 500m thick. These dykes are the feeders of the massive basaltic bodies overlying the detachment system. A further evidence that magma emplacement is syn-exhumation is the observation that along the basal part of thick extrusive complexes the basalts deformed under green-schist facies conditions. These observations show that most magma in the Lower Platta unit is syn-tectonic.

5.6 Alteration of rock, hydrothermal systems and mineralisations

Almost all rocks in the Platta nappe are affected by hydrothermal processes as indicated by the serpentinization and calcification of mantle rocks and spillitization and rodingitization of the mafic rocks. Hydration reactions and alteration in general are in most cases penetrative and occur early, i.e. during the emplacement of the rocks. The penetrative serpentinization of the mantle occurs during exhumation, as indicated by the fault rocks (cataclasites, gouges) show that when the mantle is exhuming at the seafloor, it is already serpentinised (see also *Pinto et al.*, 2017). Ophicalcites, also often characterized as a process occurring at the seafloor (*Früh-Green et al.*, 1990), appear to occur in a late stage of exhumation, as indicated by the observation that most of the veins are oriented perpendicular to the transport direction (Figs. P3- 3C and 5B). Furthermore we can observe different generations of calcite veins, with some of them which are folded and cross cut by undeformed calcite veins. For these examples it can be shown that the calcite is syn-detachment faulting.

Spillitization and rodingitization are, as discussed above, also related to the early stage of emplacement and locally it can be shown that these processes are syn-tectonic, as shown by the fact that they constitute the minerals forming the extensional foliation within the basalts. Apart from these penetrative processes, localized mineralizations show that more focused hydrothermal systems existed as well. These systems, shown in figures P3- 1B and 10 with red stars, are aligned along the interface between thick magmatic bodies and mantle rocks along the flanks of paleo-corrugations. These systems are associated with the emplacement of syn-tectonic magma and sea-water derived fluids that resulted in mineralizations into serpentinites. The fact that these systems are also developing mineralizations into sediments (red pentagon, Figs. P3- 1B and 10) may suggest that these systems are long-lived. While the mineralizations in the serpentinised peridotite are more related to S_2, Fe, Cu, Ni, Co, and Zn, within the sediments mineralizations include Mn, Cu, Fe. Similar sites of hydrothermal vents are described at present day from OCC (e.g. lost city on MIR, *Boschi et al.*, 2008)

5.7 Comparison to ultra-slow spreading ridges and OCC

Present-day exposed Oceanic Core Complexes (OCC) in ultra-slow spreading ridges (e.g. Atlantis Massif, Mont Dent, and many others at Mid-Atlantic Ridges (MIR)) show similarities with observations reported from the Lower Platta unit. However, there are also differences that enable to propose a transitional type, which we called proto-Oceanic Core Complex (proto-OCC).

The principal similarities that we can observe between present-day OCC and the Lower Platta unit are: 1) the lithologies containing exhumed mantle rocks, gabbros, basalt and breccias; 2) the morphology with dome form and similar size (~15 x 20km); and 3) fluid circulations with ophicalcites, hydrothermal vent and rare talk.

However, main differences to present-day OCC can be noted. 1) the proto-OCC is made of sub-continental mantle, 2) the numerous occurrences of continent derived blocks over the proto-OCC mark the proximity to continental crust, and 3) the polyphase tectono-magmatic evolution.

All these observations show that in contrast to OCC, proto-OCC are not yet in a mature steady state system, neither from the magmatic, nor from the tectonic point of view. Moreover, the proximity to continental lithosphere may also control that thermal state and the composition of the mantle rocks. Thus, inheritance still plays an important role in ultra-distal exhumed mantle domains.

It is also interesting to note that the proportion of lithologies between OCC and proto-OCC seems different. Indeed, in the Lower Platta unit, a very small amount of gabbro can be observed (~2% of paleo-surface, Fig. P3-15) whereas in present day OCC the proportion between gabbros and mantle rocks recovered from exhumed surfaces is more consistent (~60% of dredge rocks for the Mt Dent, MIR, after *Harding et al.*, 2017, Fig. P3-15). This lower concentration of gabbro could be the major difference between a proto-OCC and an OCC. This difference could be linked to the close position of the Lower Platta unit with respect to the hyper-extended domain. Indeed the hyper extended stage of the Adriatic margin is completely free of magma, and the first exhumed mantle is cold and of sub-continental origin. Magma appears in the system only after the exhumation of the Lower Platta unit. Thus, the Platta units may correspond to an initial stage of magma emplacement, which may explain why gabbros are still rare. Another explanation is that gabbros were emplacing much deeper, due to the thick mantle lithosphere in the OCT and detachment faults were not able to exhume them. This may contrast to ultra-slow spreading ridges were magma processes are more active and the gabbros emplacement is certainly more common. For the basaltic rocks it seems that there is no major difference. We estimate at less than 40% the proportion of surfaces occupied by basalts vs. exhumed mantle surfaces for proto-OCC, compared to ~20% in OCC (see dredging results for the Mt Dent, MIR, after *Harding et al.*, 2017, Fig. P3-15). The total proportion of exhumed serpentinised mantle, preserved to the seafloor, is then more important for a proto-OCC (~60%) than an OCC (~20% of dredge rocks for the Mt Dent, MIR, after *Harding et al.*, 2017, Fig. P3-15). All these observations are coherent to a kind of transition from a first stage of primary

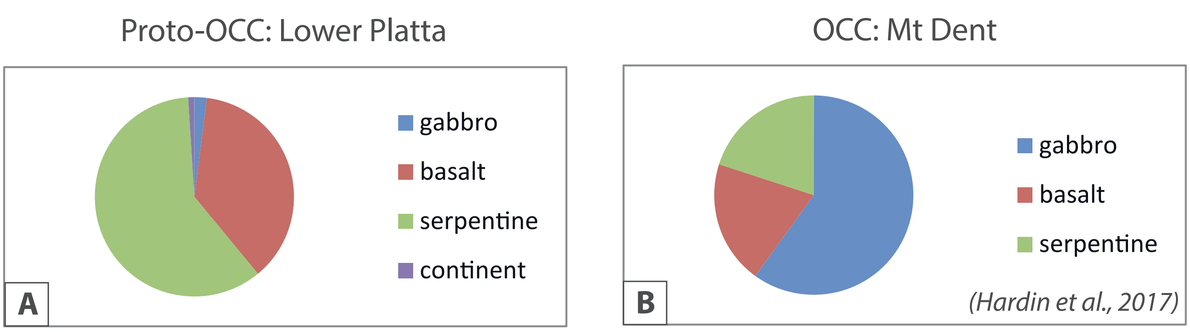


Fig. P3-15: *Representation of rock occurring at the seafloor at the Platta units (estimation of surface at the paleo-sea-floor made after restoration) and in the Mt Dent Oceanic Core Complex (after Harding et al., 2017).*

amagmatic crustal hyper-extension and mantle exhumation (exhumation of the Upper Platta unit) to, in the second stage, a magma-poor mantle exhumation. All the observations enable to propose for the Platta units a consistent conceptual model that can explain the major processes. Our results showed, based on the observations made in the Lower Platta unit, that in these ultra-distal exhumed mantle domains tectonics is yet the major driver. However, systems like those represented in the Lower Platta unit can develop into ultra-slow to slow spreading ridges. In the Alpine Tethys, we do not have evidence for the existence of a Penrose type ophiolite sequence. Therefore the existence of a fast spreading ridge cannot be supported by data.

6. Conclusions

The mapping of the Platta nappe enabled to highlight new observations on the interaction between the tectonic, magmatic and fluid evolution occurring in an ultra-distal exhumed mantle domain. Major observations are that the volume of magma increases within the Lower Platta unit oceanwards, and also the complete absence of magmatic bodies > 300 meters thick. Our observations can also show that the magma is syn-tectonic. The occurrence of several continental derived blocks onto exhumed mantle shows the proximity of the exhumed domain with the hyper-extended crust. A detailed restoration of the Lower Platta unit shows a complex polyphase evolution of this domain that includes the formation of proto-OCC that are overprinted by late normal faults and the presence of syn-tectonic magmatic activity and hydrothermal systems. Locations of active deformations and emplacement of magmas are also preferential areas of the formation of hydrothermal fluid systems rich in metals. Across the most oceanwards parts of the Lower Platta unit, the extrusive magmatic additions fill topographic lows while highs are formed by exhumed mantle, capped by topographic highs forming dome type structure. In conclusion, the Lower Platta unit preserves a transition to a potential spreading ridge system in which exhumation of the mantle, the magma, and the fluid emplacement are driven by tectonic processes.

Post face

In this paper I discuss the morpho-tectonic evolution of an ultra-distal, exhumed mantle domain and its relation to magmatic processes. This domain is defined by highs and lows, which are due to a complex polyphase tectonic and magmatic evolution. The lows are preferentially filled by basalts, while the highs are preferentially constituted of exhumed mantle, directly covered by sediments. The magmatic additions, including gabbros and basalts, are emplaced during exhumation and on top of exhumed surfaces, either associated with normal faults that truncate the detachment surface, or along the detachment surface itself. The massive basalts, made of flows, hyaloclastites, pillows and pillow breccias, show evidence of syn-tectonic emplacement. Fluids are omnipresent, as indicated by the almost complete serpentinization of the mantle, the rodingitisation of dolerites and spilitisation of basalts. Localized hydrothermal systems, related to mineralizations, occur along the interfaces between massive basalt bodies and exhumed mantle made of cataclastic damage zones. Top basement architecture and the observed relationships between exhumed mantle, magmatic additions and occurrence of hydrothermal systems is similar to what is observed at present-day at slow to ultra-slow spreading ridges.

Key results are:

- Detachment faults exhuming mantle are cross cut by late normal faults
- Detachment faults show a dome type architecture, similar to what is observed at present-day OCC.
- Detachment faults and late normal faults seem to control the magma emplacement along ultra-distal magma-poor rifted margins.
- The active and rollover area of a detachment fault is also a preferential area for fluids circulation as indicated by the occurrence of strong hydrothermal activity.
- The extrusive magma preferentially fills topographic lows, and exhumed mantle domains form topographic high.
- Exhumation of the mantle, the magma and fluid emplacement is a tectonic driven process.

Although the study resulted in new, interesting observations that enable to draw many new conclusions, some questions remain concerning the Lower Platta domain. Can the overall observations be used to demonstrate that this domain formed at a spreading ridge, or does it still correspond to a transition from exhumed mantle to a spreading ridge? How can the two settings be differentiated? How can these ultra-distal domains be characterised? What controls the quantity and distribution of magma and what composed the top basement architecture of the exhumed mantle?

Part III: Evolution and reactivation of distal and ultra-distal rifted margins: comparison with present-day analogues and models

The main questions that guided this project were:

- How, when and under what conditions does extreme crustal thinning and lithospheric breakup occur?
- How do detachment faults thin the crust and eventually exhume mantle, where do these structures root at depth, how do they accommodate strain and how do they develop in time and space?
- What is the architecture of a hyper-extended and of an exhumed mantle domain, how do tectonic and magmatic processes interact during their formation and what is the role of fluids during exhumation?
- What is the role of inheritance during extension and reactivation of distal rifted margins?

Answering to these questions is difficult because of the lack of direct observations and the difficult access to these settings that are at deep water and often covered by thick sedimentary successions. This is the main reason why I focused my study on a fossil analogue. The advantage of working with fossil analogues is that nature of contacts and lithologies can be directly observed in the field. However, since they have been emplaced in mountain belts, the problem remains that these domains need to be restored, and that the structures related to their formation and reactivation need to be distinguished. In most cases, this work is difficult and the pre-compressional structures and lithologies are completely overprinted and destroyed during their emplacement in a collisional orogen. Therefore, before comparing to present-day systems, the compressional history needs to be understood and the structures restored. This is at present-day only possible for few examples. The aim of this part of the PhD thesis is to summarize the key observations made in the field examples and to compare them with present-day analogues and models. Moreover, the observations made in the Err and Platta nappes enabled to find answers to some of the questions that are at the origin of this work. However, this work also leads to new questions which will have to be answered in future studies (see Chapter 9,10 and 11).

Part III consists of 3 chapters. Chapter 9 discusses the general architecture of distal and ultra-distal magma-poor rifted margins. Chapter 10 discusses the evolution and processes involved in the formation of distal and ultra-distal magma-poor rifted margins, i.e. the separation of continents, the exhumation of mantle rocks and the break-up of the lithosphere and onset of oceanic seafloor spreading. Chapter 11 examines the role of the structures of distal and ultra-distal domains during the compressional reactivation.

CHAPTER 9: ARCHITECTURE OF DISTAL AND ULTRA-DISTAL MAGMA-POOR RIFTED MARGINS

The study of seismic sections from present-day ultra-distal rifted margins shows evidence for important top-basement topography including different types of basement highs. A number of questions exist related to these basement highs and lows that are, except few examples, not been drilled. The main questions are: What are the processes controlling the formation of the highs and lows? What kind of lithologies form these ultra-distal domains? What is their origin, when did they form and how? Can we predict, on a seismic section, the nature and evolution of these basement highs?

1. 2D architecture of distal and ultra-distal margins

1.1 Field observations

Thanks to the study of the Err and Platta nappes in the Alps, representing remnants of fossil hyper-extended and exhumed mantle domains, important topographic variations of top basement can be defined, formed by tectonic and magmatic processes.

In the hyper-extended domain (Err nappe), it can be shown that the topography of top basement is principally controlled by extensional structures, except for a few places, where gravitational structures related to the existence of evaporites may be important and superpose tectonic structures. Extensional structures include breakaway blocks and rider blocks (for a definition see Chapter 7). Both types of blocks are allochthonous and are supposed to derive from the delamination of the most distal European hyper-extended domain during final rifting. The major difference between the two types of blocks is their size. While breakaway blocks are typically at a kilometre scale, the rider blocks are at a hundred meter scale or smaller. Breakaway blocks bound sedimentary basins and mark important topographic highs, and are related to the breakaway of a new detachment fault. In contrast, rider blocks correspond to discontinuous, structured blocks overlying detachment surfaces. The rider blocks can be linked, as shown in this study, to gravitational gliding onto pre-rift evaporitic layers during their emplacement. The formation of breakaway blocks is intimately related to the evolution of detachment faults. These blocks are typically made of upper crustal rocks and their pre-rift sedimentary cover including Permo-Triassic to Liassic sandstones, dolomites and limestones. In the Err nappe, the occurrence of basement highs capped by detachment faults and directly sealed by post-rift sediments can be found as well.

In the exhumed mantle domain (Platta nappe), the basement topography is controlled by the complex interaction of tectonic and magmatic processes. Tectonic processes create important topographies with detachment and normal faults. Detachment faults can form dome shape structures that are aerially limited by the breakaway and the location where the footwall is daylighting. In paper 3 (Chapter 7), we show that the top of the basement corresponds to an exhumed detachment surface, which can be truncated by later normal faults, structuring the top-mantle surface. In contrast to tectonic processes, magmatic processes tend to smooth the topography. Indeed, based on the example of the Platta nappe, magma is preferentially located upon damage zones and tends to fill the topographic lows. While relatively small volumes of basalts (<100m thick) can be found over the detachment along late normal faults, more voluminous basaltic bodies (>100m thick, maximum 800m) can be found ontop of active detachment faults within the lows. The final topography is marked by topographic highs made of exhumed mantle and sealed by post-rift sediments. In contrast, basalts are observed either at highs, founded by normal faults, or over exhumed mantle in the topographic lows.

1.2 Comparison to the distal and ultra-distal domains at the Iberian margin

Seismic interpretation requires the understanding of the geological nature of reflections that results from the impedance contrasts, i.e. interfaces juxtaposing lithologies with different petrophysical characteristics. These interfaces can be of stratigraphic, tectonic or magmatic origin, or they can correspond to hydration reactions (e.g. serpentinization front). Without drill hole calibration it is not possible to clearly affirm the nature of the contact that corresponds to a reflection. The systematic seismic imaging of rift systems, combined with drilling and comparisons with field analogues enabled to determine “templates” of geological structures such as tilted blocks and their sedimentary infill. At present, these types of structures can be identified and interpreted without direct drill hole calibration. In contrast, structures located at ultra-distal rifted margins that have at present only been drilled in few places, remain difficult to interpret, due to the lack of calibration and of good field analogues. The key feature on seismic sections from ultra-distal margins is the top of acoustic basement, which provides a commonly well-defined reflection. The top acoustic basement marks, in most cases, the limit between a basement and its sedimentary cover. However, where magma or fluids are present, the top acoustic basement is more complex and often ill defined. In the case of ultra-distal magma-poor rifted margins, top basement can be made of crustal rocks or exhumed mantle capped by a detachment surface, pre-rift sediments, or magmatic additions.

The structures observed in the Err nappe present some similarities to those imaged at present-day, hyper-extended domains, located along the distal Iberian margin such as in the seismic section shown in figure 9-1. The seismic section shows a gradual thinning accompanied by large faults bounding blocks that get smaller oceanwards and are bounded by detachment faults. Ranero and Pérez-Gussinyé (2010) presented a model to explain the thinning of the crust using a balanced kinematic model. This model shows an in-sequence evolution of detachment faults stepping towards the future ocean, which is coherent with simple Andersonian fault theory. i.e. initiation of faults at 60°. This model is also coherent with the observations made on the Err detachment system (Chapter 7, paper 2).

Further distalward, in the domain where exhumed mantle has been drilled, the seismic interpretation is more challenging. In 2015, Dean et al. published new seismic profiles that images the ultra-distal extension of the Iberia margin into first oceanic crust (Fig. 9-2). These seismic profiles highlight an important topography in the ultra-distal part of a magma-poor rifted margin. While the top-basement topography in the hyper-extended domain is of tectonic origin, the domain further oceanwards is marked by the occurrence of peridotite ridges (serpentinised peridotites have been drilled in ODP Site 637). Exhumed mantle has been drilling so far at seven ODP Sites (Sites 637A, 897D-C, 899B, 1068, 1070, and 1277) in the Iberia and conjugate Newfoundland margins. It is important to mention that all these drill holes penetrated exhumed mantle on basement highs and that the exhumed domain is marked by important top basement topography. For the nature of the basement highs imaged in the seismic section shown in figure 9-2, Dean et al. (2015) discussed different possible origins: 1) continental crust, 2) oceanic crust, or 3) exhumed mantle. While they propose an oceanic origin for highs 1-2, and 3a, the highs 3b, 4 and 5 are interpreted as exhumed mantle formed in an ultra-distal domain by the combination of oceanic core complex formation and generation of new oceanic crust. This example highlights the difficulty to distinguish oceanic crust from an exhumed mantle domain (Fig. 9-2).

1.3 Implications and outlook

For the hyper-extended domain, the observations made in the Err nappe show some similarities to seismic interpretations proposed at present-day margins, but also some difference that question some of the seismic interpretations proposed for distal to ultra-distal domains. In the field, the occurrence of "intra-crustal" detachment faults can be observed in the hyper-extended domain, and only the most distal detachment fault exhumes the mantle to the seafloor. Indeed, the mantle-crust contact, commonly referred to as the "S" reflector, is only a fault in its most distal part, while, underneath the hyper-extended domain, it corresponds to a decoupling level that is passively exhumed towards the seafloor. In the Ranero and Pérez-Gussinyé (2010)

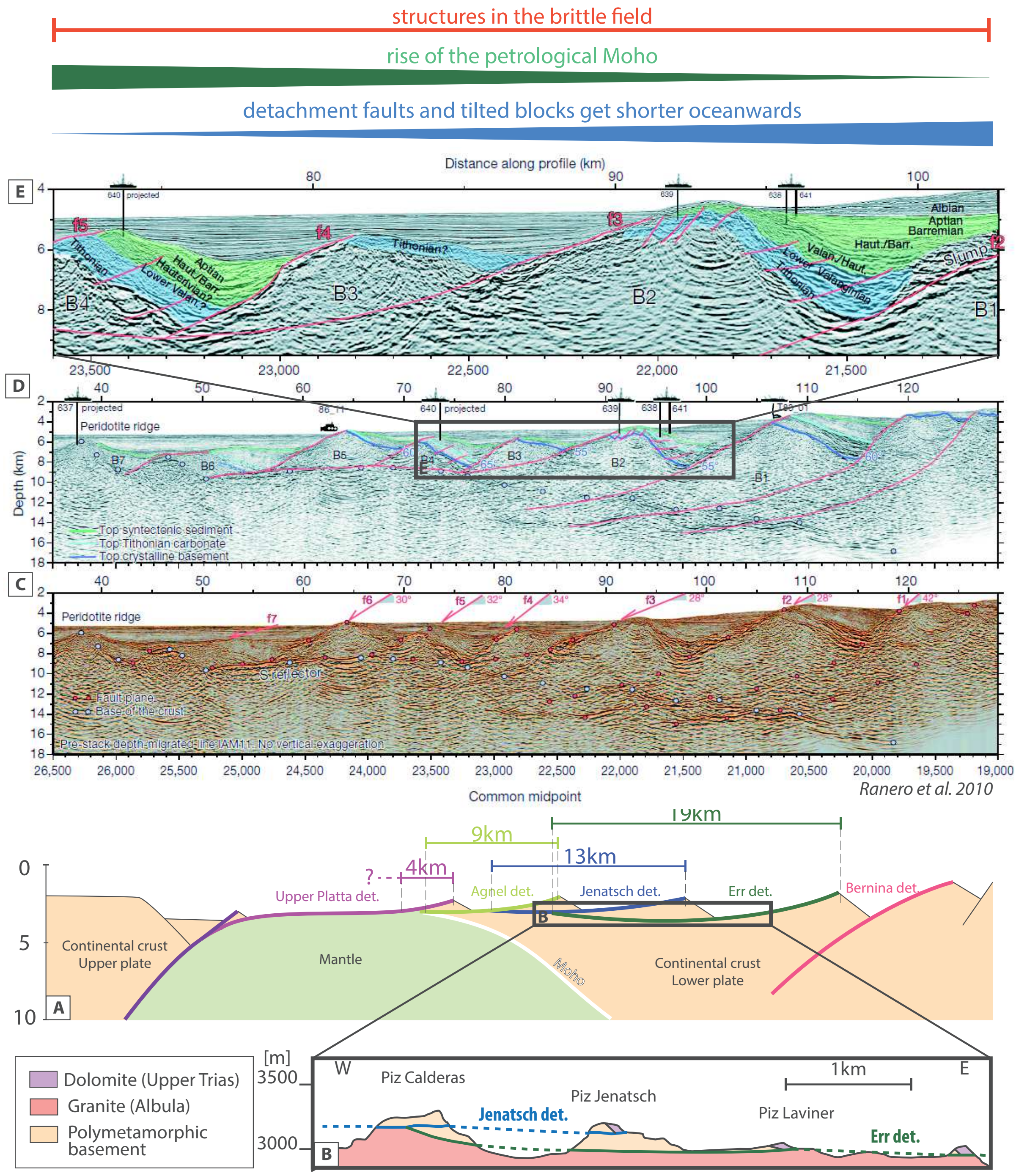
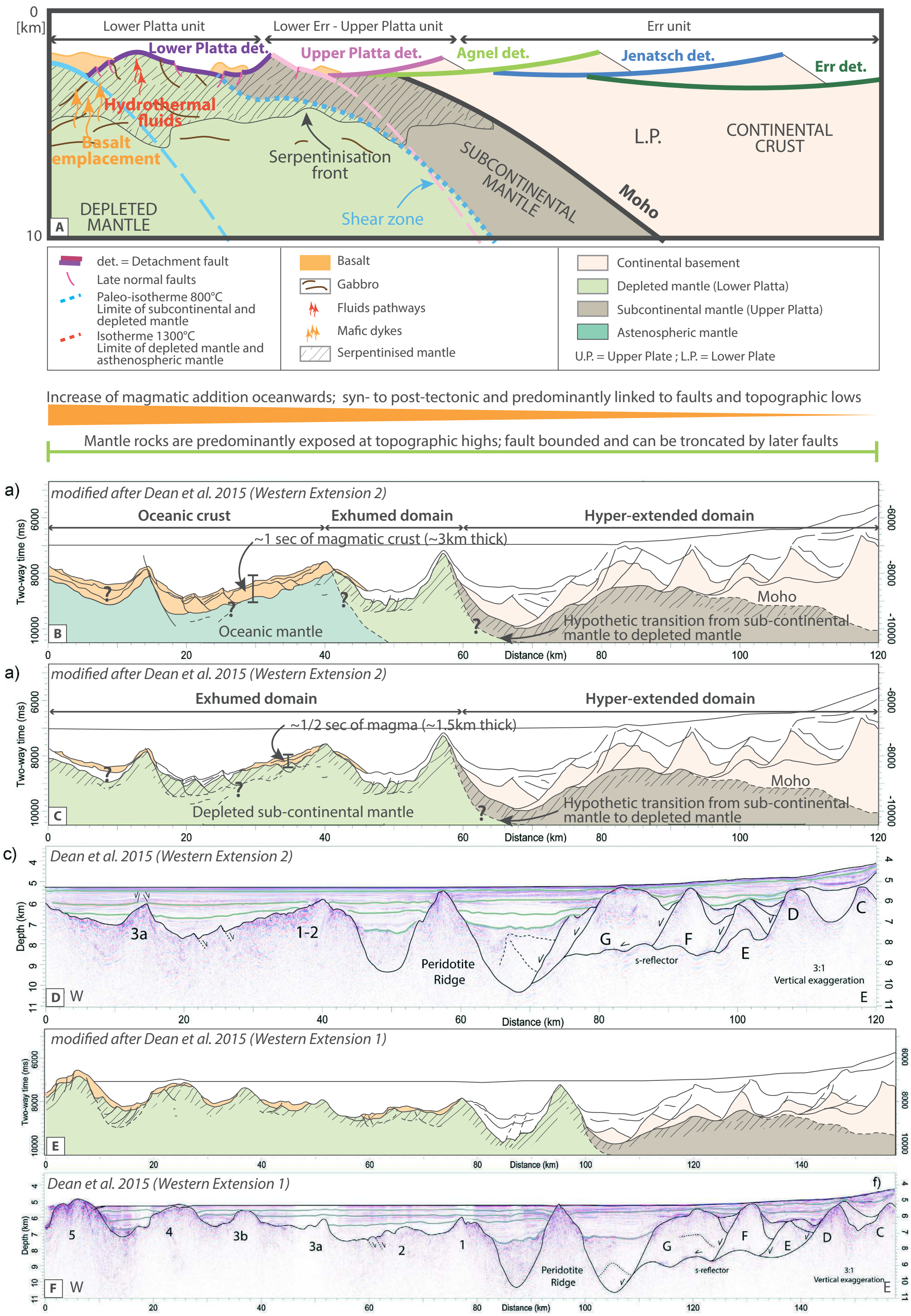


Fig. 9-1: *Structures observed in the Err nappe compared to present-day hyper-extended domain off Galicia (northern Iberia) (after Ranero and Pérez-Gussinyé, 2010).* **A:** *Schematic restoration of the Err nappe showing the location and size of the different detachment faults (Err, Jenatsch, Agnel and Upper Platta detachments).* **B:** *Zoom on the Err and Jenatsch detachment faults showing that the former is truncated by the letter.* **C, D and E:** *Seismic pre-stack depth-migrated line IAM11 (Ranero and Pérez-Gussinyé, 2010).* **C:** *Arrows and numbers indicate the average dips of the block-bounding fault segments exhumed during rifting.* **D:** *Tectonic and stratigraphic interpretation.* **E:** *Enlarged view of box in D, showing geometry and calibrated ages of sediment units.*



Lower Platta unit
Lower Err - Upper Platta unit
Err unit
Lower Platta det.
Upper Platta det.
Agnel det.
Jenatsch det.
Err det.
Hydrothermal fluids
Basalt emplacement
Serpentinisation front
Shear zone
SUBCONTINENTAL MANTLE
DEPLETED MANTLE
L.P.
CONTINENTAL CRUST
Moho
det. = Detachment fault
Late normal faults
Paleo-isotherme 800°C Limite of subcontinental and depleted mantle
Isotherme 1300°C Limite of depleted mantle and asthenospheric mantle
Basalt
Gabbro
Fluids pathways
Mafic dykes
Serpentinised mantle
Continental basement
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Astenospheric mantle
U.P. = Upper Plate ; L.P. = Lower Plate
Increase of magmatic addition oceanwards; syn- to post-tectonic and predominantly linked to faults and topographic lows
Mantle rocks are predominantly exposed at topographic highs; fault bounded and can be troncated by later faults
modified after Dean et al. 2015 (Western Extension 2)
Oceanic crust
Exhumed domain
Hyper-extended domain
~1 sec of magmatic crust (~3km thick)
Oceanic mantle
Moho
Hypothetic transition from sub-continental mantle to depleted mantle
Two-way time (ms)
Distance (km)
~1/2 sec of magma (~1.5km thick)
Depleted sub-continental mantle
Dean et al. 2015 (Western Extension 2)
Depth (km)
Peridotite Ridge
s-reflector
3:1 Vertical exaggeration
modified after Dean et al. 2015 (Western Extension 1)
Dean et al. 2015 (Western Extension 1)

Fig. 9-2: *Comparison of structures observed in the Platta nappe to those seismically imaged at present-day ultra-distal exhumed domains of Galicia (northern Iberian margin) (Dean et al., 2015).* **A:** *Schematic section illustrating the observations made in the Err and Platta nappes.* **B:** *Interpretation of the time section Western Extension 2 (WE2) showing the basement highs 3a and 1-2 associated to an oceanic crust, as proposed by Dean et al. (2015).* **C:** *Interpretation of the time section of WE2 showing the basement highs 3a and 1-2 associated to exhumed mantle truncated by later normal faults and covered locally by magmatic additions.* **D:** *Interpreted depth section of WE2 made by Dean et al. (2015).* **E:** *Interpretation of the time section of Western Extension 1 (WE1) showing the polyphase composition of the exhumed mantle domain.* **F:** *Interpreted depth section of WE1 made by Dean et al. (2015).*

interpretation of the IAM 11 profile, we can find this "intra-crustal" detachment between the blocks B2 and B3. Following our observations, all the detachment faults forming in the hyper-extended domain are connected to one and the same fault at depth and only the uppermost part corresponds to a new, in-sequence faults. If we apply our model to the interpretation of the IAM 11 profile, we propose that apart from the proximal fault (f1 to f7 *Ranero and Pérez-Gussinyé*, 2010) all the others are connected to each others as proposed by the classical rolling hinge model (Fig. 9-1A). The general architecture of this most distal, hyper-extended domain is completely controlled by the in-sequence fault propagation and the rocks forming the allochthonous blocks are made of upper crustal rocks only. A key question is if this mode of deformation can be used to explain all hyper-extended domains, and if not, what may explain hyper-extended domains that are made by ductile shearing as suggested by Clerc et al. (2017).

For the exhumed mantle domain, it can clearly be seen in the field that the final architecture is complex and controlled by the interaction of tectonic and magmatic processes. These observations ask to rethink the quantity of magma present at ultra-distal magma-poor rifted margin. Indeed, in the field, we observe an important volume of basalts occurring at topographic lows while exhumed gabbros and serpentinised peridotites occur at topographic highs (Fig. 9-2A). The observations made in the fossil exhumed domain in the Platta are coherent with the hypotheses developed by Dean et al. (2015). These authors suggested a complex distribution of exhumed mantle and magma. The smooth, rounded structure described by Dean et al. (2015) at the high 3b for example may correspond to a dome-type structure made of exhumed mantle, similar to the one observed in the Lower Platta unit (Chapter 8). Assuming that this comparison is valid, one can suspect the occurrence of magma around this structures within the basins. The high 5 described by Dean et al. (2015) presents a more complex structure with a structured basement that underlies the post-rift level. In the figure 9-2, I propose two alternative interpretations of the Western extension 2; one corresponding to a transition from hyper-extended continental crust to exhumed domain to a domain with an embryonic oceanic crust, and the second corresponding to a transition from hyper-extended continental crust to a domain of exhumed mantle. This high in the exhumed mantle domain could correspond to a high made of serpentinised mantle, cross cut by later normal faults and covered by extrusive magma. Although Dean et al. (2015) interpreted this structure as an oceanic core complex, the main question remains if the Lower Platta unit can really be compared to an Oceanic Core Complex and if the domain was already formed at a spreading ridge?

Based on the observations made in the field and the comparison to the present-day distal Iberian margin, the question arises if the "non-magmatic" nature of the Iberia margin is influenced by the drilling of basement highs only. If one would use the Lower Platta unit as an analogue, drilling in topographic lows would be expected to penetrate mainly basalts. Our study shows the complex polyphase history of this domain and shows the strong lateral variability that needs to be expected at the distal parts. One yet unresolved question is also if the transition from exhumed mantle to a steady state oceanic crust is gradual or abrupt, and how far the observations made in the Lower Platta unit are compared to those made at present-day Oceanic Core Complexes? Field observations clearly show that throughout the Lower Platta unit, mantle was exhumed everywhere. Basalts were emplacing onto mantle, either after or during exhumation. In present-day slow to ultra-slow spreading ridges, mantle exhumation and formation of an Oceanic Core Complex are ill defined and interpretations exist that suggest that magma formed before, simultaneously and after formation of an OCC (*MacLeod et al.*, 2009). How far detachment fault and post-exhumation normal faults can serve as feeder systems that may facilitate the emplacement of magma remains unclear in present-day systems. In the case of the Lower Platta unit, these faults seem to control the magma-transport towards to seafloor. In conclusion, the general geometry of basement highs seems to be controlled by the nature of the rocks and the tectonic and magmatic processes forming the highs (see Annex 2)

2. 3D architecture of a hyper-extended domain

2.1 3D architecture of a hyper-extended domain: field observations

Although the 2D architecture of a hyper-extended domain is fairly simple, the 3D architecture of these domains is much more complex because of the lateral complex evolution of the detachment system (Chapter 7). In the field (Err nappe) it can be shown that the lateral geometry of detachment faults can be influenced by inheritance, i.e. either the occurrence of former basins, or of evaporites. The field observations show that the detachment faults in the Err nappe invert Permian rift basins resulting in lateral ramps parallel to the axes of the former basin. It can also be seen that allochthonous blocks can terminate along strike (e.g. southern termination of the Bardella block; see Fig. 9-3). Such an abrupt termination may be controlled by the bending of the breakaway fault and incising into a pre-existing fault as suggested by the southernmost, E-W directed section across the Err domain (see Fig. 9-3).

2.2 Comparison to present-day 3D architecture of a hyper-extended domain

An example of a present-day 3D architecture of the Iberia margin has been presented by Péron-Pinvidic et al. (2007). The first order architecture of this domain is controlled by several tilted blocks that overlie hyper-exteded crust or exhumed mantle. The 3D mapping show that although the geometry along dip lines, i.e. lines parallel to transport direction, is simple, strike lines show more variability and can show the transition from tilted block geometries to exhumed domains. This is well documented along the domain between CAM 144 and LG 12 (Fig. 9-3), where the lateral transition from breakaway blocks made of pre-rift sediments and upper crust changes along strike to topographic highs made of continental crust and exhumed mantle (e.g. Hobby High in the Iberia example). In our field (Err nappe), a similar lateral transition can be observed along strike from north to south.

2.3 Implication and outlook

Although the examples we compare are not at the same scale and the exhumed rocks are different; it is important to note that hyper-extended structures (detachment faults and related breakaway blocks) can show a complex lateral evolution. In the Err example, detail mapping of detachment structures can explain the lateral variation of the hanging wall geometry, such as the lateral termination of a hanging wall block. By appyling this interpretation to the Iberian example, the formation of the Hobby High could be explained by the formation of a new detachment incising into a previous detachment over the crest of the high. This would explain the overtilting of the continental block (block B4, Fig. 9-3E and F) and of the underlying "H" reflection and its present dipping to the east. This type of fault interactions has been proposed by Gillard et al. (2016b). The examples proposed by these authors are very similar, despite the different observational scales This leads us to the question whether observations made at different scales can be compared? If this would be the case, this would suggest that these structures are scale independent. This could be tested by comparing the field observations made in the Err with those made on a high resolution 3D seismic block at a present-day, hyper-extended magma-poor rifted margin.

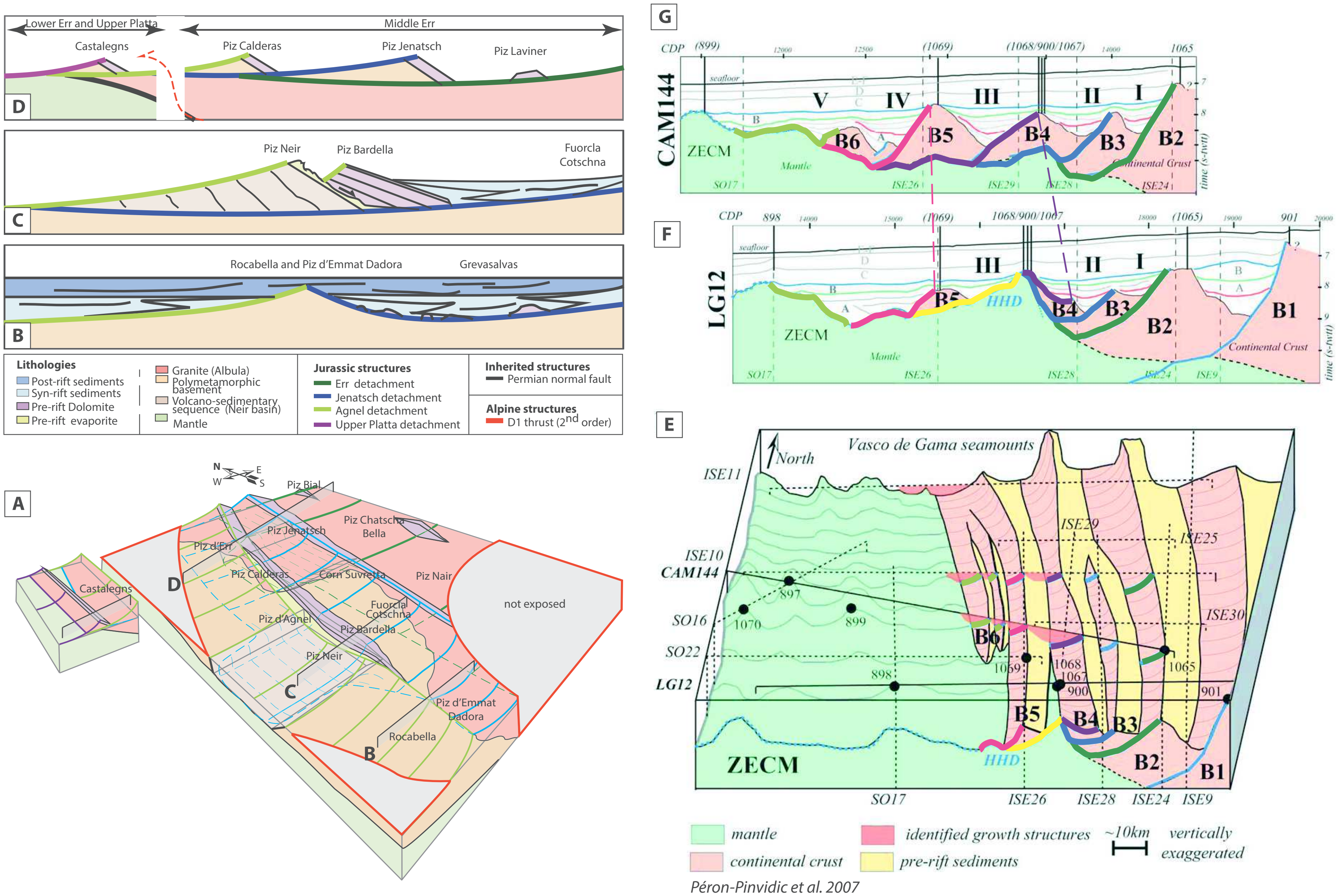

D
Lower Err and Upper Platta
Middle Err
Castalegns
Piz Calderas
Piz Jenatsch
Piz Laviner
C
Piz Neir
Piz Bardella
Fuorcla Cotschna
B
Rocabella and Piz d'Emmat Dadora
Grevasalvas
Lithologies
Post-rift sediments
Syn-rift sediments
Pre-rift Dolomite
Pre-rift evaporite
Granite (Albula)
Polymetamorphic basement
Volcano-sedimentary sequence (Neir basin)
Mantle
Jurassic structures
Err detachment
Jenatsch detachment
Agnel detachment
Upper Platta detachment
Inherited structures
Permian normal fault
Alpine structures
D1 thrust (2nd order)
A
Piz Bial
Piz Chatscha Bella
Piz Jenatsch
Piz d'Err
Piz Calderas
Corn Suvretta
Piz Nair
not exposed
Castalegns
Piz d'Agnel
Fuorcla Cotschna
Piz Bardella
Piz Neir
Piz d'Emmat Dadora
Rocabella
G
CAM144
ZECM
Mantle
Continental Crust
V
IV
III
II
I
B6
B5
B4
B3
B2
F
LG12
seafloor
HHD
ZECM
Mantle
Continental Crust
B5
B4
B3
B2
B1
E
North
Vasco de Gama seamounts
ISE11
ISE29
ISE25
ISE10
CAM144
SO16
SO22
LG12
ISE30
B6
B5
B4
B3
B2
B1
ZECM
HHD
SO17
ISE26
ISE28
ISE24
ISE9
mantle
continental crust
identified growth structures
pre-rift sediments
~10km
vertically exaggerated
Péron-Pinvidic et al. 2007

Fig. 9-3: *3D architecture of hyper-extended domain.* **A:** *Restored block of the Err nappe showing the location of different detachement faults.* **B:** *Simplified restored section through the southern segment.* **C:** *Simplified restored section through the Piz Neir, Piz Bardella, Fuorcla Cotschna domain showing local complexities due to the presence of salt.* **D:** *Simplified restored section through the northern Err and Upper Platta domains.* **E:** *3D schematic representation of the basement structures (Péron-Pinvidic et al., 2007). Dashed lines mark the location of the seismic lines used to construct the diagram. Numbers refer to ODP sites. ZECM = Zone of Exhumed Continental Mantle; HHD = Hobby High Detachment fault. Interpretation of seismic profile LG12 (F) and CAM144 (G).*

3. 3D architecture of an exhumed mantle at an ultra-distal margin

3.1 3D architecture of an exhumed mantle domain: field observations

The study of the Lower Platta unit shows diagnostic top-basement topography. The central part of the Lower Platta unit preserves a basement high made of exhumed mantle and sealed by late post-rift sediments. North and south, as well as to the west, this high is surrounded by topographic lows and is covered by extrusive magmatic rocks and sealed by early post-rift sediments. The eastern part of the Lower Platta unit preserves an exhumed mantle, structured by normal faults and covered by small basaltic bodies. The general architecture of the exhumed mantle domain, characterized by highs and lows and structured by late normal faults can be compared to mega-mullions described from slow to ultra-slow spreading ridges (Fig. 9-4). The general distribution of the rocks on the Lower Platta unit is principally made of exhumed mantle (60%) and basalts (37%). Exhumed gabbros (<2%) and allochthonous blocks can be observed, but are rare (<1%).

3.2 Comparison with present-day Oceanic Core Complex

In the last twenty years, more and more examples of mega-mullions also referred to as Oceanic Core complexes (OCC) have been found and described from slow and ultra-slow spreading Mid Oceanic Ridges. An OCC can generally be defined as an oceanic tectonic structure with a dome shape form made of either gabbros and/or serpentinite, in rare cases also basalts (*Sauter et al.*, 2013). An OCC can be 10 to 150 km large (strike direction), 5 to 15 km long (dip direction), and reaches topographies between 500m and 1500m (for a description see *MacLeod et al.*, 2009; *John and Cheadle*, 2010; *Whitney et al.*, 2013). The rocks surrounding and overlying the OCC are often made of volcanic and sedimentary sequences. OCC are often grouped and occur along the spreading centre (*MacLeod et al.*, 2009), or can be more isolated and located in an inside-corner situated in the proximity of a transform fault (*Blackman et al.*, 1998). Proportions of rocks distributed at the seafloor can vary in function of the spreading rate.

The restored mantle high in the Lower Platta unit shows many similarities with the

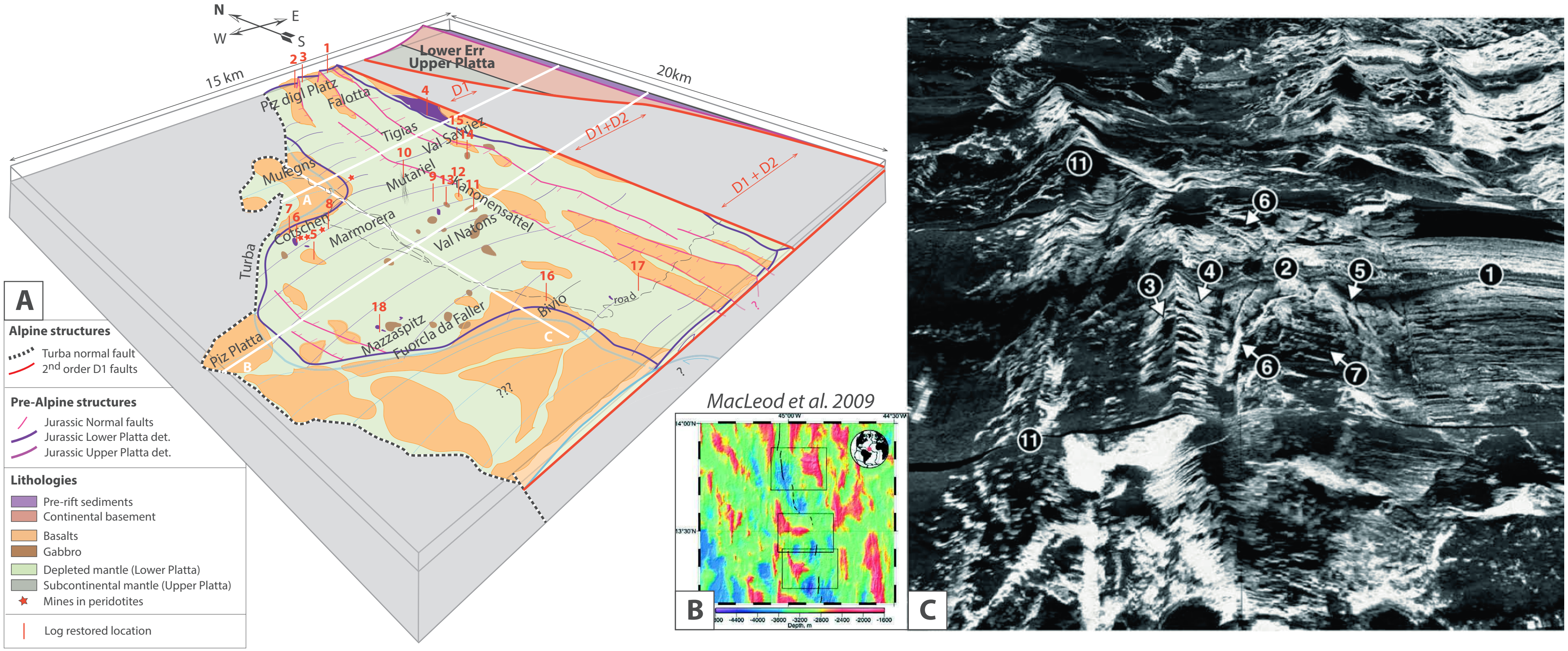


Fig. 9-4: *3D architecture of an exhumed mantle domain.* **A:** *3D restoration of the Platta units showing a complex paleo-geography and distribution of lithologies. Numbers refer to locations of Logs and white lines refer to sections described in paper 3, Chapter 4, Part II.* **B:** *Bathymetric map of the area investigated by MacLeod et al. (2009), and its location along the Mid-Atlantic Ridge (see inset).* **C:** *"View of 13°19'N OCC looking NNE. Distance from emerging toe of detachment to breakaway ridge crest is 9 km. (1) striated detachment fault surface; (2) central horst; (3) outward-tilted volcanic ridge at breakaway; (4) inward-dipping fault scarp at breakaway (original headwall of detachment); (5) inward-dipping fault separating smooth dome from central horst; (6) outward-dipping faults; (7) disrupted remnant of original striated detachment surface slipped down flanks of central horst (note striations similar to but rotated from those on the smooth dome); (8) inactive, faulted, sediment covered volcanic terrain (low-backscatter); (9) screes (high-backscatter) derived from disaggregation of basaltic hanging wall shed onto striated detachment surface at point of emergence; (10) high-backscatter active volcanic ridge in axial valley to north of 13°19'N OCC; (11) outward-tilted volcanic surfaces + inward-dipping ridge flank faults in slightly older terrain to west of OCC" (MacLeod et al., 2009).*

Mid Atlantic Ridge (MAR) near 13°N described by MacLeod et al. (2009) (Fig. 9-4). The restored Lower Platta unit presents a structure of approximatively 15km long (dip direction) and 20km large (strike direction) of 800m. Although the top-basement morphology of the restored dome of serpentinite in the Lower Platta unit may show some similarities, the distribution of lithologies is different. In slow spreading ridges, OCCs are principally made of gabbros (60% after *Harding et al.*, 2017). In ultra-slow spreading systems, OCCs are principally made of serpentinite and the proportion of gabbro is less important (2% of exhumed gabbros by weight of recovered samples, *MacLeod et al.*, 2009). However, the proportion of gabbro found at ultra-slow spreading ridges remain nevertheless more important than the one found in the Lower Platta unit. Moreover, the occurrence of continent derived ribbons over the exhumed mantle and the sub-continental nature of the mantle rocks suggest that the Lower Platta unit is not yet representing a mature, steady state MOR.

3.3 Implication and outlook

The major difference that can be noted between the two examples is that in the case of the OCC located at the MOR the extrusive magma is interpreted to be emplaced before and after the exhumation of the mantle. In the Lower Platta unit, field observations suggest an emplacement of the magma syn- to post-exhumation of the mantle. There is no evidence of extrusive magma emplaced before the mantle exhumation, apart from the gabbros, which are emplaced at deeper mantle levels before being exhumed to the seafloor (Amman et al. in prep). The second major difference is the presence of continent derived blocks onto the exhumed mantle of the Lower Platta unit. While such blocks are not observed at OCC of MOR, their occurrence may show the proximity of continental crust during the formation of the Lower Platta domain. This is in line with the interpretation of the Lower Platta unit as derived from an OCT of an ultra-distal, magma-poor rifted margin.

The comparison of the structures observed in the Lower Platta unit with those at MOR leads to the question whether mega-mullions formed at OCT and at MOR are controlled by the same processes and if not, how can the two structures be distinguished, and how did the transition between the two occur?

CHAPTER 10: EVOLUTION OF DISTAL AND ULTRA-DISTAL MARGINS

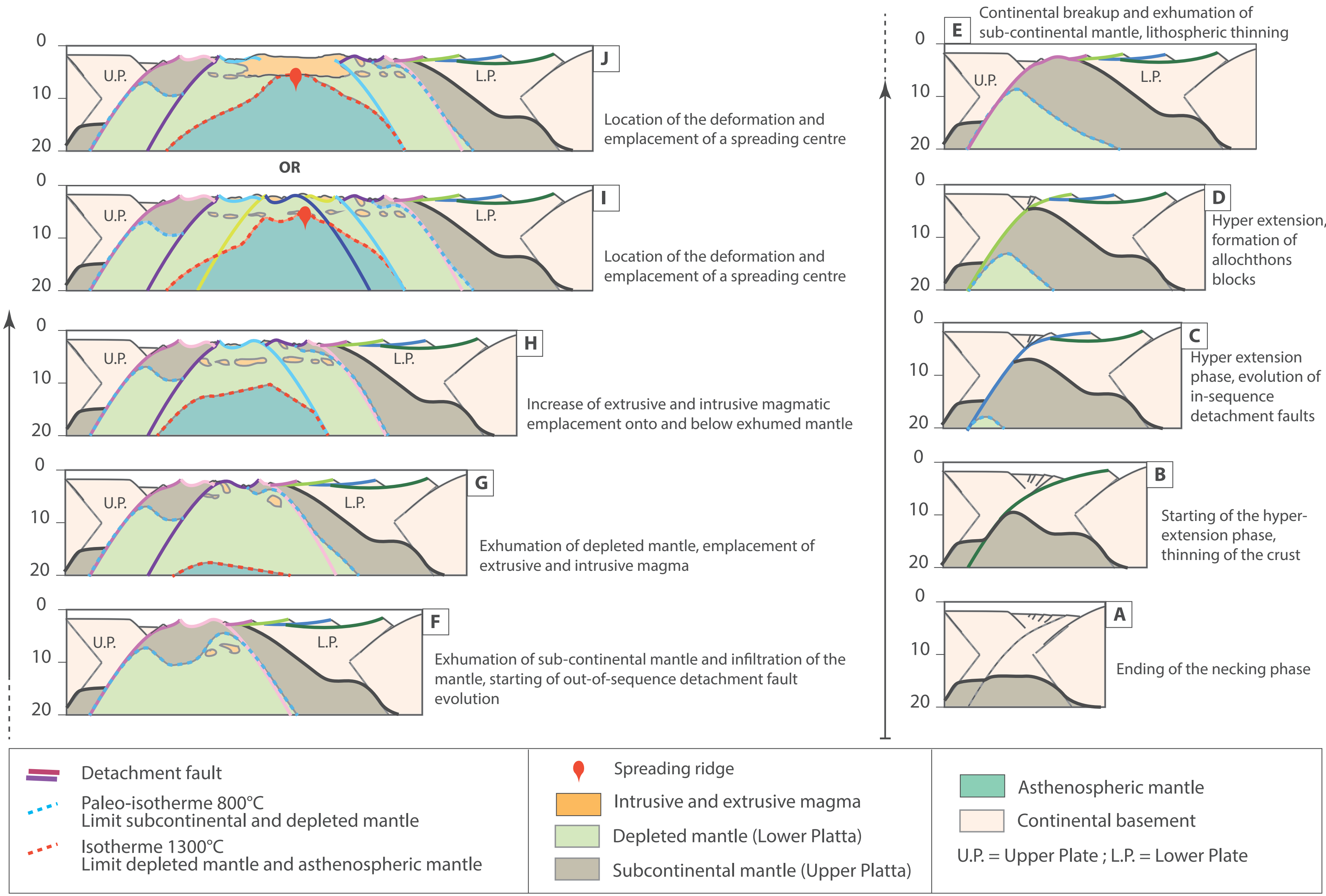
At present, the formation of distal and ultra-distal margins is little understood and many questions remain un-answered. How, when and under what conditions does extreme crustal thinning, mantle exhumation and lithospheric breakup occur and what is the role of detachment faulting and magmatic processes during this final stage of thinning? What is driving lithospheric breakup? How do detachment faults in exhumed mantle domains form, where do they root, how do they accommodate strain and how do they develop in time and space and interact with magmatic additions, and how can detachment faults occurring in the hyper-extended domain be compared with those exhuming mantle in OCTs and MORs? Although my work is based on field observations, there are some observations that help to answer, at least indirectly, to those questions.

1. Evolution of distal margin

1.1 Evolution of hyper-extended domains: field constraints

The Err detachment system described in this study presents a complex in-sequence evolution of at least 4 different detachment faults (Err, Jenatsch, Agnel, Upper Platta detachment fault) (Fig. 9-2A). The observation that the Jenatsch detachment fault truncates the Err detachment fault shows that these faults formed in sequence, indicating a rejuvenation of the faults oceanwards (Fig. 10-1). Based on the work of Pinto et al. (2013; 2015), the Err detachment fault is the first fault along which the fault rocks show Cr and Ni enrichments, indicating that mantle derived fluids were channelled along this fault. Therefore, Pinto et al. (2013; 2015) suggested that this fault was the first to penetrate into the mantle. The more proximal fault, the Bernina and the Campo-Grosina faults described by Mohn et al. (2012), do not show any evidence for coupling, suggesting that these faults did not yet penetrate into the mantle. This suggests that the Grosina and Bernina faults were active while there were still ductile levels in the crust, i.e. the crust was, at the time when these faults were active, thicker than 10-15km. The thinning of the crust during the formation of the distal margin is also recorded in the sedimentary sequence, however, there is unfortunately little constraints on the paleo-bathymetric evolution of the distal margin.

Fig. 10-1: *Evolution of hyper-extended domain to exhumation of the mantle and possible formation of a spreading ridge.* **A:** *Termination of the necking phase.* **B:** *Starting of the hyper-extension phase and first coupling.* **C and D:** *Hyper-extension phase, evolution of in-sequence detachment faults.* **E:** *Continental separation, first exhumation of sub-continental mantle, emplacement of gabbro.* **F:** *Exhumation of sub-continental mantle and infiltration of the mantle, starting of first out-of-sequence detachment fault, emplacement of gabbros.* **G:** *Exhumation of depleted mantle, emplacement of extrusive and intrusive magma.* **H:** *Increase of extrusive and intrusive magmatic emplacement on and underneath exhumed mantle.* **I and J:** *Formation of a spreading ridge.* **I:** *Emplacement of a slow or ultra-slow spreading centre, and evolution on the "flip-flop" model.* **J:** *Emplacement of a normal or fast spreading centre.*



J
Location of the deformation and emplacement of a spreading centre
OR
I
Location of the deformation and emplacement of a spreading centre
H
Increase of extrusive and intrusive magmatic emplacement onto and below exhumed mantle
G
Exhumation of depleted mantle, emplacement of extrusive and intrusive magma
F
Exhumation of sub-continental mantle and infiltration of the mantle, starting of out-of-sequence detachment fault evolution
E
Continental breakup and exhumation of sub-continental mantle, lithospheric thinning
D
Hyper extension, formation of allochthons blocks
C
Hyper extension phase, evolution of in-sequence detachment faults
B
Starting of the hyper-extension phase, thinning of the crust
A
Ending of the necking phase
U.P.
L.P.
0
10
20
Detachment fault
Paleo-isotherme 800°C
Limit subcontinental and depleted mantle
Isotherme 1300°C
Limit depleted mantle and asthenospheric mantle
Spreading ridge
Intrusive and extrusive magma
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Asthenospheric mantle
Continental basement
U.P. = Upper Plate ; L.P. = Lower Plate

Although it is difficult to estimate the crustal and lithospheric thinning associated with detachment faulting there are observations that can provide some insights on how the crust and the lithosphere thinned during detachment faulting. The observation that mantle derived fluids percolated along the Err detachment fault are compatible with the interpretation that this fault penetrated mantle (Err detachment), suggesting a crustal thickness of ≤ 15km. The observation that mantle was exhumed in the footwall of the Lower Platta detachment shows that when this fault was active, the crustal thickness was 0km. Since the same detachment also exhumed infiltrated mantle that had to be at about ≥ 1100°C during infiltration (e.g. *Müntener et al.*, 2009), the mantle lithosphere had to be very thin ≤ 30km during this stage, which is also compatible with the first formation of extrusive MOR basalts (Fig. 10-1). Although not yet proven, we interpret the oceanwards increase of magma over a short distance of less than 10km as a change in polarity of the detachment system and the rise of the lithosphere underneath the distal Lower Platta domain. This would also explain the syn-magmatic normal faulting and the strong increase of the magmatic budget going oceanwards.

1.2 Comparison with active systems undergoing breakup and dynamic models

Unfortunately, there are no present-day analogues, except the northern Red Sea, where lithospheric breakup is about to occur in an Atlantic type rift system. From the Red Sea, no direct observations from the breakup process are available. Ligi et al. (2012) suggested that breakup was forced by magmatic processes, which would exclude the exhumation of mantle. Unfortunately, there is at the moment little direct evidence about how the crust was thinning and the lithosphere ruptured, because of the lack of available data. Present-day MOR may show structural analogies with ultra-distal margins, however, these domains already underwent breakup and can therefore not explain the evolution and conditions occurring during breakup.

Therefore, an alternative way is to compare the results obtained from the field with those of numerical models that are able to produce magma-poor rifted margins. Although these models do not have a resolution as fine as what we observed in the field, at least numerical models are consistent and do not violent physics. The comparison of the observation made on the Err nappe and the numerical modelling of Duretz et al. (2016) are consistent for in-sequence faulting and creation of allochthonous blocks, thinning of the crust and mantle exhumation, and lithospheric thinning (Fig. 10-2).

2. Evolution of ultra-distal domains: interaction of tectonic, magmatic and fluids processes

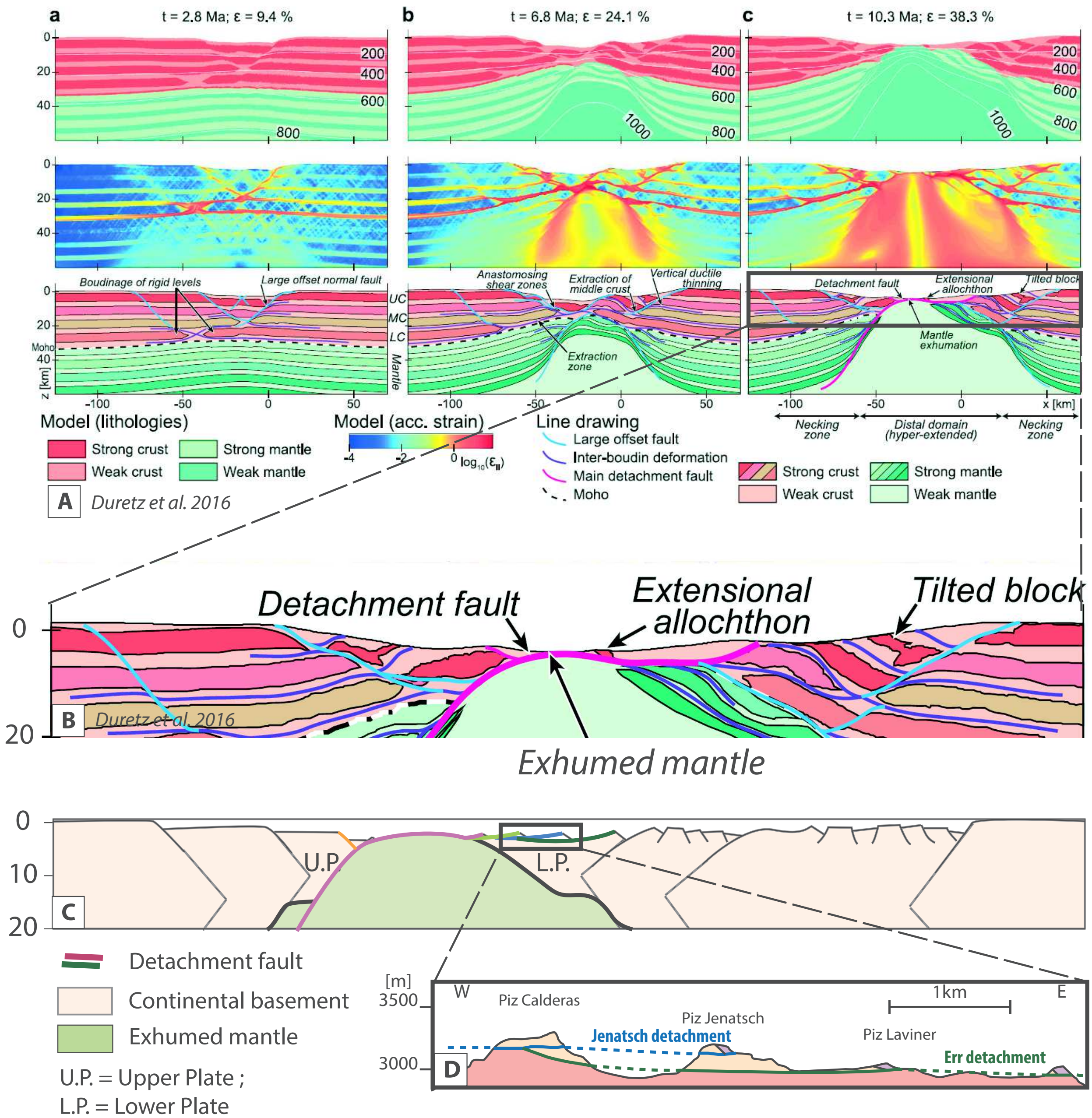


Fig. 10-2: Evolution of hyper-extended domain. **A:** *Time evolution of a model incorporating 9 competent layers (Duretz et al., 2016). «Uppermost panels represent enlargements of the lithological distribution. The panels in the middle correspond to enlargements of the accumulated von Mises visco-plastic strain. Lowermost panels depict line drawings and a geological interpretation of the model results, which emphasize the main features that developed throughout the evolution of the models» (Duretz et al., 2016). (a) Initial extension phase. (b) Model after 24.1% of extension. (c) Final stage of the rifting involving mantle exhumation.* **B:** *Zoom on the line drawing and geological interpretation of the final stage of the rifting (Duretz et al., 2016).* **C:** *General model showing the scale and location of the observation made on the Err nappe.* **D:** *Section of the Err and Jenatsch detachment made on the Err nappe (for mode detail see paper 2, Chapter 3, Part II).*

2.1 Field observations of ultra-distal exhumed mantle domains

Observations from the Lower Platta unit highlight a complex tectono-magmatic and fluid evolution of this ultra-distal domain that seems largely controlled by tectonic process. The magmatic and fluid processes seem to follow and to be controlled by the tectonic evolution.

First mantle exhumation occurred after continental separation leading to the formation of the Upper Platta domain; Fig. 10-3A). At this stage, no magma was extruding at the seafloor. First magma extrusion at the seafloor occurred during the formation of the Lower Platta domain (Fig. 10-3B). The exhumed detachment surface was dissected by later normal faults that created, together with the damage zones of the detachment faults privileged pathways for magma and fluids. Field observations show that tectonic processes seem to control emplacement and distribution of magma (for more details see Paper 3, Chapter 8). Hydrothermal systems appear to be preferentially linked to locations where syn-tectonic magma was emplaced, showing similarities to present-day OCC. Other sites showing similar observations like those made in the Lower Platta unit are the Chenaillet ophiolites in SE France (*Manatschal et al.*, 2011) and other ophiolites exposed in the Western Alps and Corsica (*Lagabrielle et al.*, 2015).

2.2 Comparison to present-day ultra-slow spreading ridges

At modern ultra-slow spreading ridges oceanic crust is formed by exhumed mantle and magmatic additions. Models suggest that at ultra-slow spreading ridges, Oceanic Core Complex formed at stages of magma-starvation. MacLeod et al. (2009) described the life cycle of an OCC (Fig. 10-3D). At an ultra-slow spreading centre, a minor volcanic activity created a thin, strongly structured oceanic crust. Onset of normal faulting marks the initial stages of OCC formation. At a mature stage of the OCC, infiltration of magma modifies the strength and rheology of the ridges, and initiates the accretion that results into the formation of magmatic oceanic crust. Such a cyclic evolution is not compatible with the observations made in the Lower Platta unit where magmatic processes and exhumation appear to occur simultaneous. Indeed, the principal difference between the life cycle of an Oceanic Core Complex and the Lower Platta detachment is that the formation of the OCC occurs before and during the emplacement of magma. In the Lower Platta unit, the magma emplacement took place after the exhumation but during high-angle faulting that transected the exhumed mantle surface, and further oceanwards also during exhumation. However, there is no evidence of a pre-existing oceanic crust prior to mantle exhumation. But without considering the initial stage (oceanic crust) of the life cycle of a mega-mullion described from a present-day MOR, all the rest is very similar to what is observed in the Lower Platta unit. Therefore it can be assumed that the major difference between observations made at a MOR and the OCT is that MOR are at a steady state, while OCTs are not at a steady state but are about to develop into a system that evolves into a steady state regime. This would mean that the Lower Platta unit marks the transition into a spreading centre, and that the elevated magmatic budget observed in the most distal Lower Platta unit (around the Piz Platta area) would be the onset of seafloor spreading. If so, this would also mean that subduction is

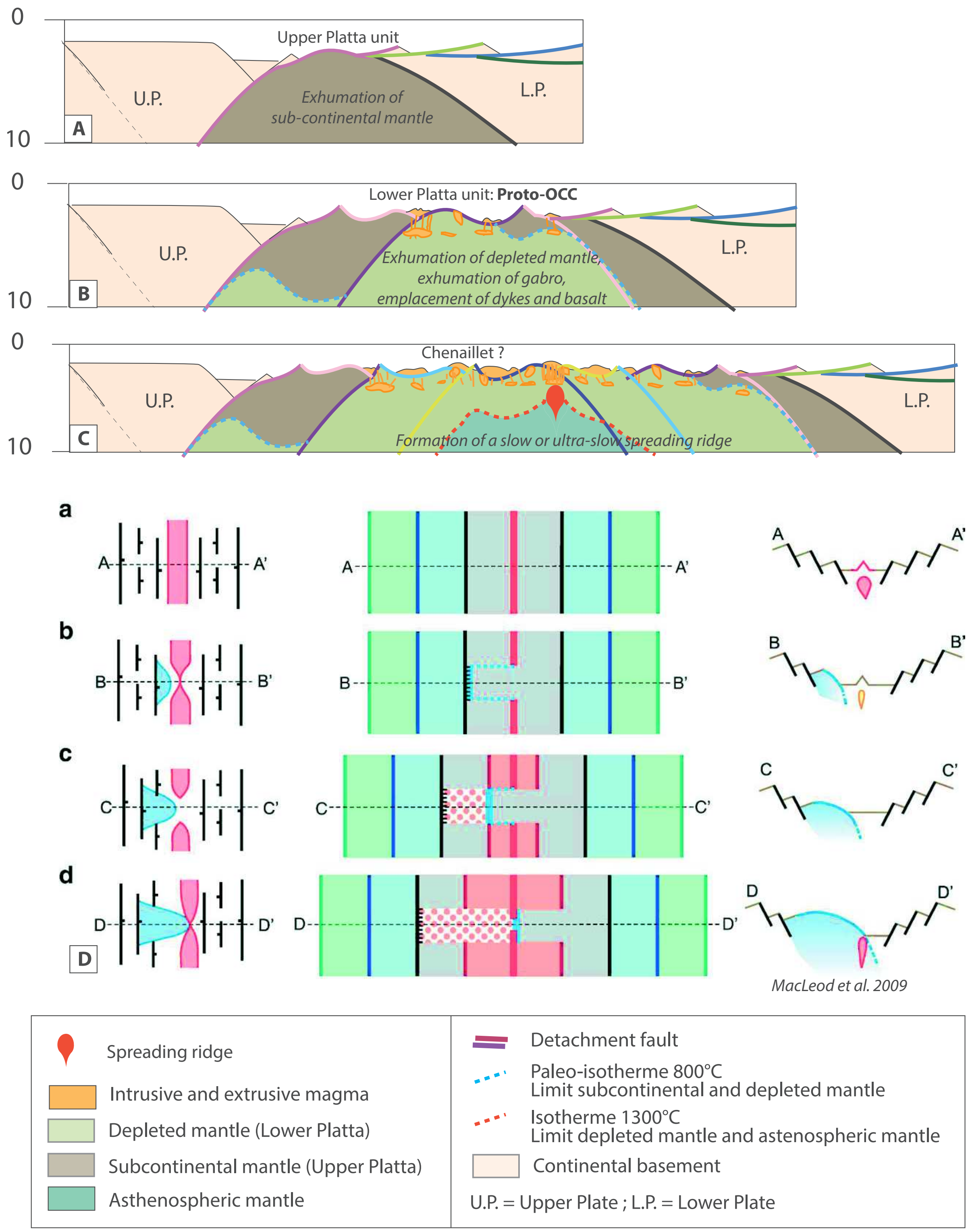


Fig. 10-3: *Comparison between a proto-OCC in an OCT with an OCC at a MOR.* **A:** *Exhumation of sub-continental mantle associated to the Upper Platta unit.* **B:** *Exhumation of depleted mantle associated to the Lower Platta unit, exhumation of gabbro, emplacement of dykes and basalts that transect and cover exhumed serpentinised peridotites. Formation of a proto-OCC.* **C:** *Evolution of the system and increase of magmatic emplacement, leading to the formation of a spreading ridges, which could be the start of a new life cycle leading to the formation of an OCC present in D according to MacLeod et al. (2009).* **D:** *«Cartoon illustrating the life cycle of oceanic core complex. Left column: schematic illustration observed seafloor geology, where red indicates the neovolcanic zone, blue the emerged detachment fault, and black line are other normal faults. Centre: schematic plan view of plate tectonic development. Right: vertical sections through the left-hand diagrams» (MacLeod et al., 2009).*

preferentially initiated at this transition with the first oceanic crust (see Chapter 11).

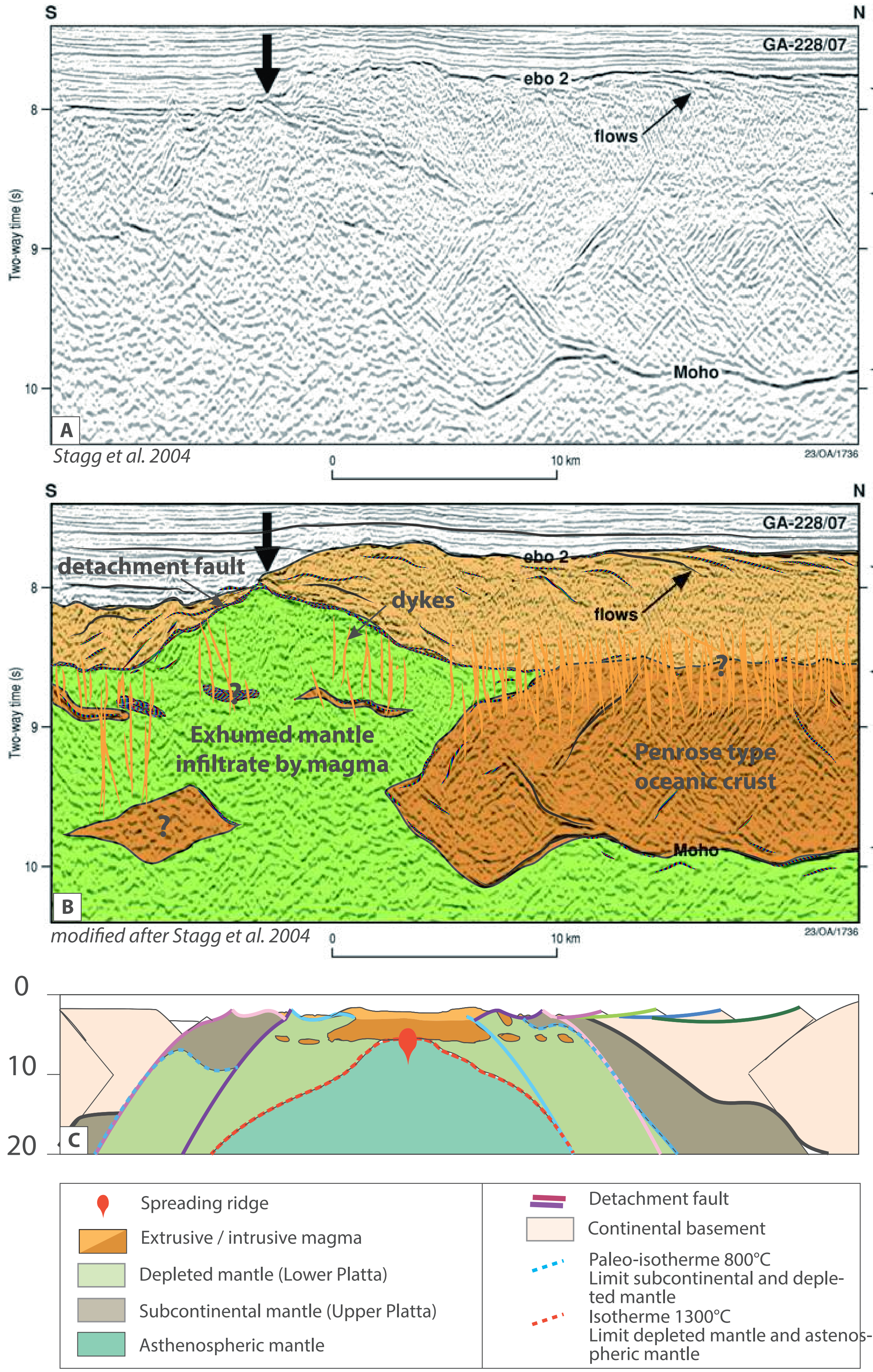
In figure 10- 1 and 2 a schematic model of the transition from exhumed mantle in the ultra-distal margin to a first spreading centre is shown. Field observations suggest that this transition is discrete and that the first magmatic additions that are related to lithospheric breakup are emplaced over previously exhumed mantle. This observation is supported by seismic sections imaging the transition to normal oceanic crust at the Enderby and Mac Robertson Lands, East Antarctica (*Stagg et al.*, 2004) (Fig. 10-4). Similar observations are made by Gillard et al. 2017 presenting newly released high-resolution seismic reflection profiles that image the complete transition from unambiguous continental to oceanic crusts.

2.3 Implications and outlook

At present, little is known about how continents separate, lithosphere breaks and oceans form. This is mainly due to the lack of observations and data. The study of the Err and Platta nappes and the restoration of the pre-Alpine Jurassic architecture and their link to crustal thinning, mantle exhumation and onset of magmatic extrusions is a key to understand these processes. This work enabled to assess the main structures, to describe the main architecture of these ultra-distal domains and to investigate the related processes.

More detailed work is necessary to understand the processes and answer the key questions, however, it will be clear that these next steps can be built on the work presented in this thesis. Although the present work may not yet enable to quantify breakup processes, it provides at least a contribution to established key observations and gives access to a so far unique field laboratory where the processes leading to crustal separation and lithospheric breakup can be observed.

Fig. 10-4: *Transition from exhumed mantle domain to a spreading ridge.* **A:** *Zoom on a seismic detail from the line GA-228/07 showing the interpreted continent-ocean boundary zone east of 58°E (continental crust to the south) made by Stagg et al. (2004). It shows the step up from continental/ transitional crust on the left to oceanic crust on the right, and the abrupt southward termination of the Moho reflection beneath the inboard edge of oceanic crust at ~10 s TWT. Stagg et al. (2004) described the horizontal partitioning of the oceanic crust into a thin upper layer of short, seaward-dipping flows; semi-transparent upper-middle crust; lower, highly-reflective crust; and a high-amplitude, continuous Moho reflection visible on the seismic section.* **B:** *Interpretation based on results from this work of seismic line GA-228/07 presented by Stagg et al. (2004) showing the transition from exhumed mantle infiltrated by magma to Penrose type oceanic crust.* **C:** *Schematic representation of the transition from a magma-poor rifted margin to a steady state spreading ridge.*


S
N
GA-228/07
ebo 2
flows
Moho
Two-way time (s)
8
9
10
transparent
reflective
A
Stagg et al. 2004
0
10 km
23/OA/1736
S
N
GA-228/07
detachment fault
ebo 2
dykes
flows
?
Exhumed mantle
infiltrate by magma
Penrose type
oceanic crust
Moho
Two-way time (s)
8
9
10
transparent
reflective
B
modified after Stagg et al. 2004
0
10 km
23/OA/1736
0
10
20
C
Spreading ridge
Extrusive / intrusive magma
Depleted mantle (Lower Platta)
Subcontinental mantle (Upper Platta)
Asthenospheric mantle
Detachment fault
Continental basement
Paleo-isotherme 800°C
Limit subcontinental and depleted mantle
Isotherme 1300°C
Limit depleted mantle and asthenospheric mantle

CHAPTER 11: REACTIVATION OF A DISTAL MARGIN

A prerequisite to study the architecture and processes controlling the evolution of ultra-distal, magma-poor rifted margins in orogens is to understand the reactivation and emplacement processes. Therefore, an important part of my study was dedicated to understand the Alpine tectonic evolution of the studied area with the aim of restoring the former rift structures and to distinguish between Alpine and pre-Alpine structures. Main questions addressed in my study were: Why are the remnants of the distal Adriatic margin so well preserved? What are the main Alpine structures and how far were they controlled by structures inherited from the former rifted margin?

In my work I was particularly interested to understand the reactivation of the distal and ultra-distal rifted margin preserved in the Err and Platta nappes and to investigate how the main rift structures/contacts have been used during initiation of the subduction and subsequent collision.

1. Reactivation of an OCT: field observations

Reactivation of the former Adriatic margin occurred by the emplacement of main west-vergent thrusts linked to the closure of Meliata-Vardar domain (*Froitzheim et al.*, 2008; *Mohn et al.*, 2011; *Ferriere et al.*, 2016). Thus, the former distal margin was first reactivated in an external part of the Eo-Alpine orogen, prior to the onset of subduction of the Alpine Tethys that initiated during latest Cretaceous time (*Froitzheim et al.*, 1994; *Froitzheim and Manatschal*, 1996; *Froitzheim et al.*, 2006; *Mohn et al.*, 2012). Thus, subduction initiated, when the OCT was already stacked into the Austroalpine nappe stack. When and where subduction initiated exactly is difficult to determine, however, since the Platta nappe forms the hanging wall of the south-directed subduction and the associated accretionary wedge, the subduction had to form in front and dip underneath the Err and Platta domains. The present-day contact with the European units is formed by the Turba mylonite zone , which truncates the nappe stack (*Nievergelt et al.*, 1996). Thus, the subduction plane is not directly exposed and can therefore not be directly investigated in the study area.

An important observation made in the Austroalpine and South Penninic nappe stack is that some thrusts within the nappe stack juxtapose remnants derived from different rift domains (proximal margin over distal margin or exhumed mantle over European units), while others juxtapose rocks derived from the same domain or the same basin, suggesting that there are thrusts that accommodated a lot of deformation and thrusts that were of minor importance. In my study I developed a method that enables to hierarchize thrusts into 1st, 2nd and 3rd order structures. 1st order thrusts correspond to major nappe displacement along the Albula-Zebru movement zone and the Lunghin-Mortirolo movement zone; 2nd order thrusts separate paleogeographic domains of the margin; and 3rd order thrusts separate sub-unit derived from the same paleo-geographic domain. The study of the Err and Platta nappes enabled to demonstrate that most of the Alpine structures reactivated inherited rift structures of the former distal margin. The approach described in Paper 1 (Chapter 6) consists in mapping reactivated distal domains by using diagnostic criteria to identify preserved pre-Alpine structures within units separated by 3rd order thrusts. With this approach, it is possible to propose more precise restorations of complex areas. We show that serpentinised peridotites play a major role in the reactivation of 3rd and 2nd order thrusts. Based on the units accreted in the nappe stage, we can determine that the depth of decollement had to be located in the uppermost few kilometres, which is compatible with serpentinization of the mantle playing a major role during reactivation of the distal margin.

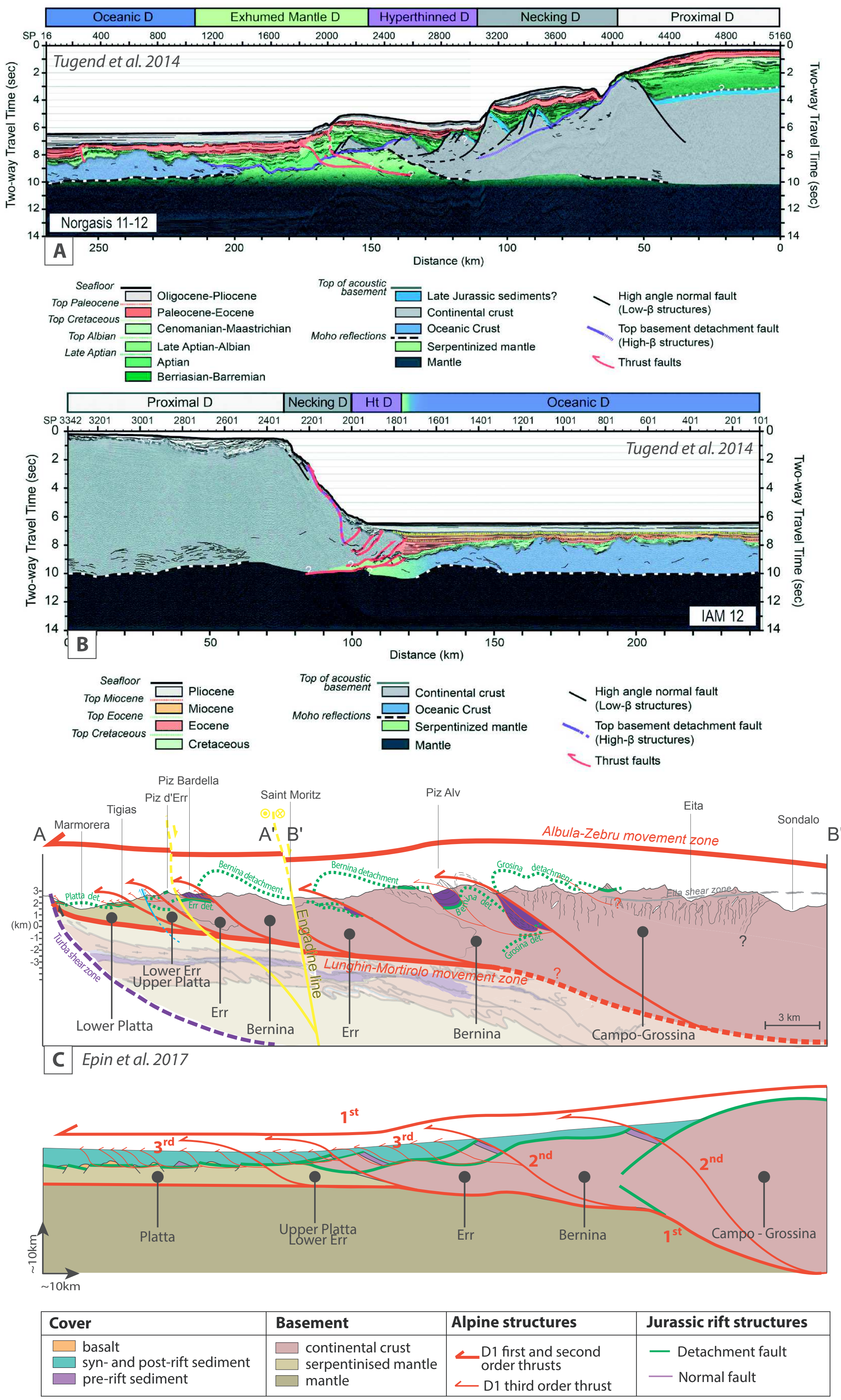
2. Comparison to present-day reactivation

Indeed, serpentinised layers seem to play an important role during reactivation, not only for the 2nd and 3rd order structures, but also for the localization of 1st order deformation structures. Beltrando et al. (2014) discussed the importance of serpentinization of the mantle for the reactivation of distal domains and oceanic domain in the HP metamorphic belt in the Alps. Chenin et al. (2017) discussed, at a larger scale, the possible importance that the serpentinization front may have played as a decoupling level between the subducted and accreted material during subduction. Based on the study of the Bay of Biscay and the Pyrenees, Tugend et al. (2014) investigated the progressive reactivation of a hyper-extended rift system. Their interpretation of the Western Approach Margin shows important compressional reactivation of the transition zone separating exhumed mantle and hyper-extended crust (Fig. 11-1). This deformation zone forming the Trevelyan structure has been interpreted to root in the serpentinised upper mantle (*Tugend et al.*, 2014 and reference therein). This reactivated structure can be compared to the 2nd order Alpine thrust separating the Upper Platta and Lower Err unit (hyper-extended domain and first sub-continental exhumed mantle) in the hanging wall from the Lower Platta unit (exhumed mantle domain) in the footwall (Fig. 11-1).

3. Implications and outlook

3rd order deformation structures are generally not imaged or investigated due to the high resolution required to resolve such structures in seismic sections. The study of these structures in the Err and Platta nappes enables to better understand the reactivation of distal margins, and help to better interpret the reactivation of distal margins at high resolution 3D seismic blocks.

The 2nd order deformation can be resolved in seismic images. Our interpretation of the 2nd order major Alpine reactivation between the Lower Err and the Upper Platta/Lower Platta



Oceanic D
Exhumed Mantle D
Hyperthinned D
Necking D
Proximal D
Tugend et al. 2014
Norgasis 11-12
Two-way Travel Time (sec)
Distance (km)
A
Seafloor
Top Paleocene
Top Cretaceous
Top Albian
Late Aptian
Oligocene-Pliocene
Paleocene-Eocene
Cenomanian-Maastrichian
Late Aptian-Albian
Aptian
Berriasian-Barremian
Top of acoustic basement
Moho reflections
Late Jurassic sediments?
Continental crust
Oceanic Crust
Serpentinized mantle
Mantle
High angle normal fault (Low-β structures)
Top basement detachment fault (High-β structures)
Thrust faults
Proximal D
Necking D
Ht D
Oceanic D
Tugend et al. 2014
IAM 12
B
Top Miocene
Top Eocene
Pliocene
Miocene
Eocene
Cretaceous
Piz Bardella
Piz d'Err
Tigias
Marmorera
Saint Moritz
Piz Alv
Eita
Sondalo
A
A'
B'
Albula-Zebru movement zone
Bernina detachment
Grosina detachment
Platta det.
Err det.
Engadine line
Turba shear zone
Lunghin-Mortirolo movement zone
Lower Err
Upper Platta
Lower Platta
Err
Bernina
Campo-Grossina
3 km
C
Epin et al. 2017
1st
2nd
3rd
Platta
Upper Platta
Lower Err
Err
Bernina
Campo - Grossina
~10km
Cover
basalt
syn- and post-rift sediment
pre-rift sediment
Basement
continental crust
serpentinised mantle
mantle
Alpine structures
D1 first and second order thrusts
D1 third order thrust
Jurassic rift structures
Detachment fault
Normal fault

Fig. 10-5: *Interpretation of the* **A:** *Norgasis 11-12 and* **B:** *IAM12 proposed by Tugend et al. (2014) compared to* **C:** *the restoration of the Adriatic margin based on the classification of the deformation in 1st, 2nd, and 3rd order thrusts (Epin et al., 2017).*

domain (interpreted as a 2nd order thrust), and between the Middle Err and Lower Err (2nd or 3rd order thrust; for more detail see Paper 2, chapter 7), change the perception of the distal domain as well as the final width of the margin. Indeed we assumed that the hyper-extended domain (Middle and Lower Err- Upper Platta) and the exhumed mantle domain (Lower Platta unit) are well preserved (only affected by 3rd order deformation), because the reactivation was localized between these two domains along weak zones. As proposed by Beltrando et al. (2014), these thrusts could sole out in the serpentinised mantle underlying the distal margin. This serpentinised layer can also play as a decoupling layer between the Lower Platta unit and the units that went into subduction. However, since the base of the Platta nappe is not exposed, it is not possible to confirm that the serpentinization front controlled the onset of subduction.

Conclusions

Thanks to fossil analogues of hyper-extended and exhumed mantle domains, it was possible to highlight processes that are controlling the transition from final rifting to continental separation, to lithospheric breakup leading to the formation of a new plate boundary and its later reactivation. This study focused on 3 major aspects: 1) the reactivation of a distal margin and how it is preserved in the present-day Err and Platta nappes: 2) the architecture and evolution of a hyper-extended domain; and the 3) architecture and evolution of an exhumed mantle domain. The main results of my PhD can be summarized as follow:

1) **Defining rift inheritance and describing its role during reactivation:**

- Characterization of diagnostic criteria to describe rift inheritance of a former ultra-distal magma-poor rifted margin includes characteristic fault rocks (cataclasites and gouges) with a mantle derived fluid signature, and tectono-sedimentary breccias that rework footwall material and grade up-section into late syn- and post-rift sediments.
- Development of a methodology which enables to map rift related detachment faults, analyzing their role during reactivation and formation of a thrust stack, and defining first, second and third order thrust systems.
- Definition of the importance of rift-inherited structures for the localization of the deformation during a subsequent collisional reactivation of an OCT.
- The results of this study enable to better define the Alpine and pre-Alpine deformation history of the Err and Platta nappes and may help, in a more general way, to better identify remnants of former distal margins in orogenic systems.

2) **Architecture of detachment systems in hyperextended crust and their role in continental thinning**

- The current described detachment system can be defined by different detachment faults that developed in-sequence (Err, Jenatsch, Angel and Upper Platta detachment faults). The sequential evolution of these faults allows to interprete the detachment system by the rolling hinge model.
- The occurrence of inherited weaknesses such as Permian basins and Triassic pre-

rift evaporites results in a strong pre-structuration of the extended domain leading to the local occurrence of lateral ramps of the detachment system and complexities in the hanging wall blocks due to gravitational movements.

- The overall observations made in the Err nappe allow to describe how extensional detachments systems can explain the final rift evolution preceding mantle exhumation, and how hyper-extended continental wedges are formed.

3) **Polyphase tectonic, magmatic and fluid processes related to mantle exhumation in ultra-distal rifted margins**

- Detailed mapping of parts of the Platta nappe enabled to document the top basement architecture of an exhumed mantle domain and to investigate its link to later, rift/oceanic structures, magmatic additions and hydrothermal fluid systems.
- The deformation history is polyphase with mantle exhumation along exhumation faults overprinted by later high-angle normal faults.
- The geometry of detachment faults created topographic highs of exhumed mantle, sealed by late post-rift sediments.
- Normal fault offsetting the exhumed surfaces and the damage zone of the detachment system represent pass ways for syn-tectonic magma as well as for hydrothermal fluids.
- Basalts are emplaced over exhuming or exhumed mantle surfaces
- Gabbros were emplaced at deeper levels and have been subsequently exhumed at the seafloor where they are overlain by younger extrusive magmatic additions or sediments.
- Damage zones of detachment faults represent important pass ways for fluids and are linked to ophicalcitization, and mineralizations.

In conclusion, the main results of my PhD, which are essentially based on a field approach, enabled to improve the knowledge of magma-poor, ultra-distal rifted margins and its transition to first oceanic crust. These new observations enable to discuss the processes associated to continental separation, lithospheric breakup and onset of seafloor spreading. The observations have to be compared to observations made at other fossil examples and up-scaled and integrated in the interpretation of seismic and other geophysical data, which will be part of my post-doctorate project.

Remaining questions and outlooks

This study addressed three major themes, and in each of the themes, research work was guided by questions.

The first theme was the description of hyper-extended domains and the key questions were: How, when and under what conditions does extreme crustal thinning occur and how do detachment faults thin the crust and eventually exhume mantle, where do these structures root at depth, how do they accommodate strain and how do they develop in time and space?

The second theme was based on the study of an exhumed mantle domain and the key questions were: What is the architecture of an exhumed mantle domain, how do tectonic and magmatic processes interact during their formation, what is the role of fluids during exhumation and how is final lithospheric breakup achieved?

The third theme was based on the role of inheritance especially during compressional reactivation. The key question addressed in this part was: What is the role of inheritance during extension and reactivation of distal margin?

In my thesis, I was able to show some results that enable to answer to some of these questions based on new field observations. However, the study of the remnants of distal margins exposed in the Err and Platta nappes also resulted in new questions such as:

Can the nature of basement highs in ultra-distal margins be correctly predicted?

Seismic sections of ultra-distal margins highlight complex architectures that are difficult to interpret. Well described field examples that can be used as analogues are missing so far. It would be interesting to develop synthetic seismic sections of the different field analogues to define the seismic characteristics of the different examples, including a classification of the different type of basement highs that can be found at ultra-distal magma-poor rifted margins.

What is the influence of the complex 3D architecture of ultra-distal margins on the deposition of sediments and circulation of fluid systems?

Field observations show the important topography across the ultra-distal domain that is mainly controlled by the tectonic and magmatic regime of these domains. After the structural investigation made on the Err and Platta nappes, a more focused study on the sedimentary architecture and fluid interaction in the Err and Platta nappes remains to be developed.

What is the link between the detachment faults occurring in the hyper-extended domain and in the exhumed mantle domain?

The hyper-extended domain and exhumed domain is clearly controlled by detachment faults. The transition from the hyper-extended domain to exhumed domain seems to be controlled by detachment faulting. How this transition occurs, and whether it corresponds to the evolution of one detachment fault or the formation of several new detachment faults is unclear. To investigate this question, high resolution seismic sections that image across this transition may help to understand the role of detachment faults in exhuming subcontinental mantle.

How does the transition from mantle exhumation to the establishment of a stable spreading centre occurr?

The exhumed mantle domain investigated in the Lower Platta nappe presents a lot of similarities with an Oceanic Core Complex, without being identical. The Lower Platta nappe records the transition from an exhumed mantle domain in an OCT to the formation of an ultra-slow-spreading centre. To try to better understand the transition from an exhumed mantle domain to a spreading centre (fast, slow, or ultra-slow), investigation of high resolution seismic sections through an ultra-distal margin can help to understand this domain. Present-day, high resolution seismic data enable to image new structures never observed before (see Gillard et al. 2018) that can be compared to field observations made in the Lower Platta nappe, and in the Bonassola area (Italie, Decarlis et al. under review) and may eventually enable to propose new models to explain lithospheric breakup at magma-poor rifted margin.

How do ultra-distal rift structures influence the location of the deformation during initiation of subduction and collision?

The initiation of the subduction in the case of the Alpine orogeny is largely debated. More detailed work is necessary to investigate where and when this subduction initiated and how it was controlled by the inherited margin architecture and the presence of serpentinization during reactivation.

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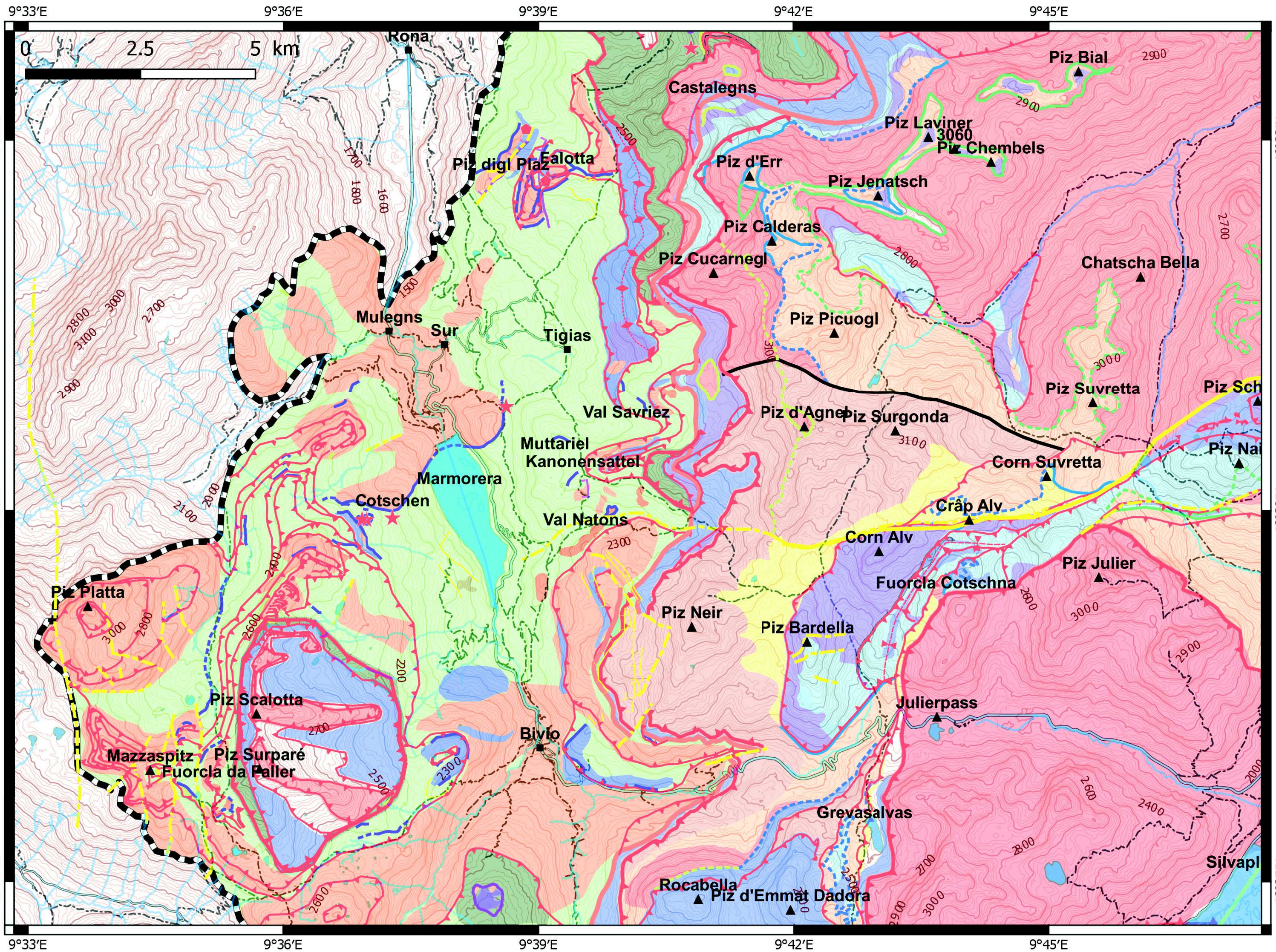
ANNEX

Annex 1.1.1
Geological map of the Err-Platta nappes

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schalteger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



BASEMENT LITHOLOGIES

Bernina nappe
- basement

Err nappe
- Granite (Albula)
- Polymetamorphic basement
- Volcano-sedimentary sequence (Neir basin)

Platta nappe
- Basalt
- Gabbro
- Subcontinental mantle (Upper Platta)
- Depleted mantle (Lower Platta)
- Mines in sediments
- Mines in peridotites

SEDIMENTARY LITHOLOGIES

post-rift
- Radiolarian Cherts, Aptychus and Palombini Fms. (Malm to Cretaceous)

syn-rift
- Saluver and Bardella Fms. (Dogger)
- Agneli Fm. (Lias)

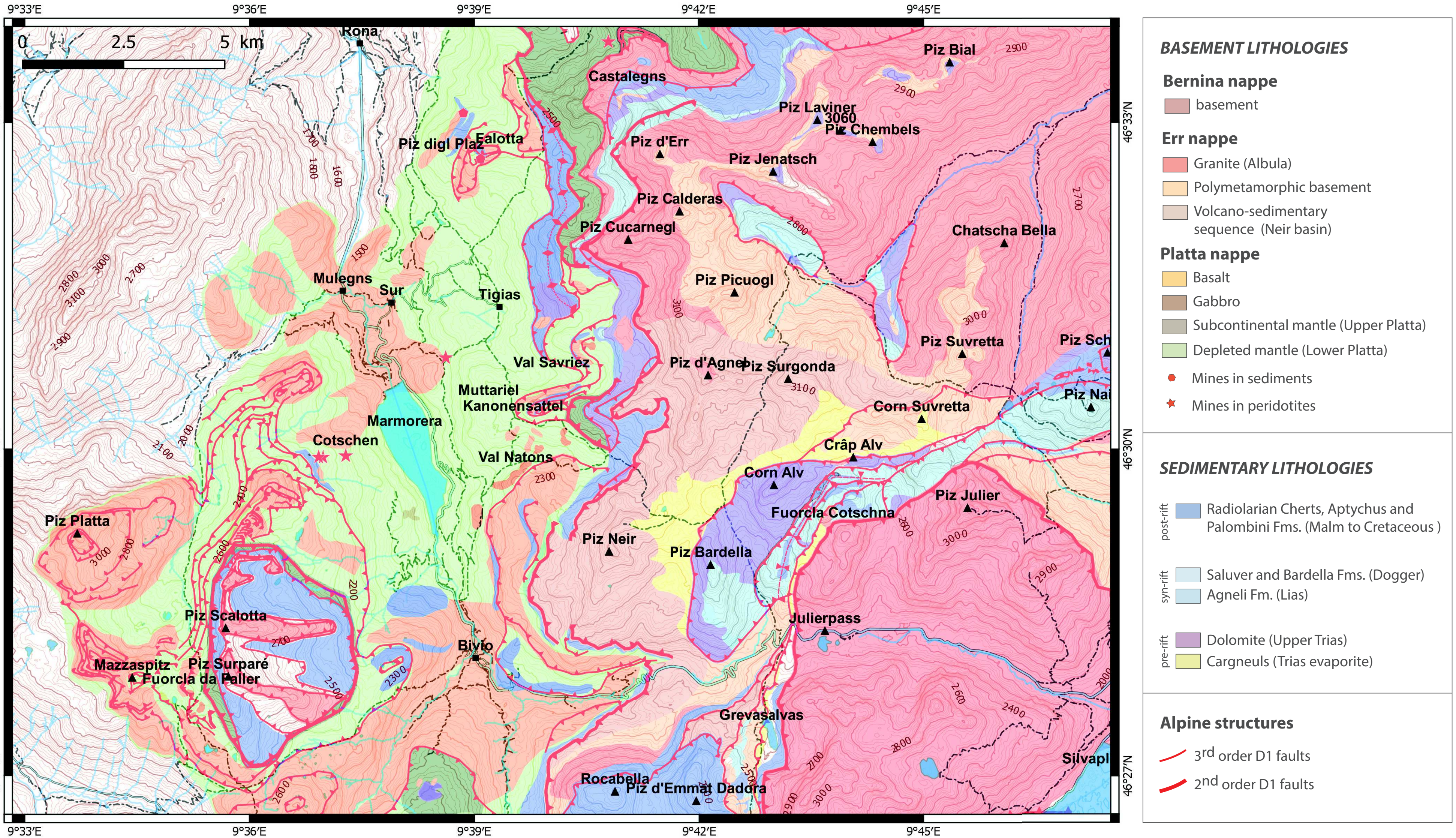
pre-rift
- Dolomite (Upper Trias)
- Cargneuls (Trias evaporite)

Pre-Alpine structures
- Jurassic Normal faults
- Jurassic Upper Platta detachment
- Jurassic Lower Platta detachment
- Jurassic Agnel detachment
- Jurassic Jenatsch detachment
- Jurassic Err detachment
- Permian normal fault

Alpine structures
- Late faults
- Turba normal fault
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults
- 1st order D1 faults

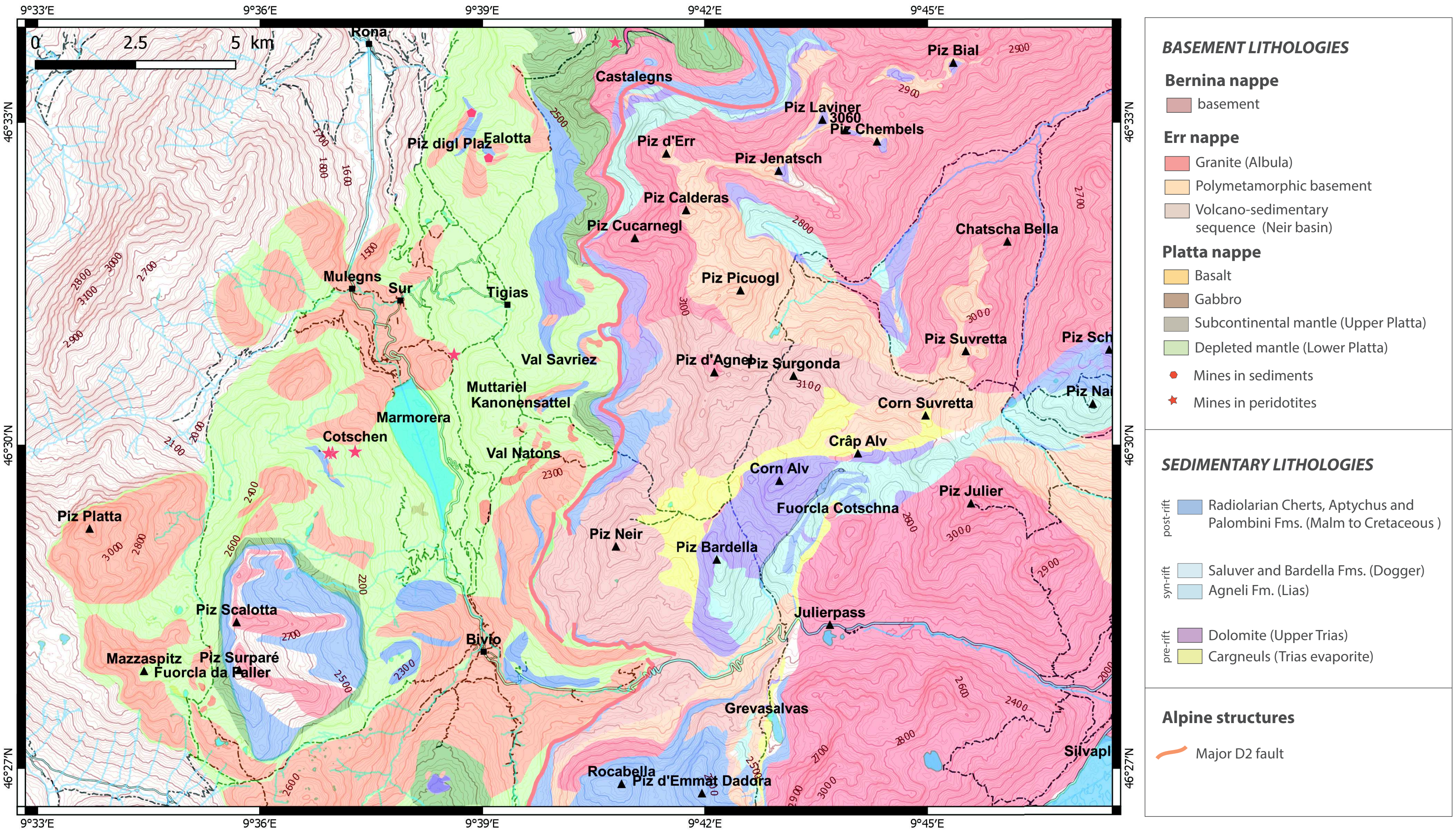
Annex 1.1.2
Geological map of the Err-Platta nappes
Highlighting the D1 deformation

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schalteger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



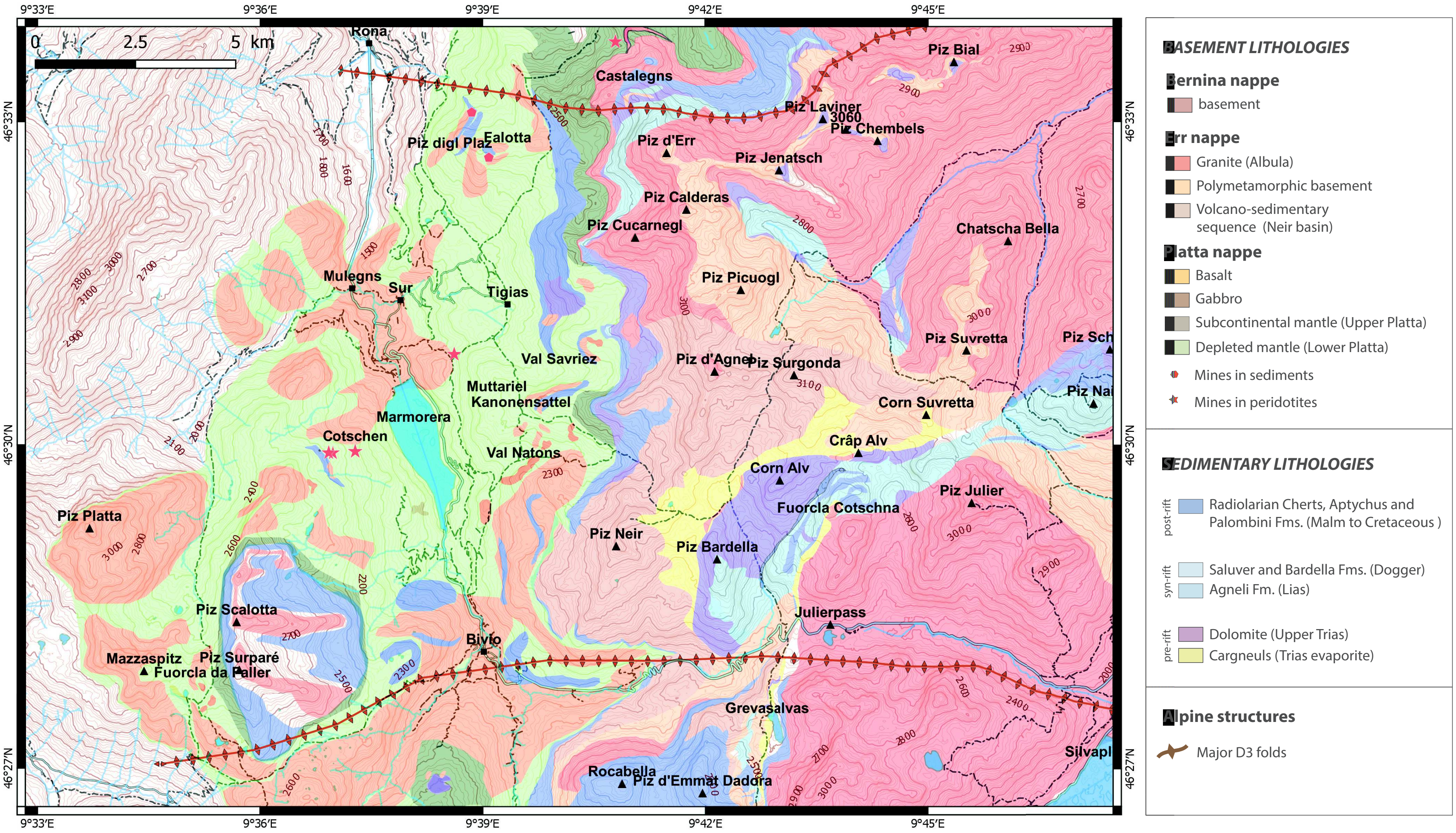
Annex 1.1.3
Geological map of the Err-Platta nappes
Highlighting the D2 deformation

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schalteger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



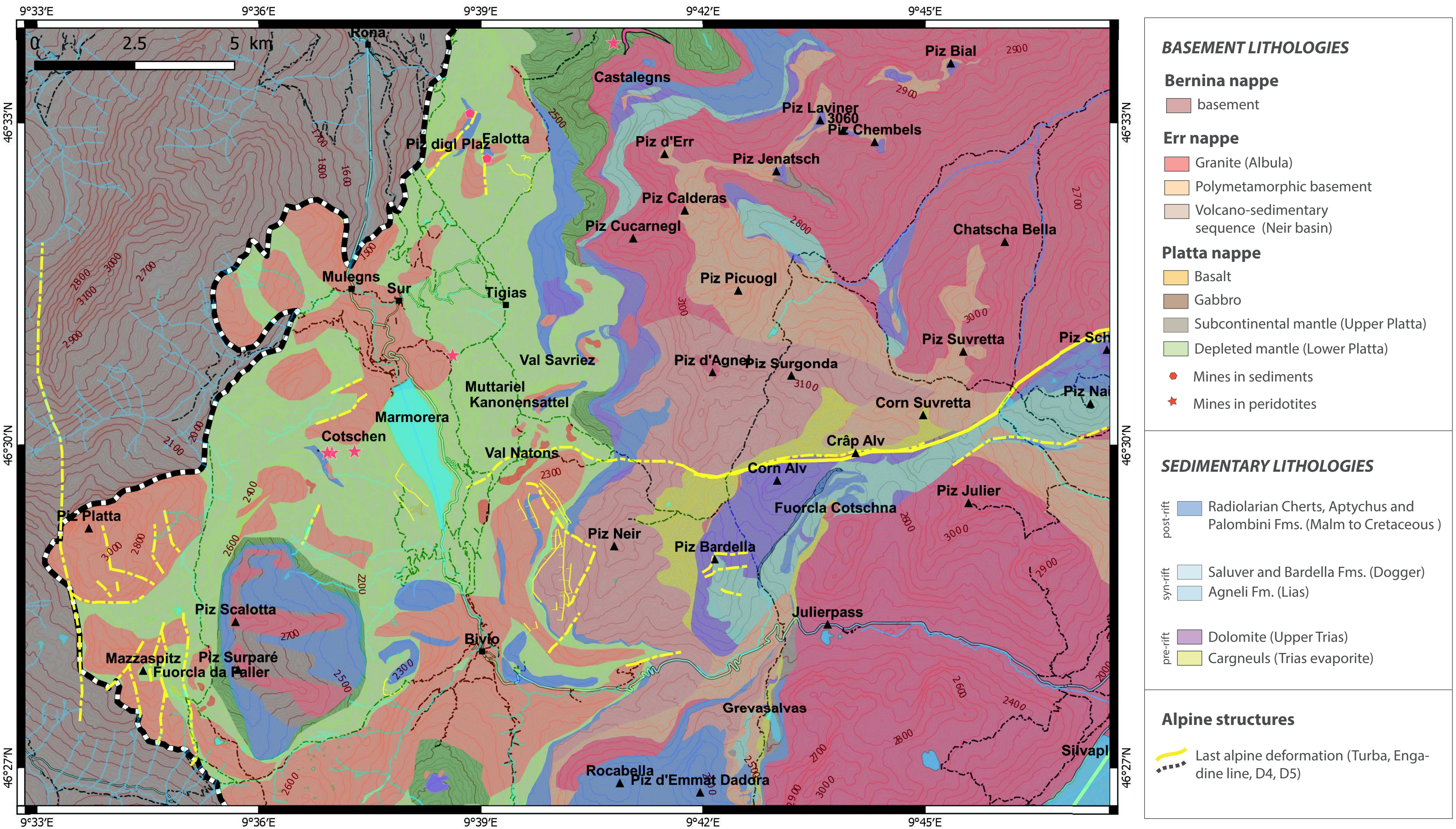
Annex 1.1.4
Geological map of the Err-Platta nappes
Highlighting the D3 deformation

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schalteger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



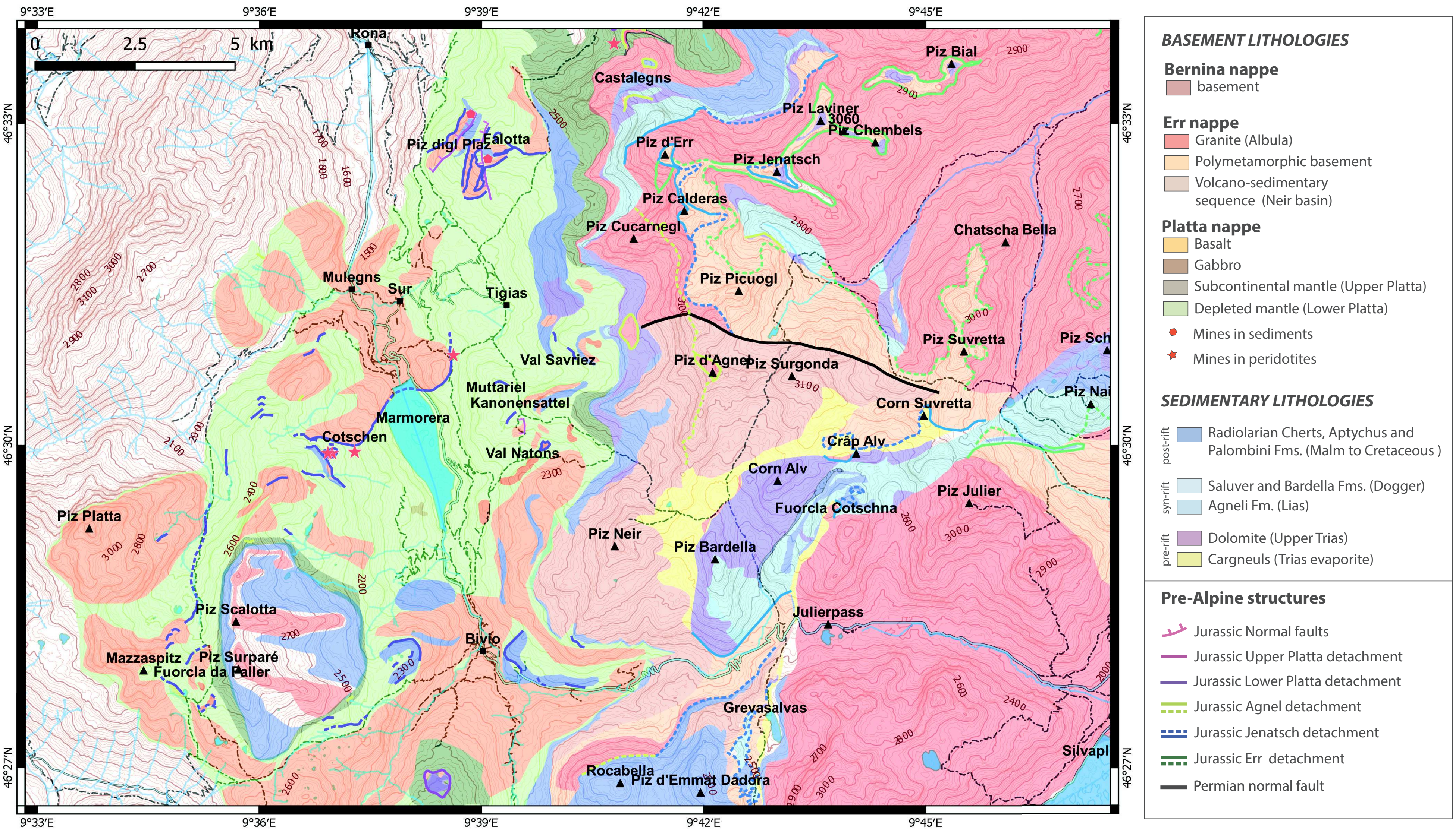
Annex 1.1.5
Geological map of the Err-Platta nappes
Highlighting the last Alpine deformation

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schalteger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



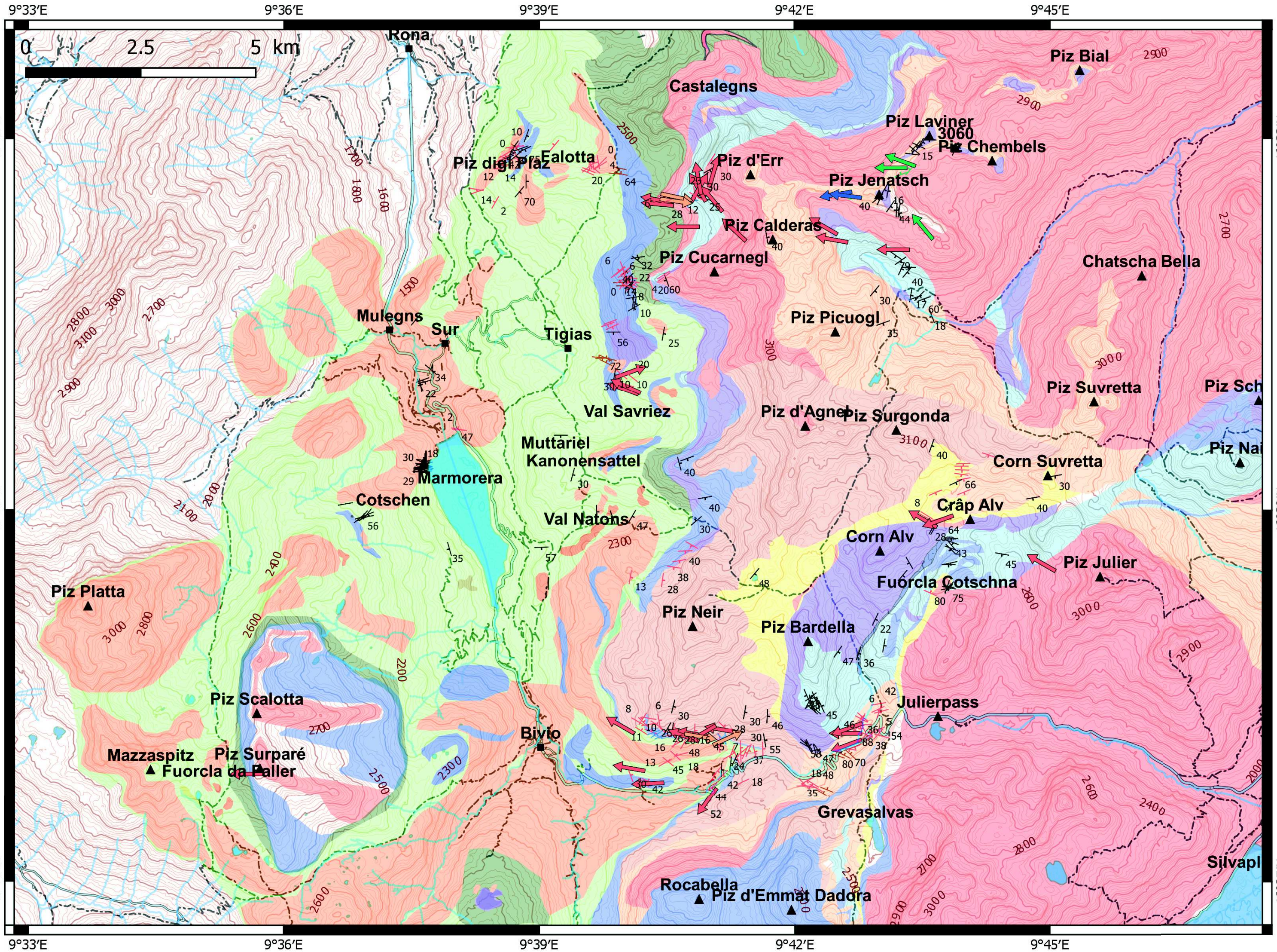
Annex 1.1.6
Geological map of the Err-Platta nappes
Highlighting the pre-alpine structures

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schalteger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



Annex 1.1.7
Geological map of the Err-Platta nappes
Highlighting the structural data

modified after Staub,1916; Cornelius, 1932; Staub, 1946; Liniger, 1992; Dietrich, 1969; Froitzheim and Eberli 1991; Handy 1993-1996; Manatschal and Nievergelt 1997, Peters, 2005; 2007; Desmurs et al. 2002; Schaltegger et al. 2002; Masini et al. 2011; Müntener et al. 2009; and my observations



BASEMENT LITHOLOGIES

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- Gabbro
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- Depleted mantle (Lower Platta)
- Mines in sediments
- Mines in peridotites

SEDIMENTARY LITHOLOGIES

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- Radiolarian Cherts, Aptychus and Palombini Fms. (Malm to Cretaceous)

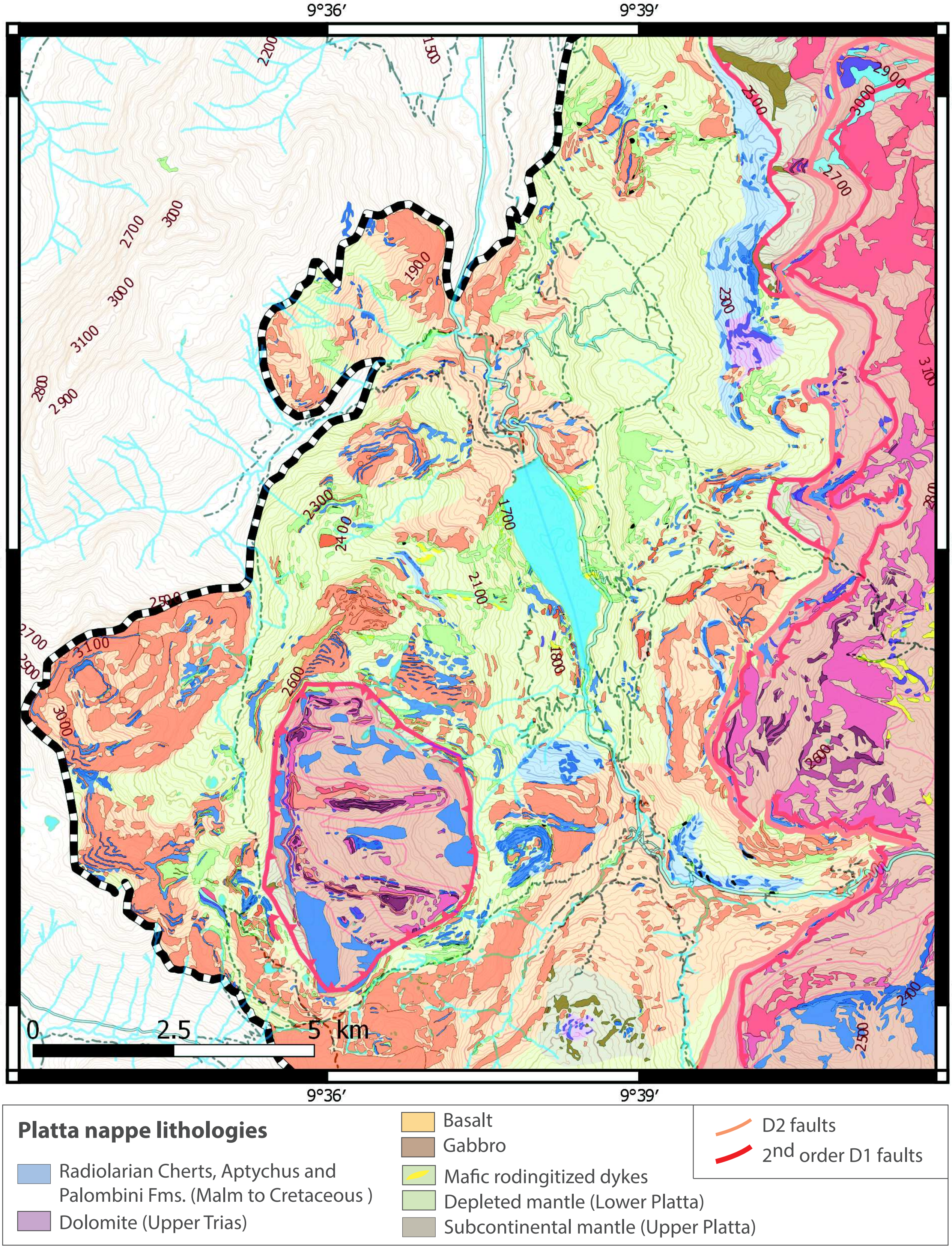
syn-rift
- Saluver and Bardella Fms. (Dogger)
- Agneli Fm. (Lias)

pre-rift
- Dolomite (Upper Trias)
- Cargneuls (Trias evaporite)

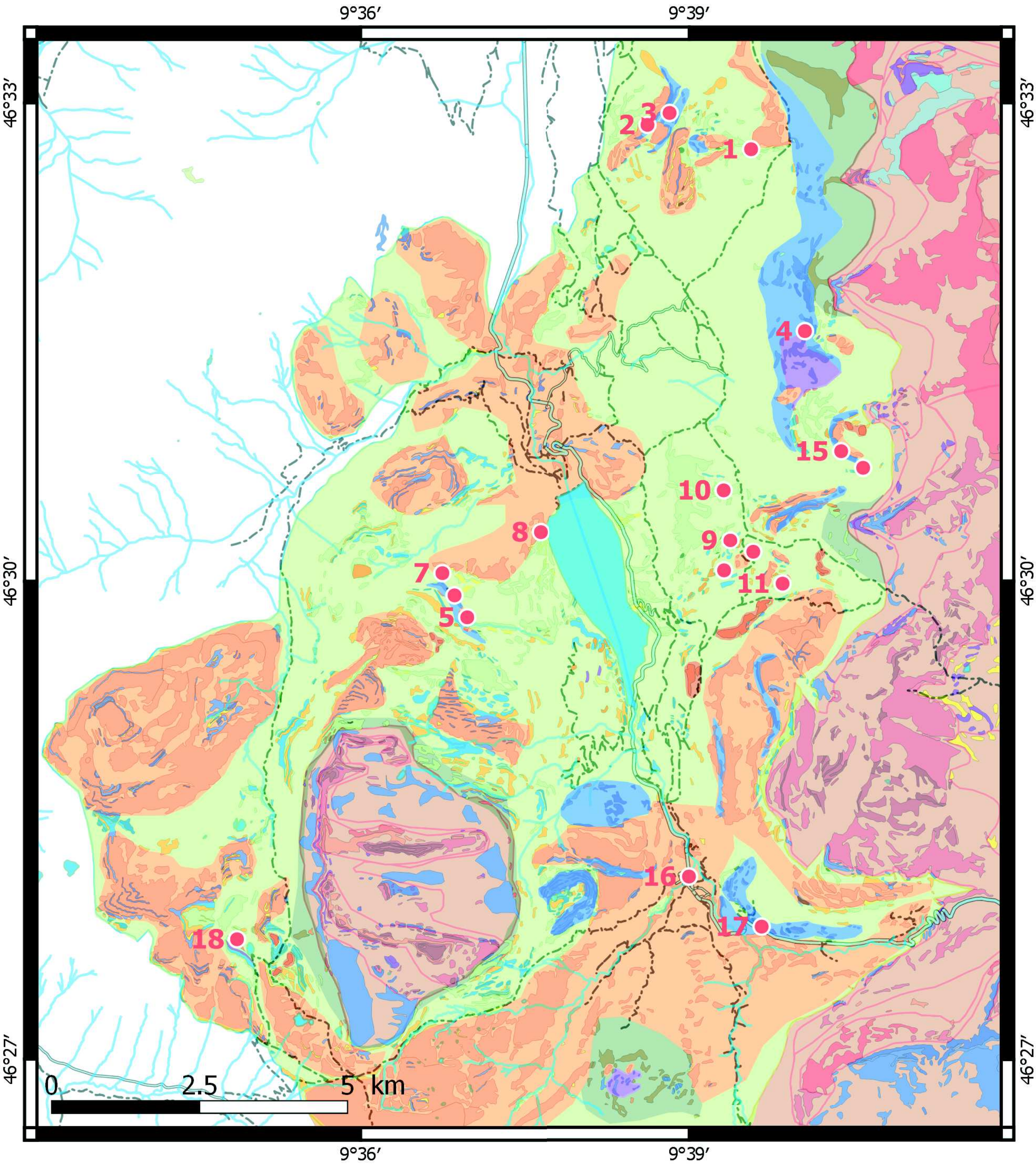
S0 S1 S2 S3

- Transport direction: Err detachment fault
- Transport direction: Jenatsch detachment fault
- Transport direction: D1
- Transport direction: D2

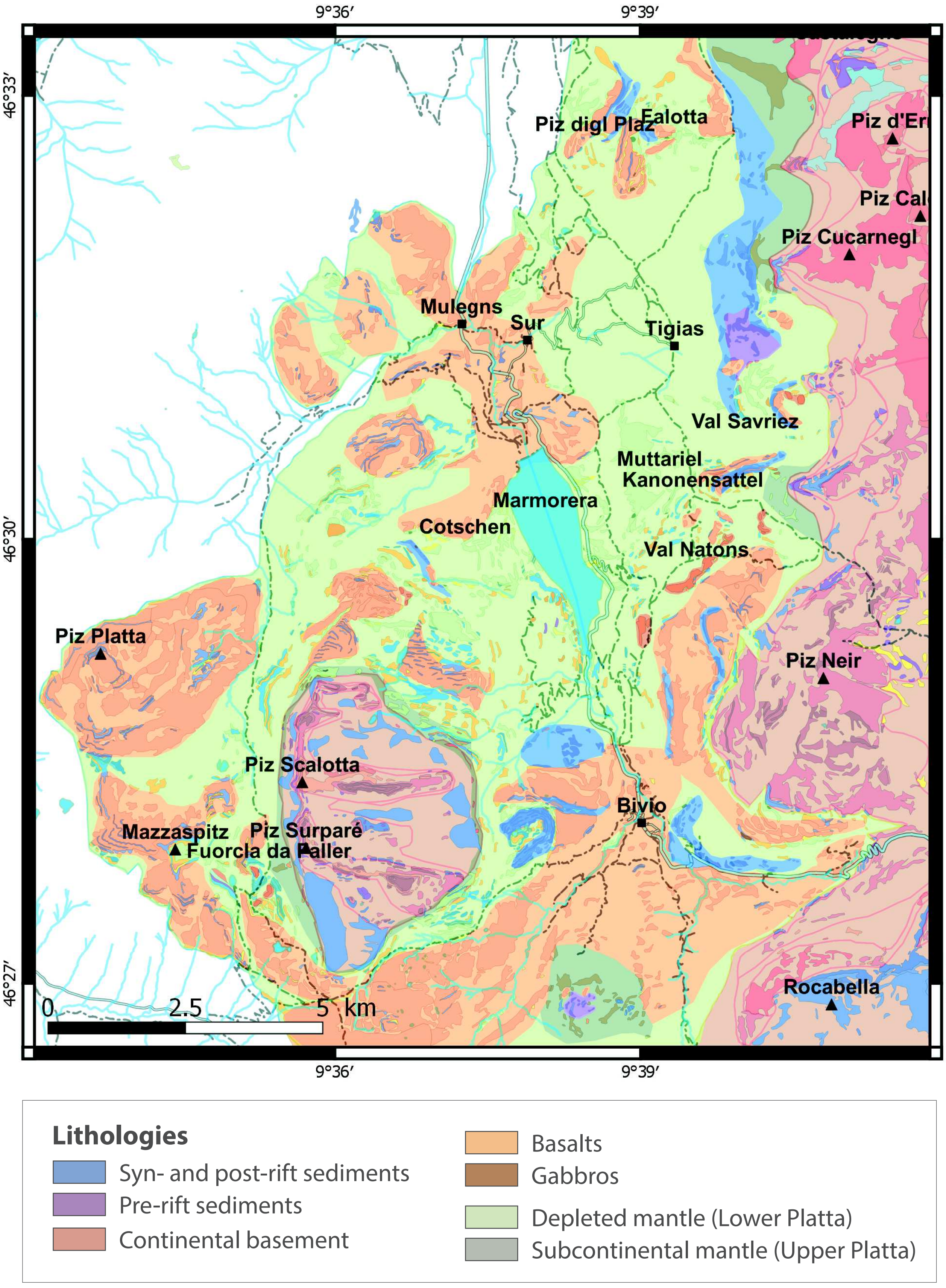
Annex 1.1.8
Geological map of the Platta nappes
Highlighting the lithlogies (outcrops)



Annex 1.2.1
Map of the Platta nappes with the location of LOGs

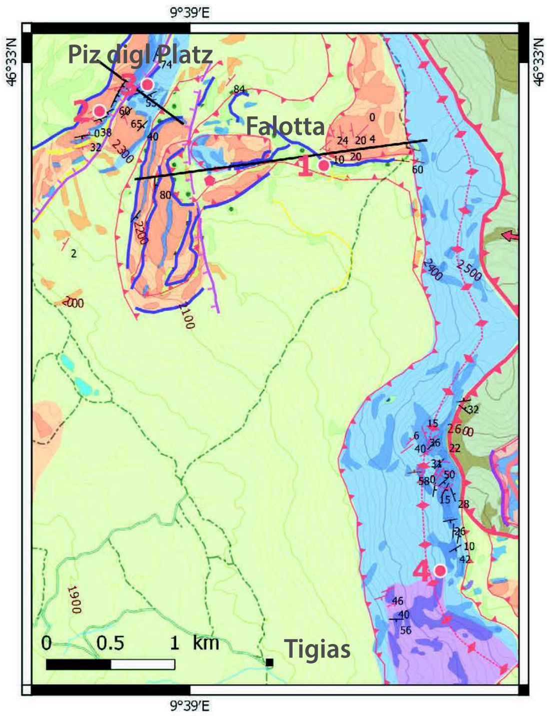


Map of the Platta with the names of the localities



Annex 1.2.2
Lower Platta unit
Falotta, Log 1

Location of the Falotta area



Lithologies

- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

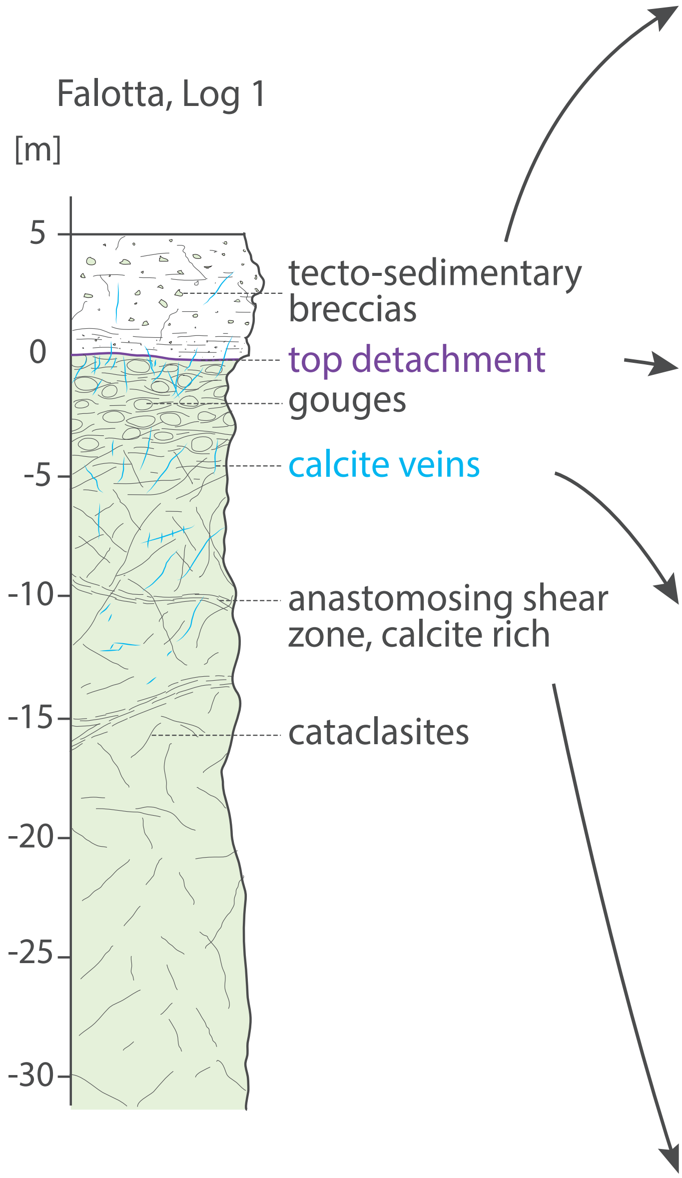
Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

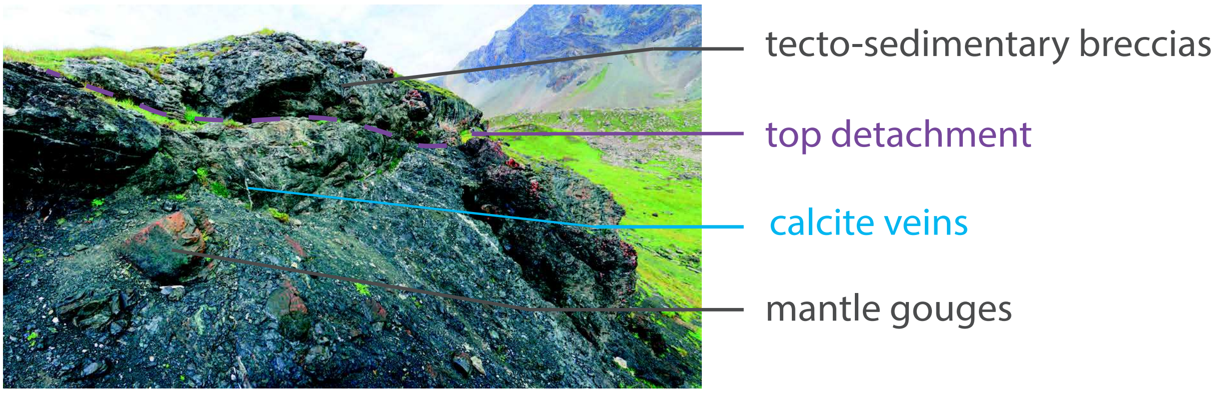
- Normal faults
- Lower Platta det.
- Upper Platta det.

Falotta, Log 1

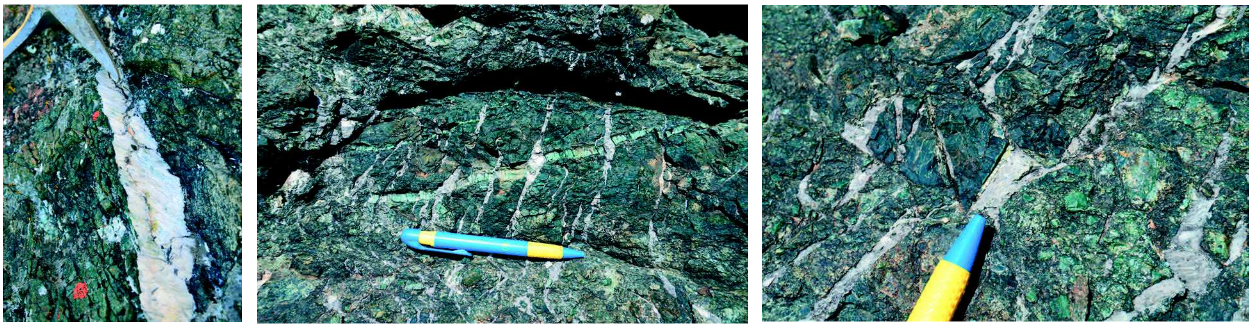


Tecto-sedimentary breccias

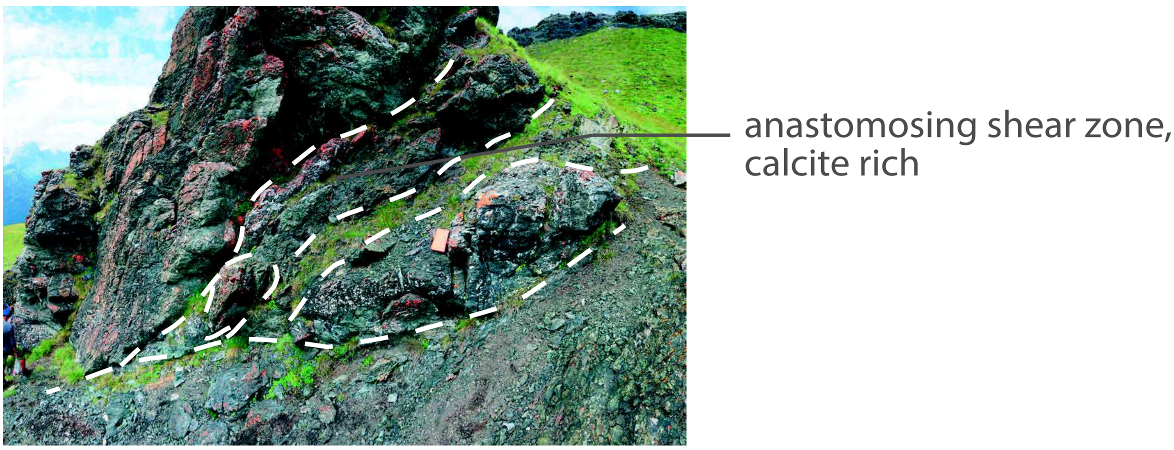
Contact between mantle gouges and tecto-sedimentary breccias



Calcite veins

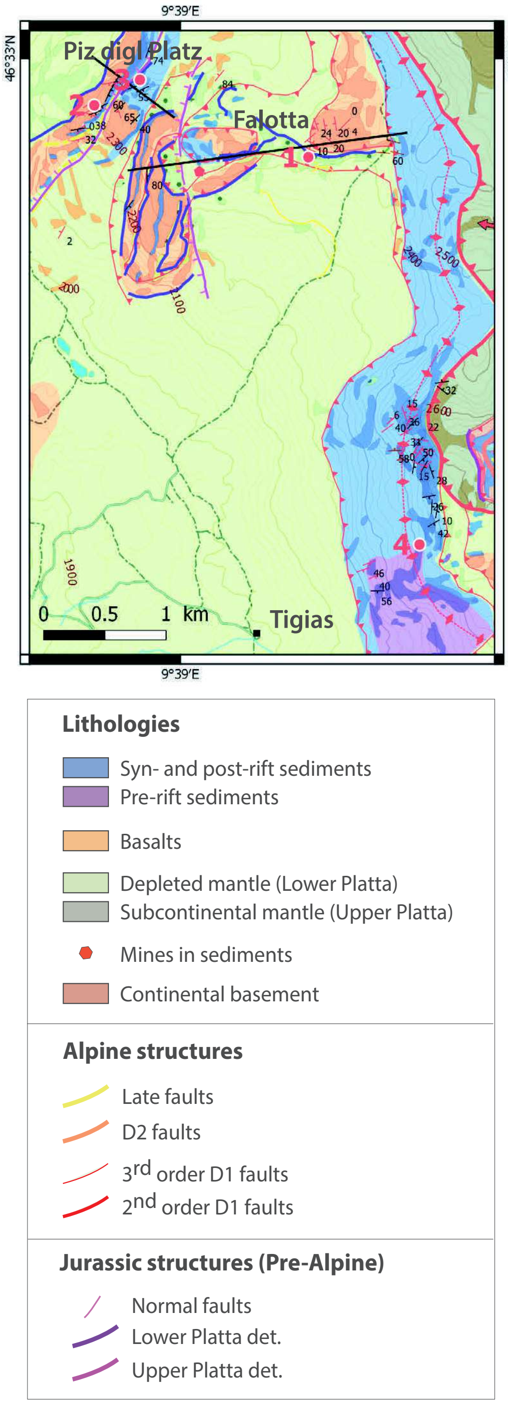


Cataclasite and sheared serpentinised mantle

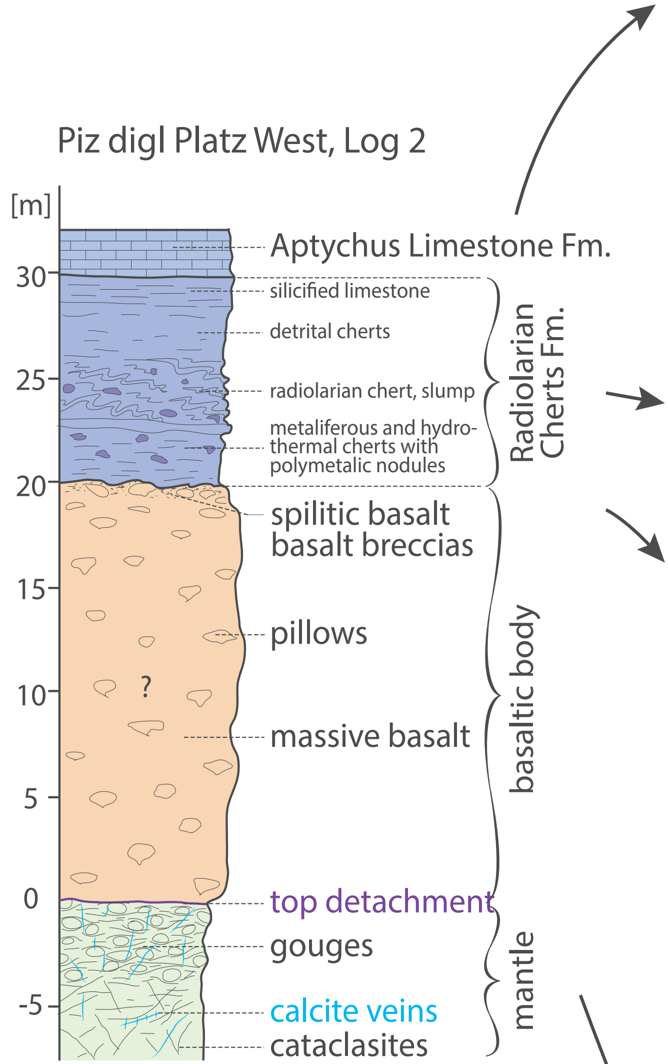


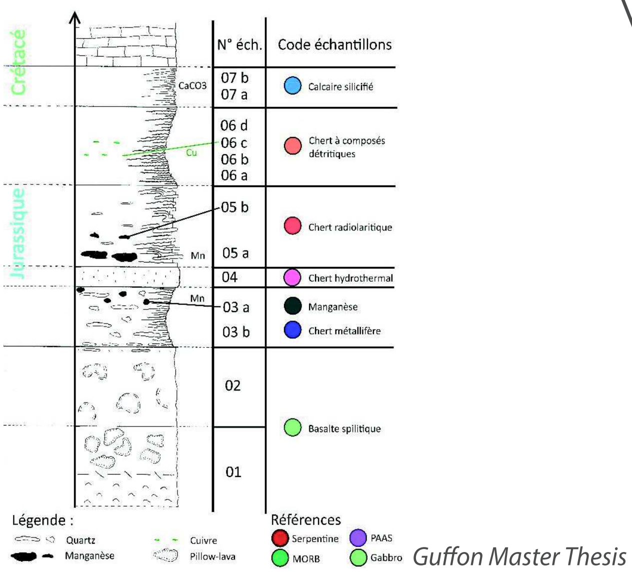
Annex 1.2.3
Lower Platta unit
Piz digl Platz West, Log 2

Location of the Piz digl Platz area



Piz digl Platz West, Log 2





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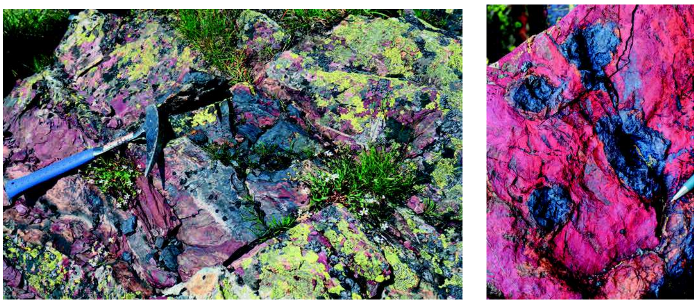
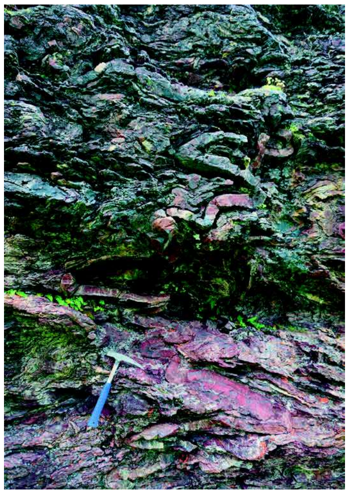
Aptychus Limestone Fm.

Polymictic nodul in Radiolarian Cherts Fm.

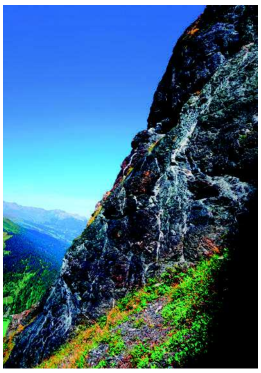


Deformation in Radiolarian Cherts Fm.

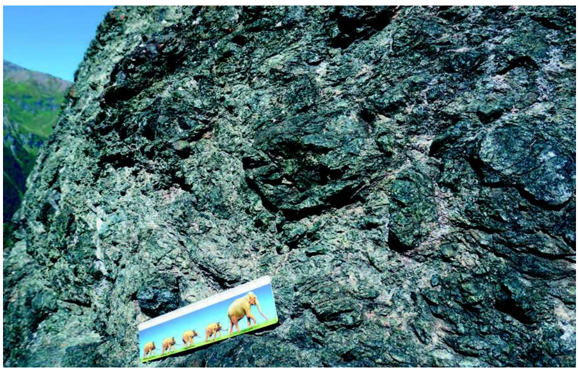


Contact between basalt and Radiolarian Cherts Fm.

Serpentinised mantle with calcite veins

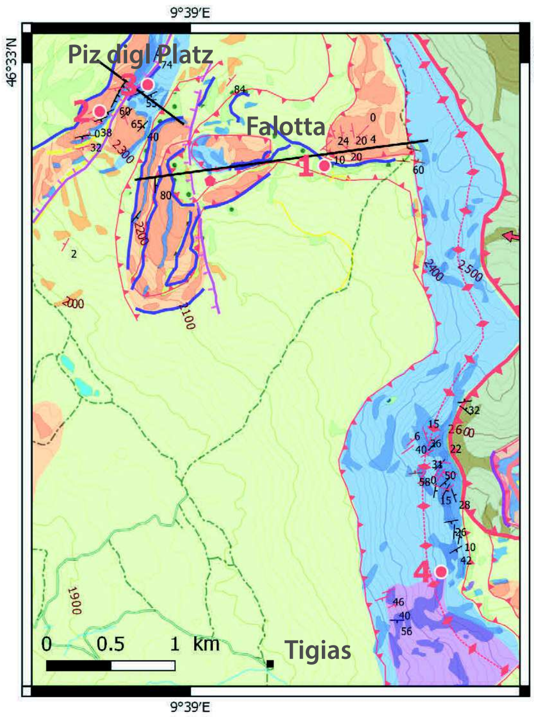


Serpentinised mantle cataclasites and gouges



Annex 1.2.4
Lower Platta unit
Piz digl Platz East, Log 3

Location of the Piz digl Platz area



Lithologies

- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

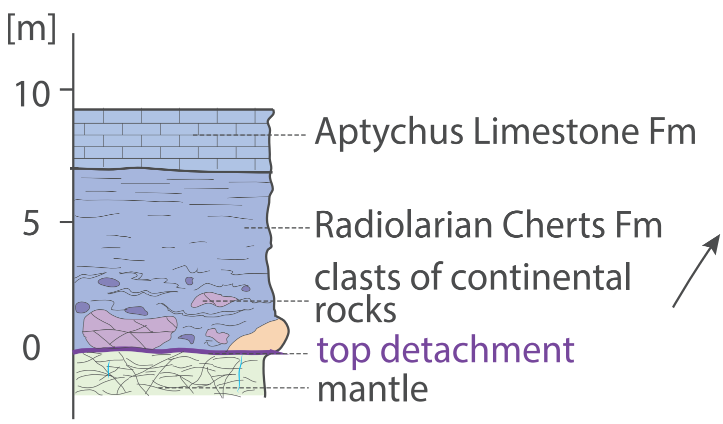
Alpine structures

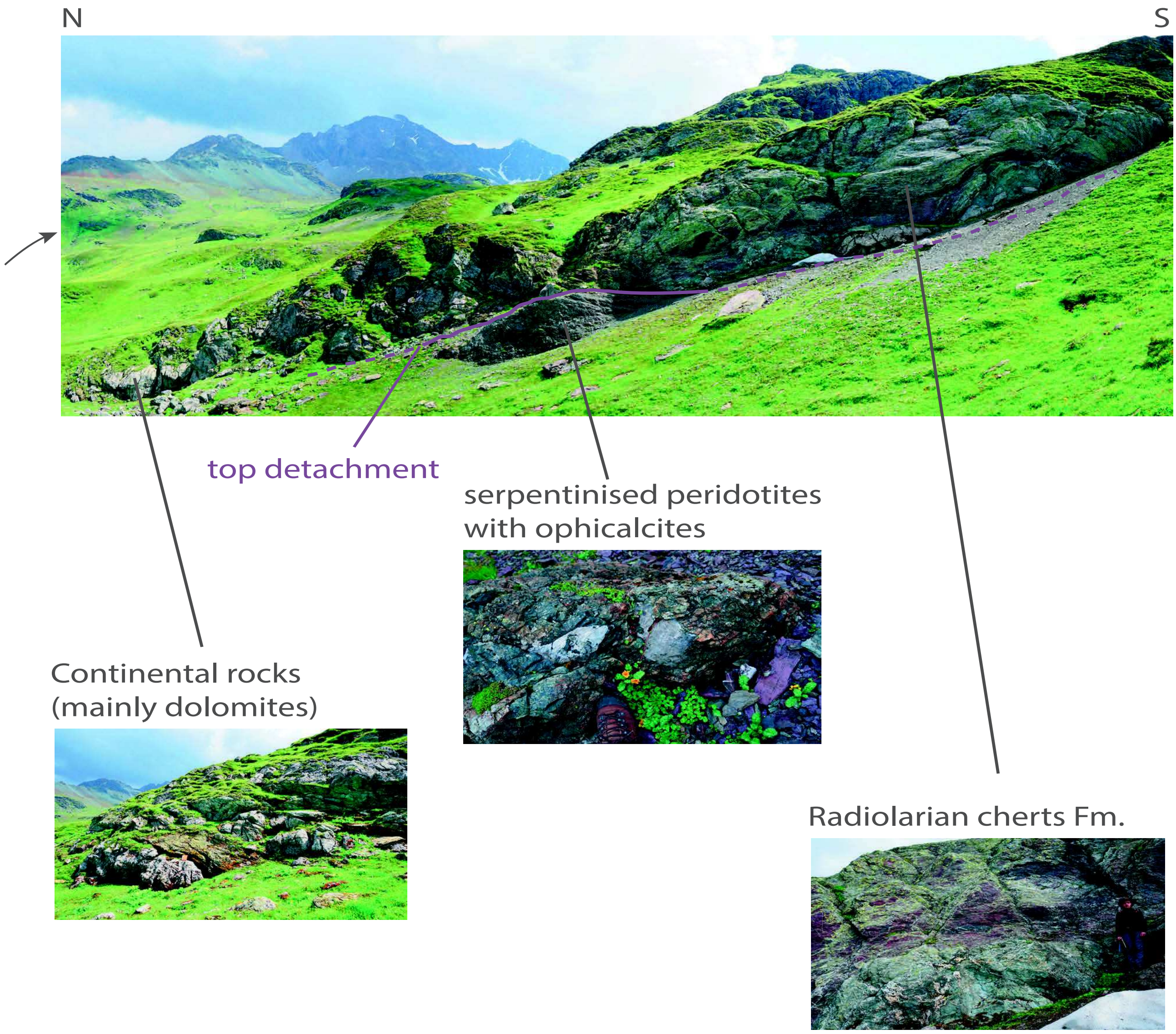
- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.

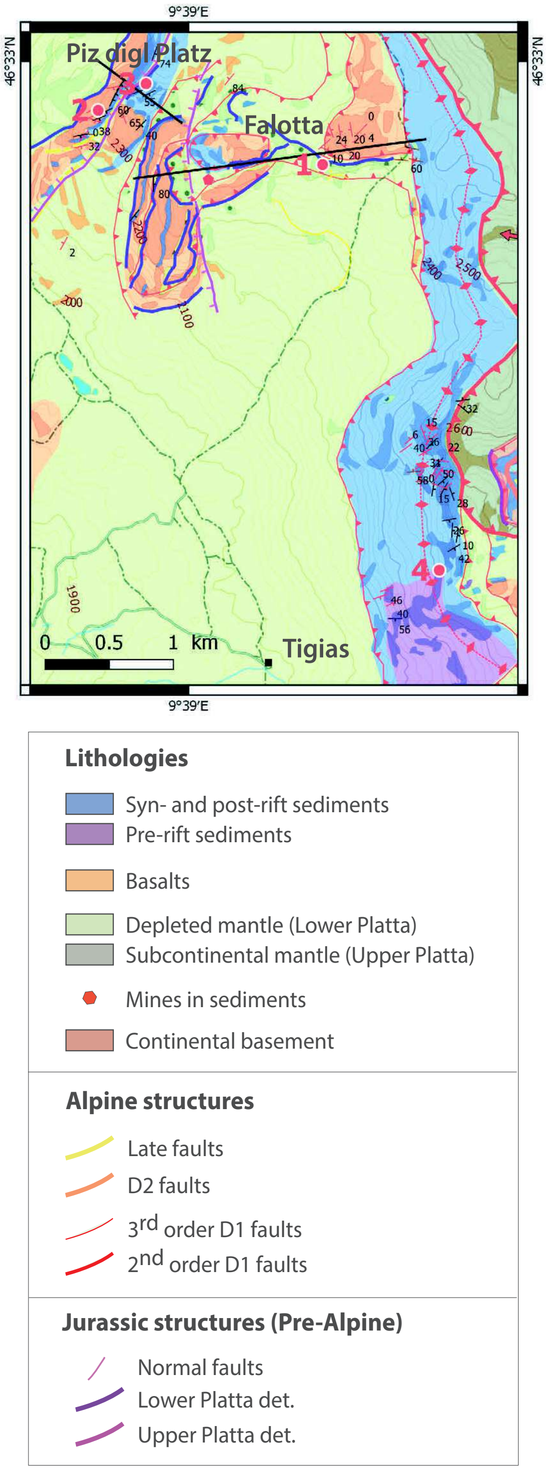
Piz digl Platz East, Log 3



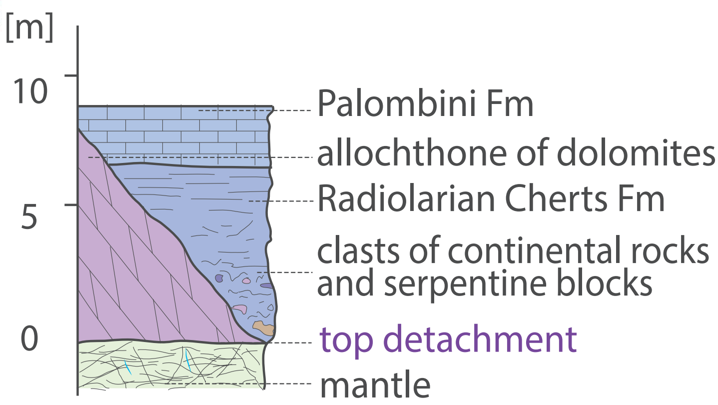

N
S
top detachment
serpentinised peridotites
with ophicalcites
Continental rocks
(mainly dolomites)
Radiolarian cherts Fm.

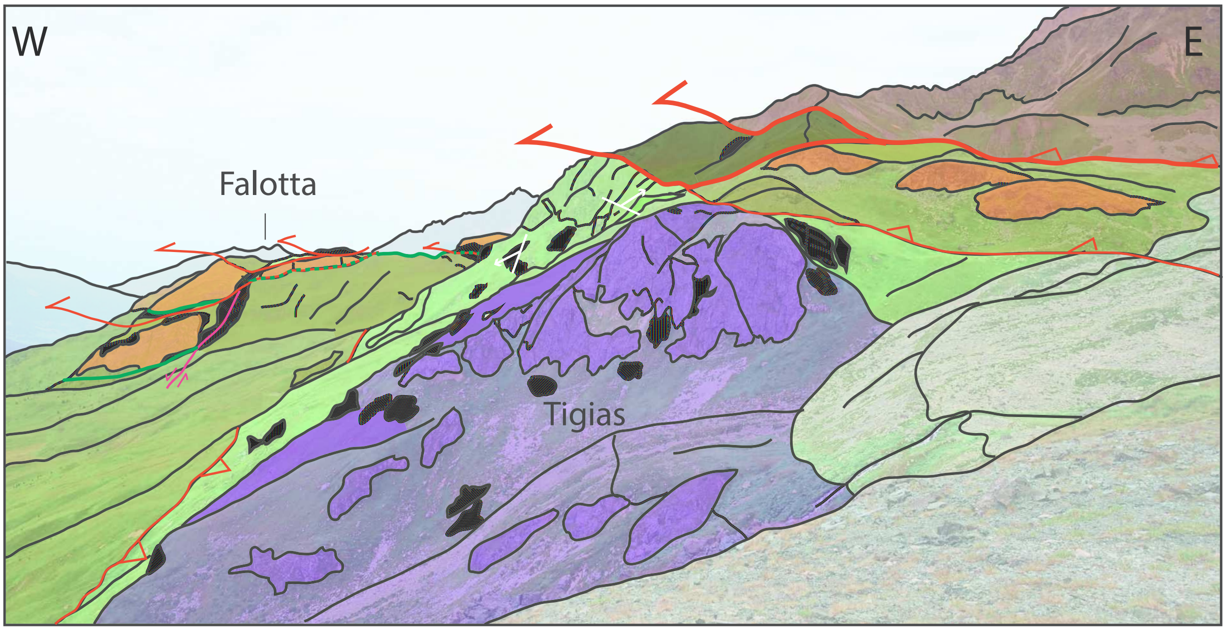
Annex 1.2.5
Lower Platta unit
Tigias, Log 4

Location of the Falotta area



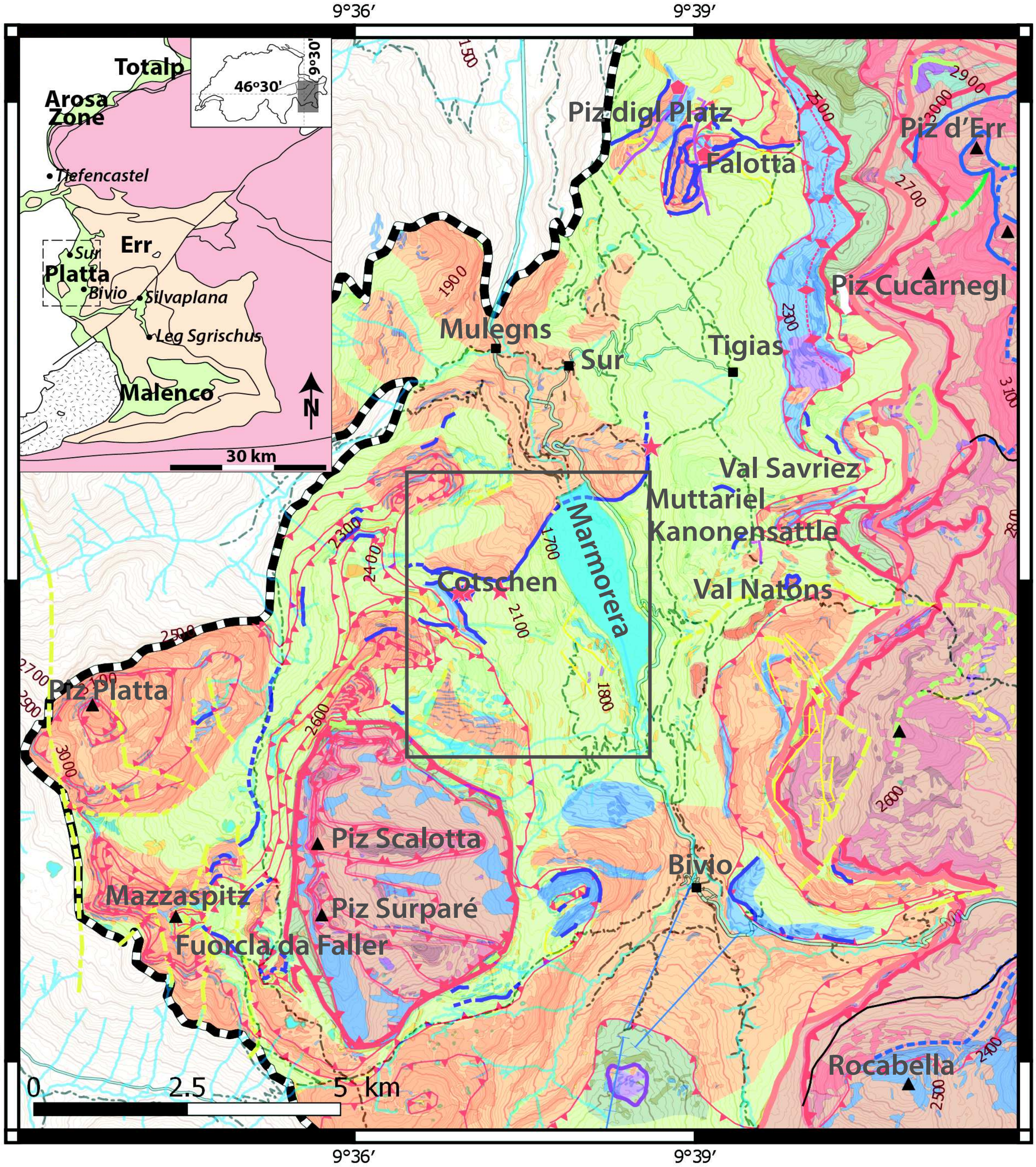
Tigias, Log 4

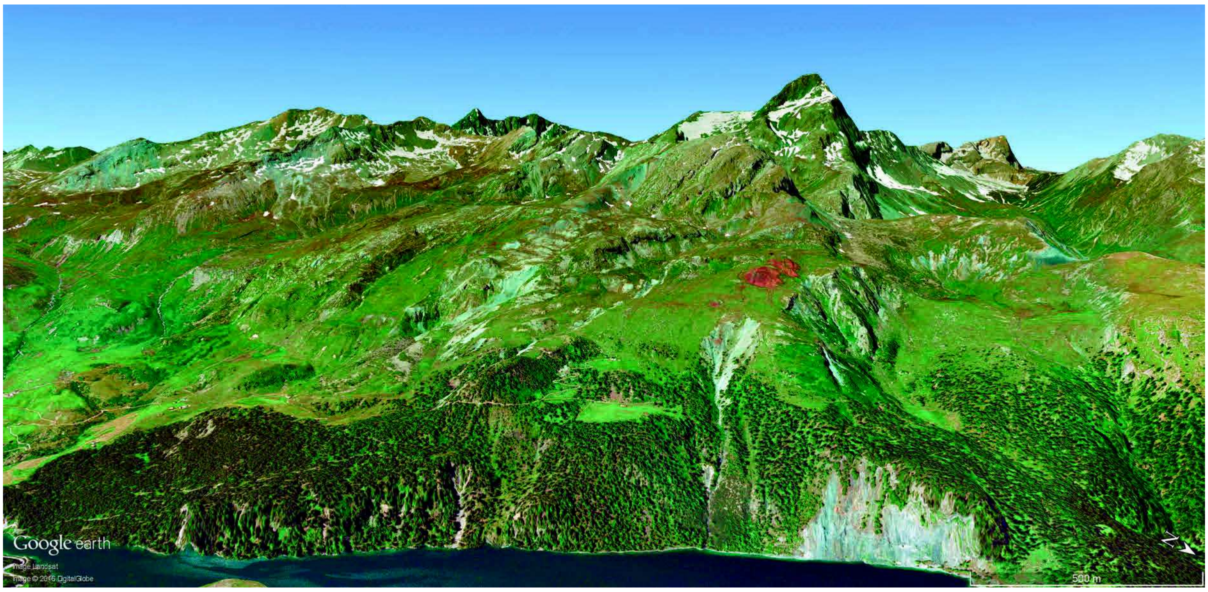


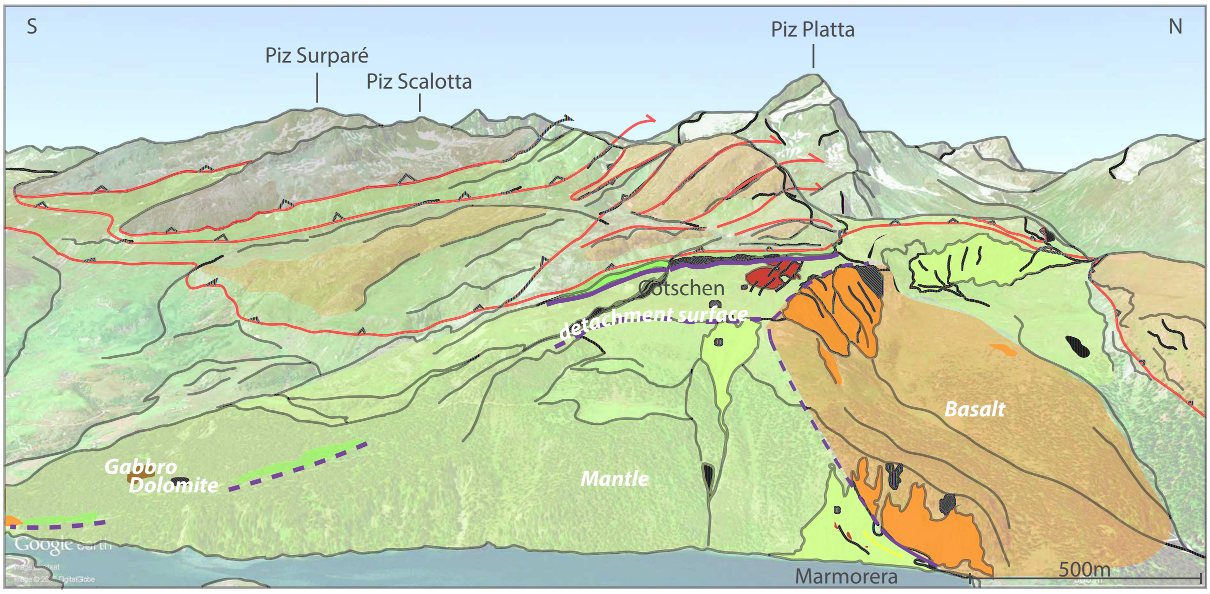

W
E
Falotta
Tigias

Annex 1.2.6
Lower Platta unit
Marmorera Cotschen area

Location of the Marmorera Cotschen area

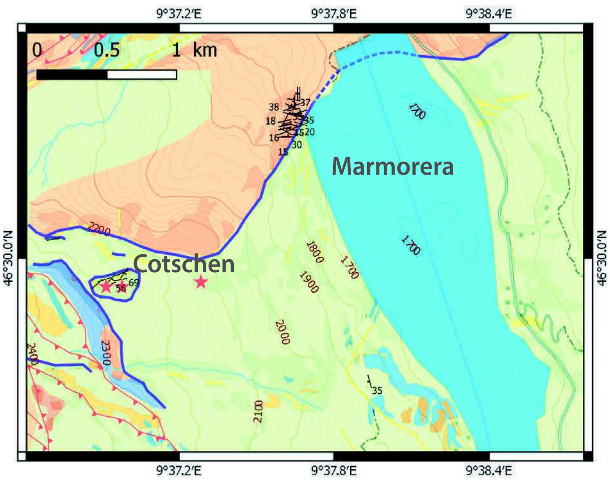



Google earth
500 m


S
N
Piz Platta
Piz Surparé
Piz Scalotta
Cotschen
detachment surface
Basalt
Gabbro
Dolomite
Mantle
Marmorera
500m

Annex 1.2.7
Lower Platta unit
Cotschen, Log 5

Location of the Cotschen area



Lithologies

- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

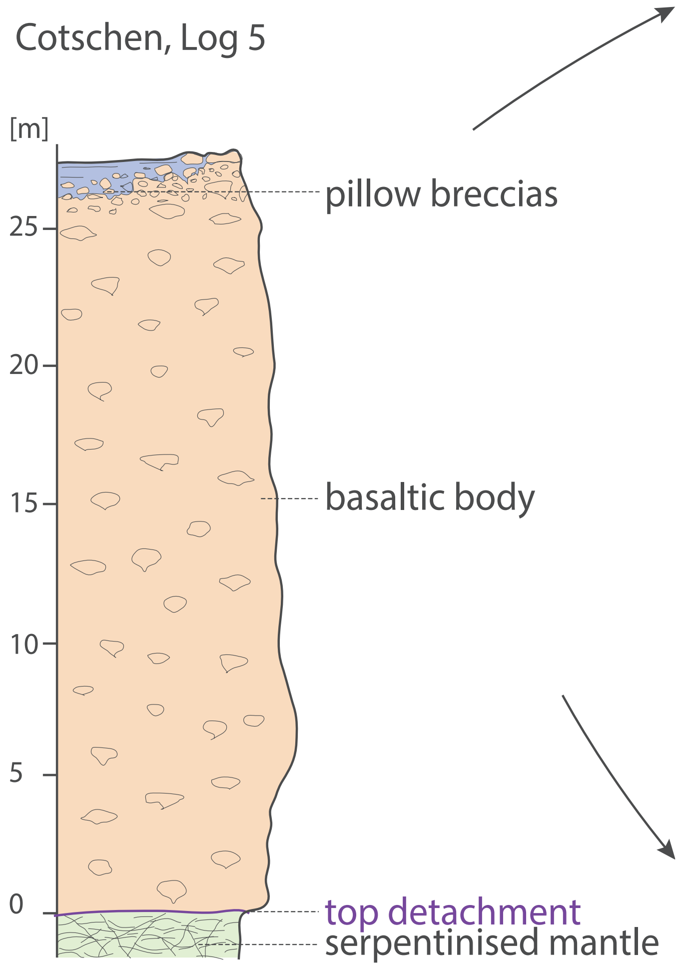
Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

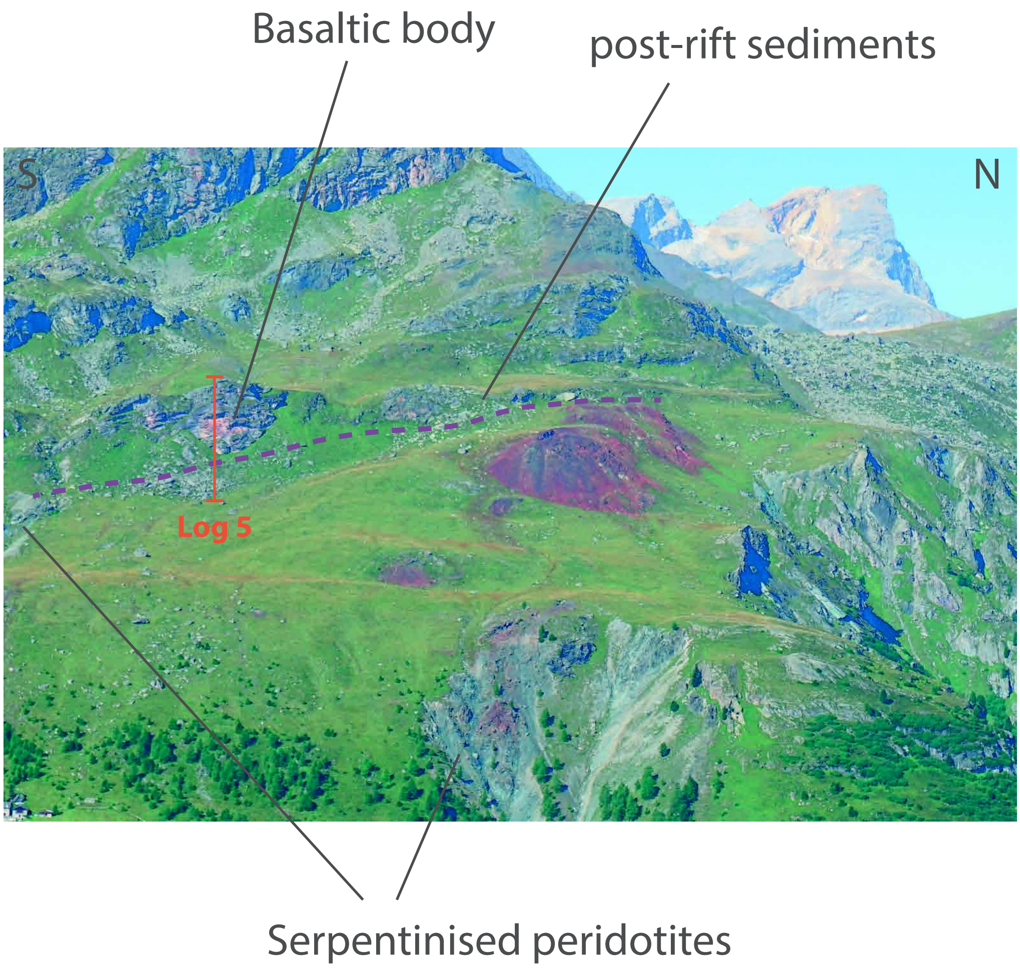
Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.

Cotschen, Log 5

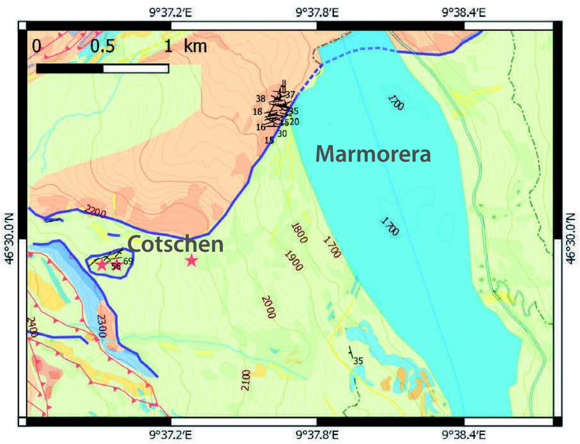


Basalt pillows

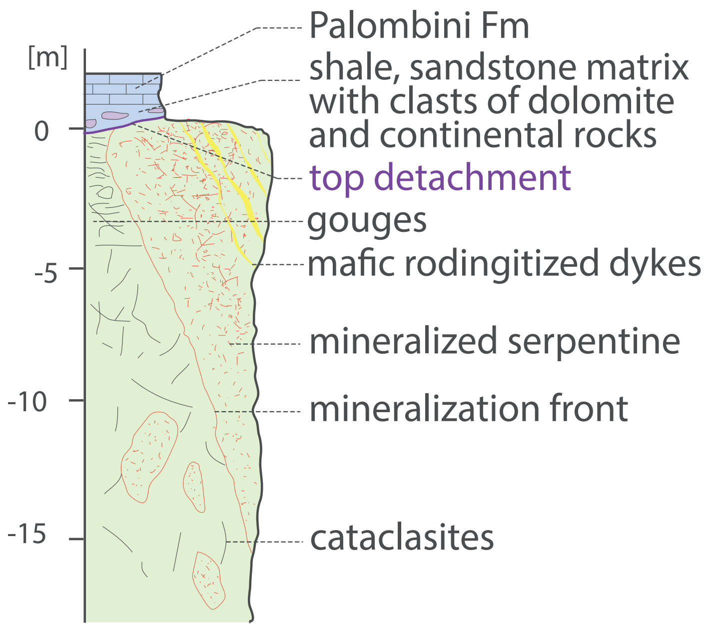


Annex 1.2.8
Lower Platta unit
Cotschen, Log 6

Location of the Cotschen area



Cotschen, Log 6



Lithologies

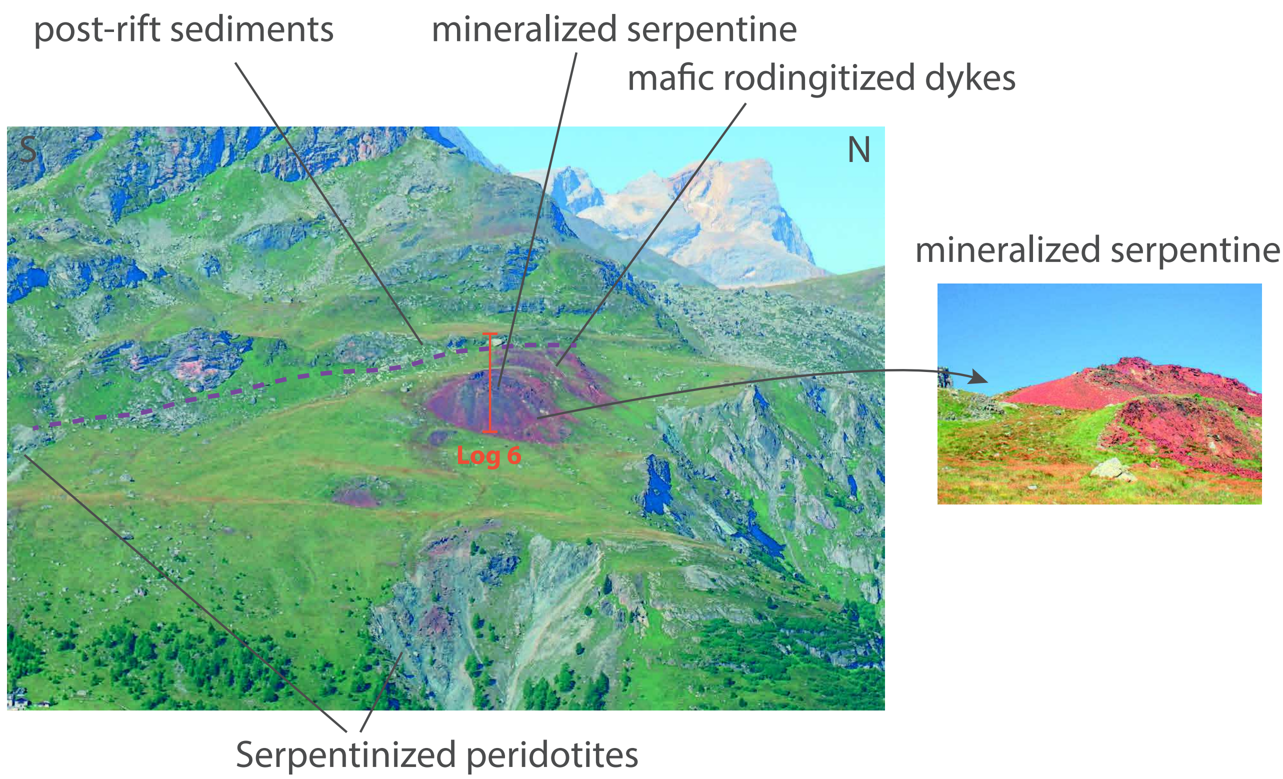
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

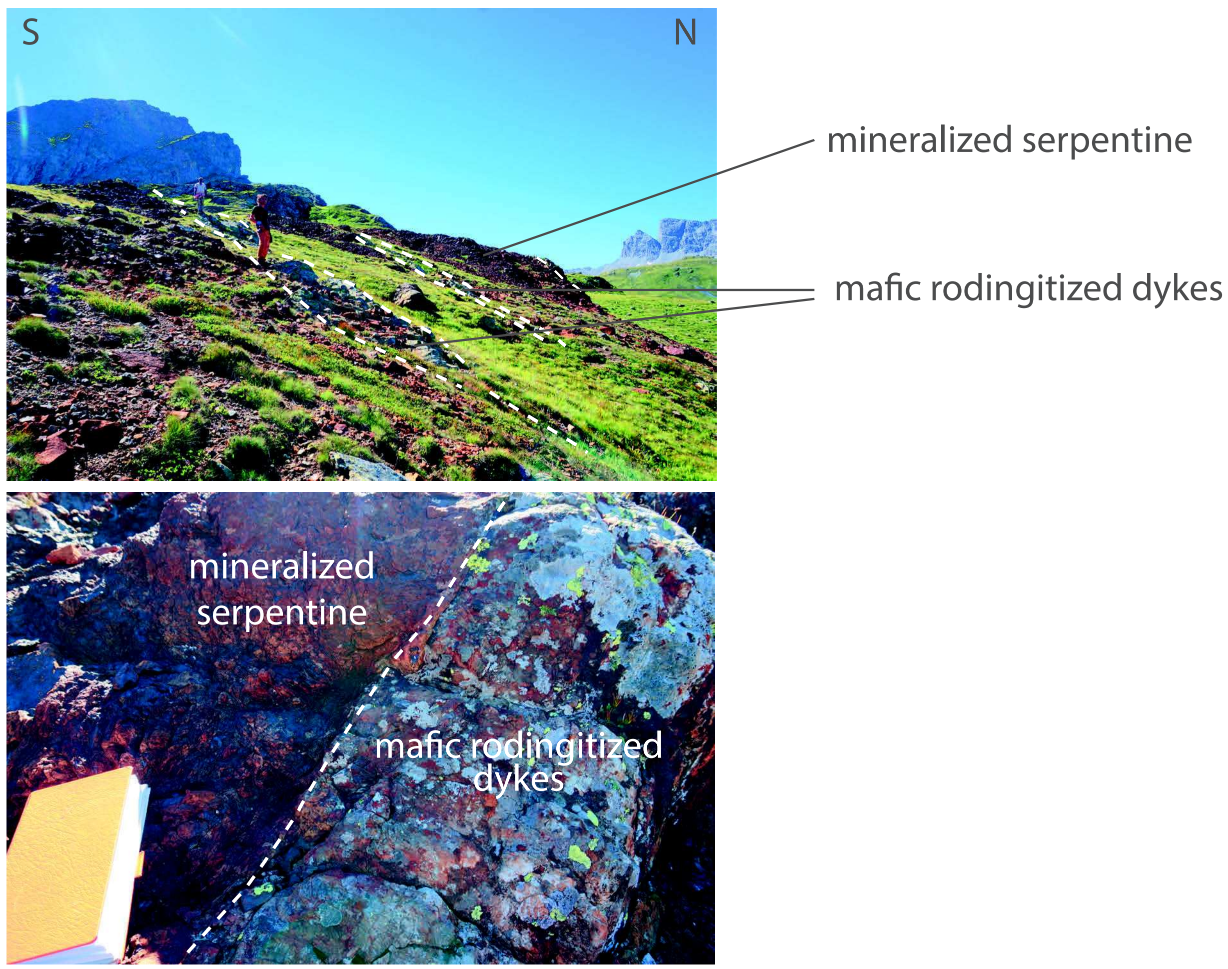
Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

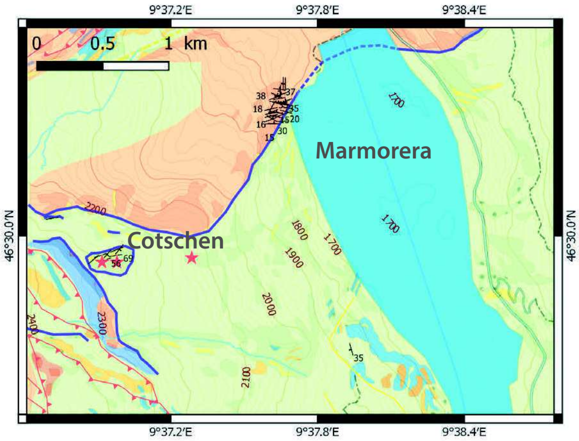
- Normal faults
- Lower Platta det.
- Upper Platta det.


post-rift sediments
mineralized serpentine
mafic rodingitized dykes
S
N
Log 6
mineralized serpentine
Serpentinized peridotites

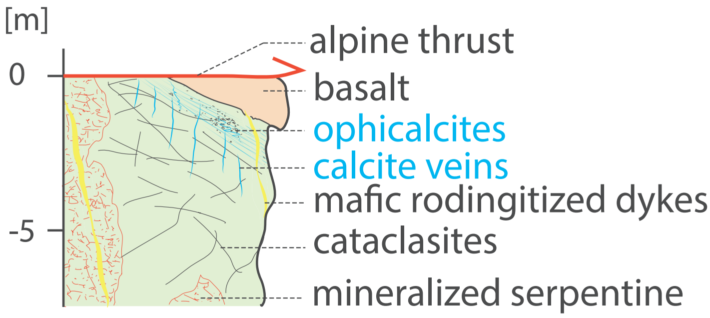

S
N
mineralized serpentine
mafic rodingitized dykes
mineralized serpentine
mafic rodingitized dykes

Annex 1.2.9
Lower Platta unit
Cotschen Nord, Log 7

Location of the Cotschen area



Cotschen Nord, Log 7



Lithologies

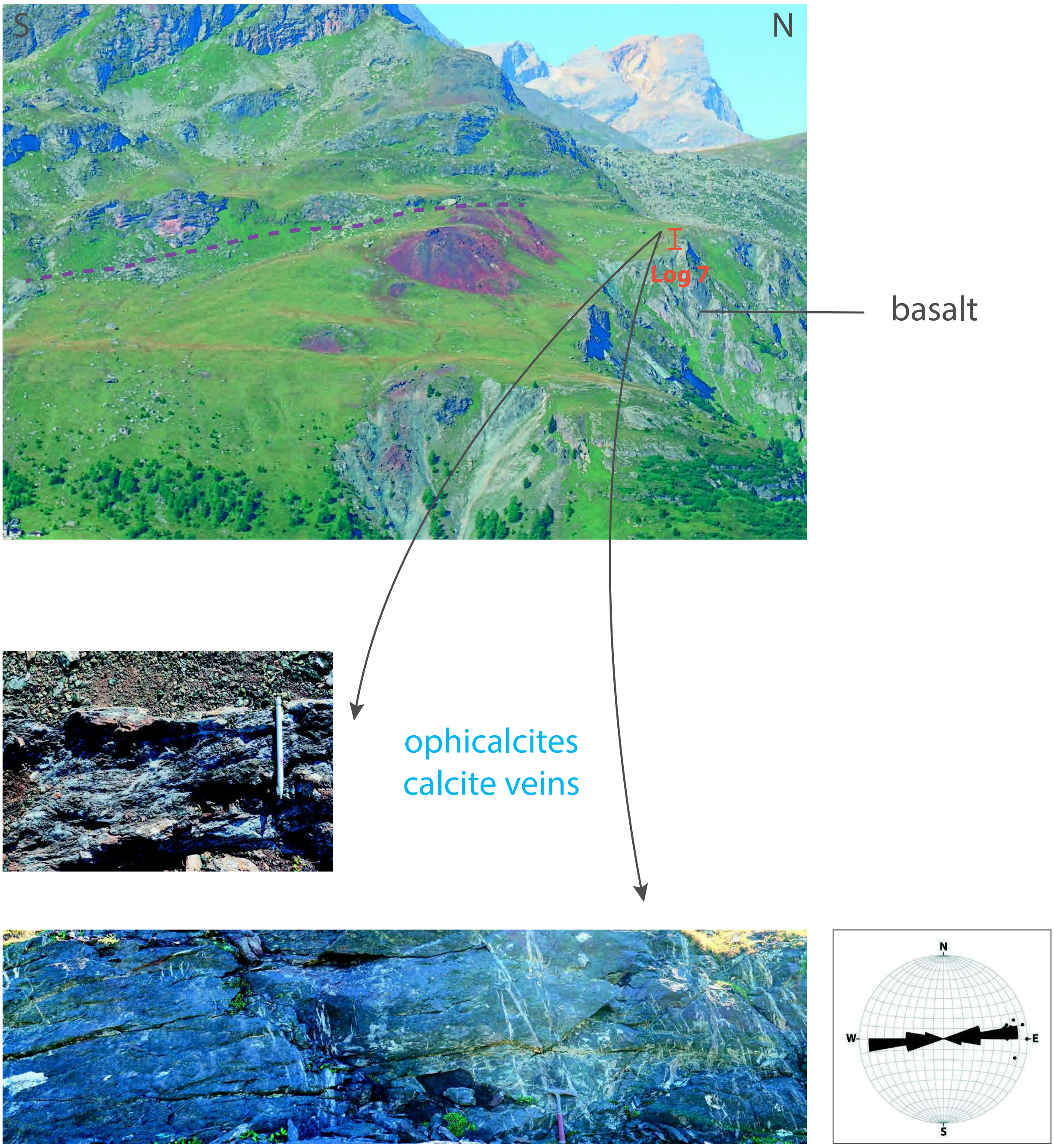
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

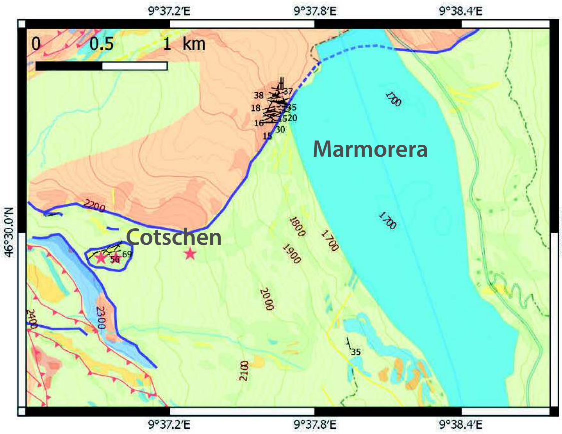
- Normal faults
- Lower Platta det.
- Upper Platta det.



Stereo-plot in lower hemisphere showing a rose diagram and poles of calcite veins at Cotschen (rose diagram explains the frequency of plan in a given orientation).

Annex 1.2.10
Lower Platta unit
Marmorera, Log 8

Location of the Marmorera area

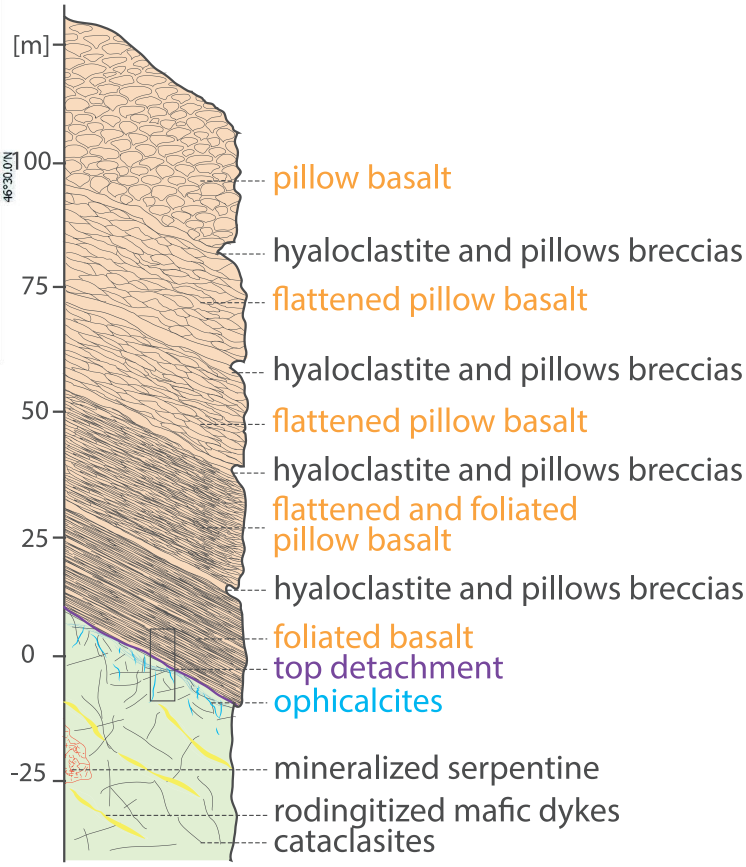


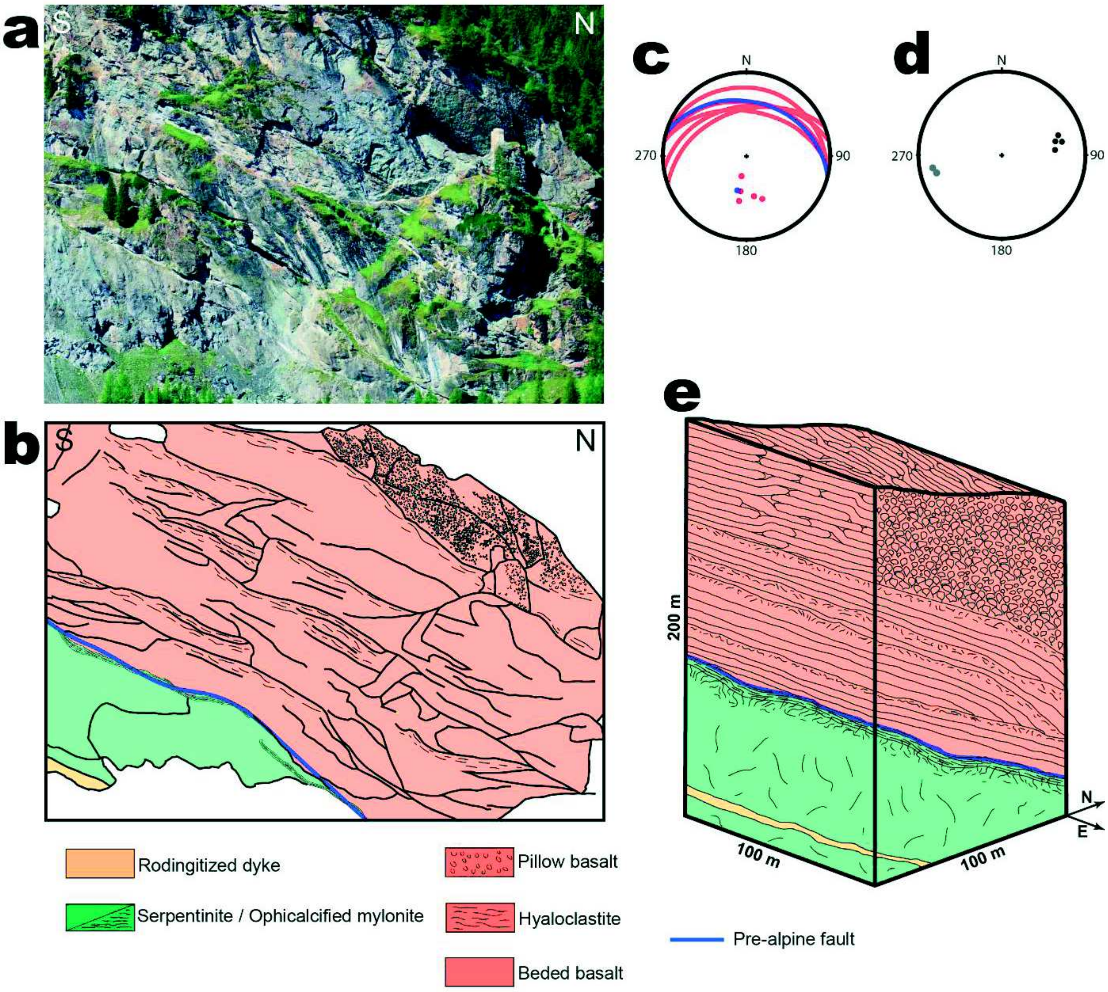
Lithologies
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures
- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)
- Normal faults
- Lower Platta det.
- Upper Platta det.

Marmorera, Log 8





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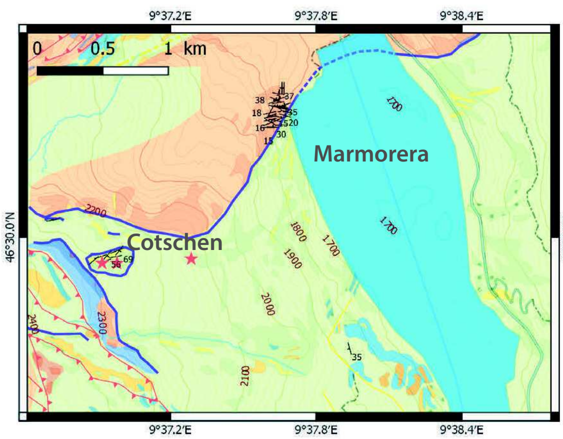
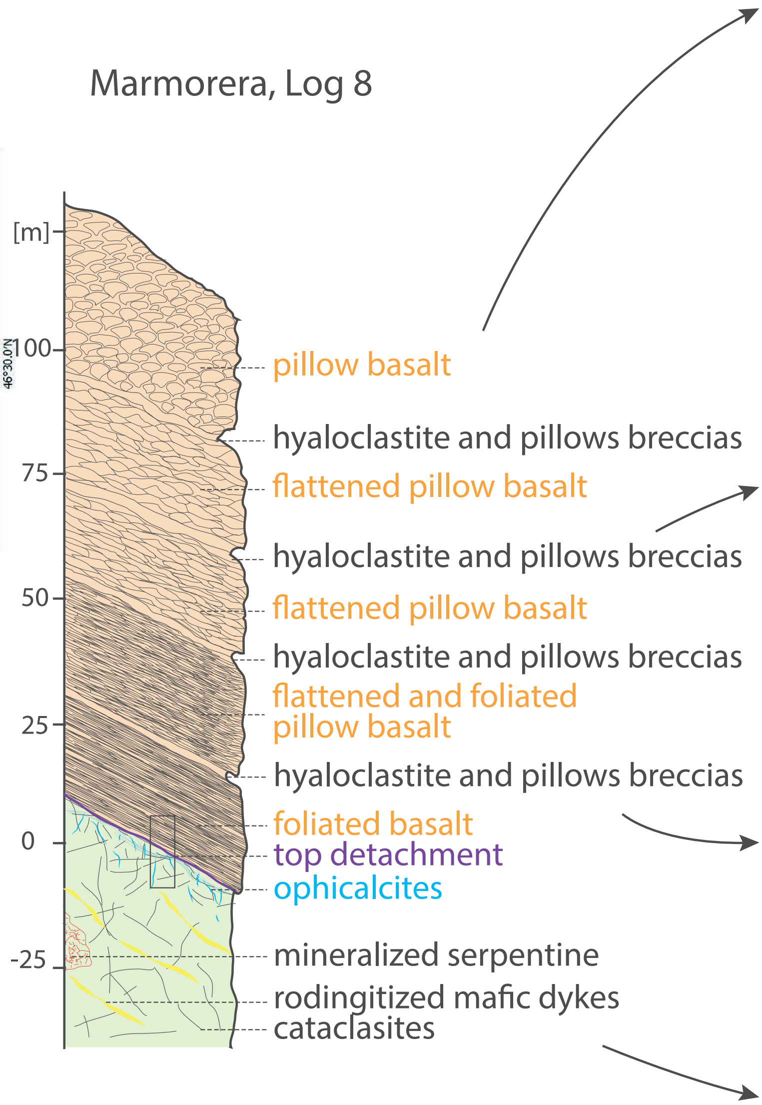
Zoom on the basaltic part of the Marmorera cliff in a and b. c Stereographic projection of 5 hyaloclastite levels (red dots and curves) and 1 measure of the general orientation of the pre-Alpine fault (blue dot and curve). d Stereographic projection of the lineation of 4 folliated basalts (black dots) and the direction of 2 tubular pillows (grey dots). e Structural 3D block of this part of the cliff showing the magmatic relationships.

Annex 1.2.10
Lower Platta unit
Marmorera, Log 8

Location of the Marmorera area



Marmorera, Log 8



Lithologies

- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

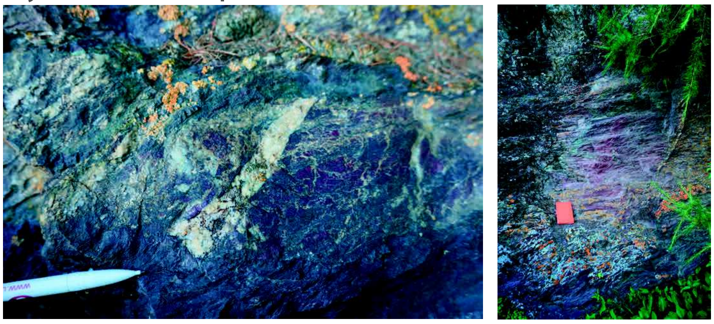
- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

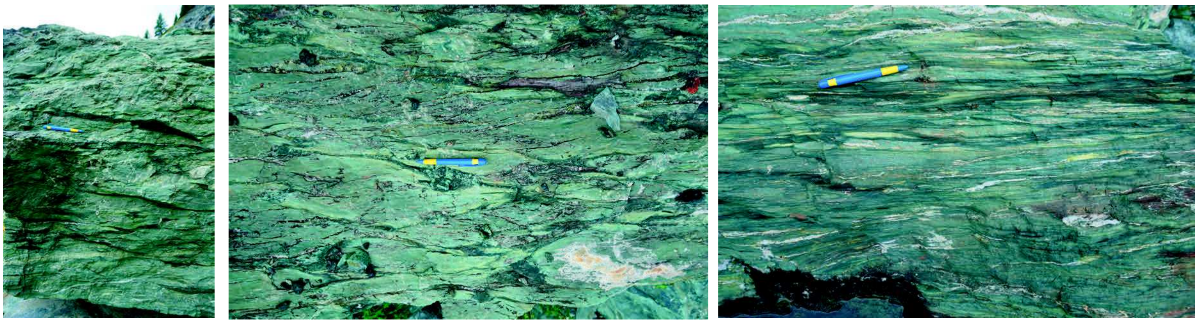
- Normal faults
- Lower Platta det.
- Upper Platta det.

Pillow basalt

hyaloclastite, pillows breccias, and Radiolarian Cherts Fm.



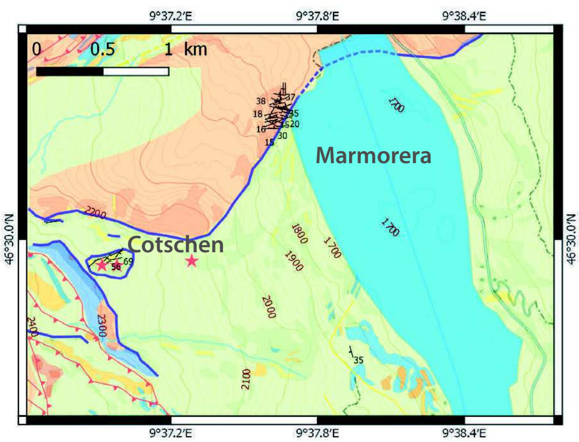
Flattened and foliated pillow basalt



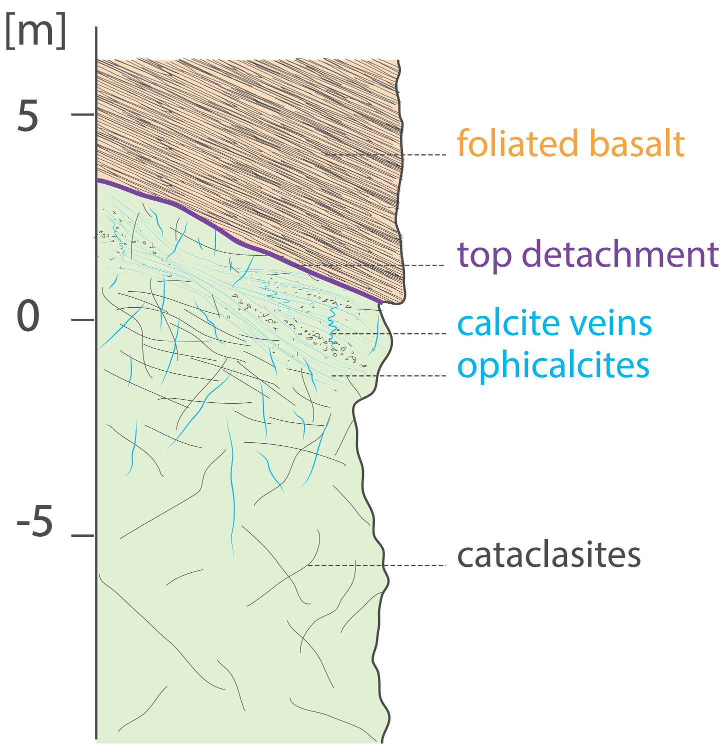
Mineralized serpentine and rodingitized mafic dykes

Annex 1.2.11
Lower Platta unit
Marmorera, Log 8'

Location of the Marmorera area



Marmorera, Log 8' (zoom)



Lithologies

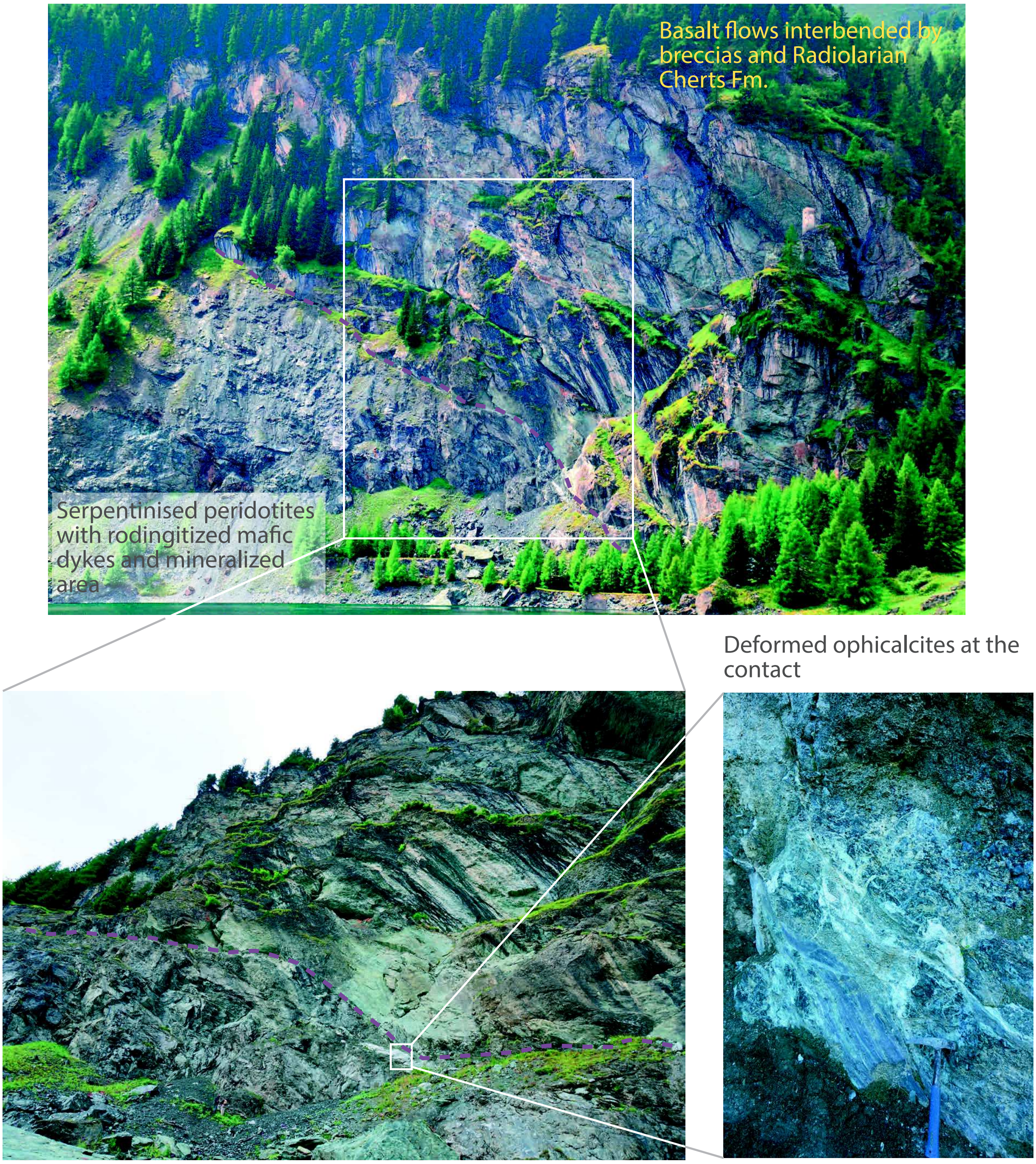
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

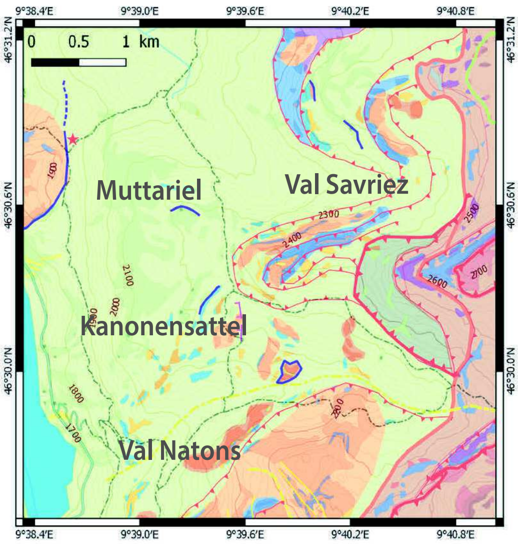
Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.

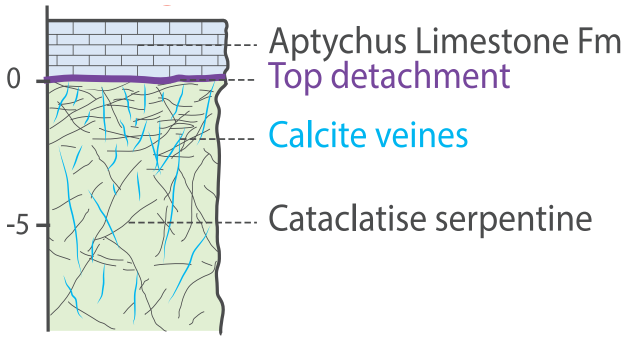

Basalt flows interbended by breccias and Radiolarian Cherts Fm.
Serpentinised peridotites with rodingitized mafic dykes and mineralized area
Deformed ophicalcites at the contact

Annex 1.2.12
Lower Platta unit
Kanonensattel, Log 9

Location of the Kanonensattel area



Kanonensattel, Log 9



Lithologies

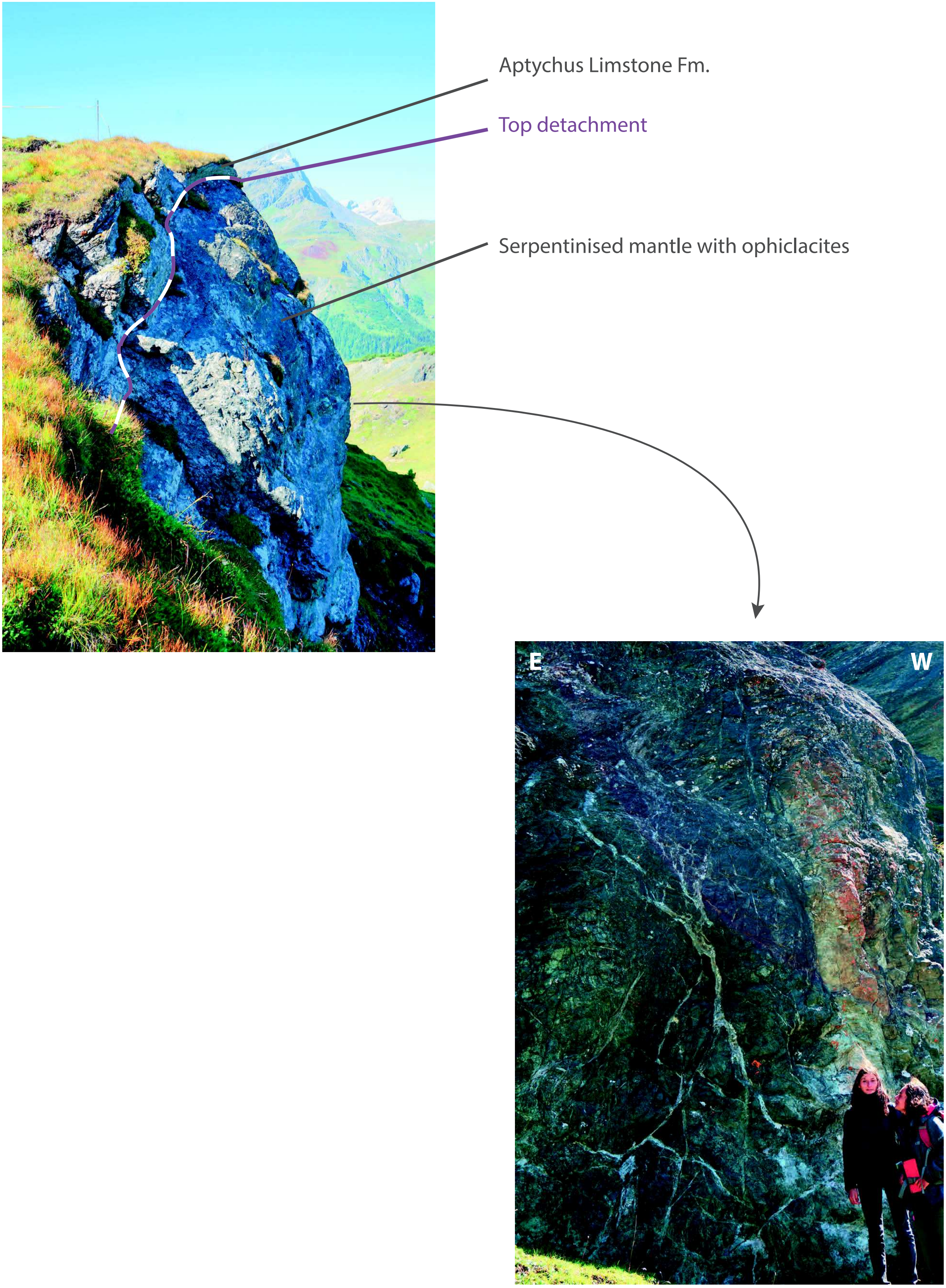
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

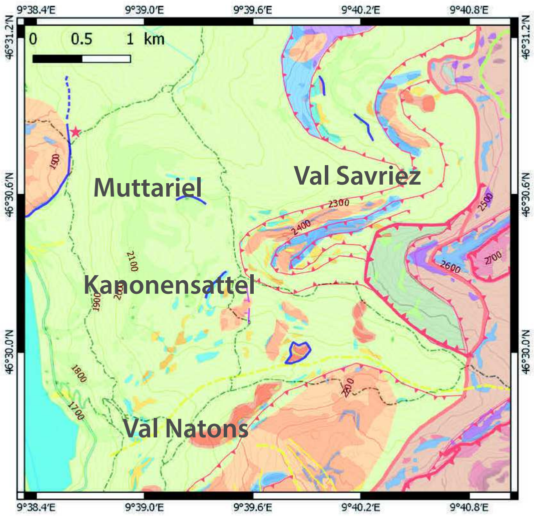
- Normal faults
- Lower Platta det.
- Upper Platta det.



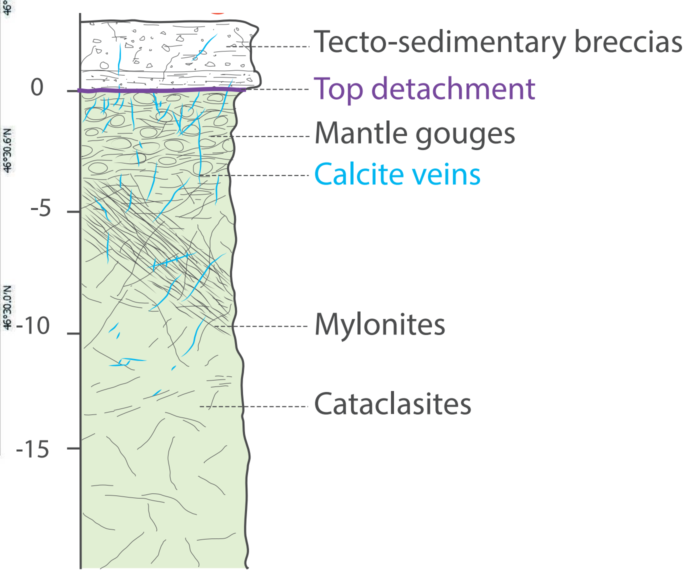
Serpentinised mantle with calcite veins

Annex 1.2.13
Lower Platta unit
Muttariel, Log 10

Location of the Muttariel area



Muttariel, Log 10



Lithologies

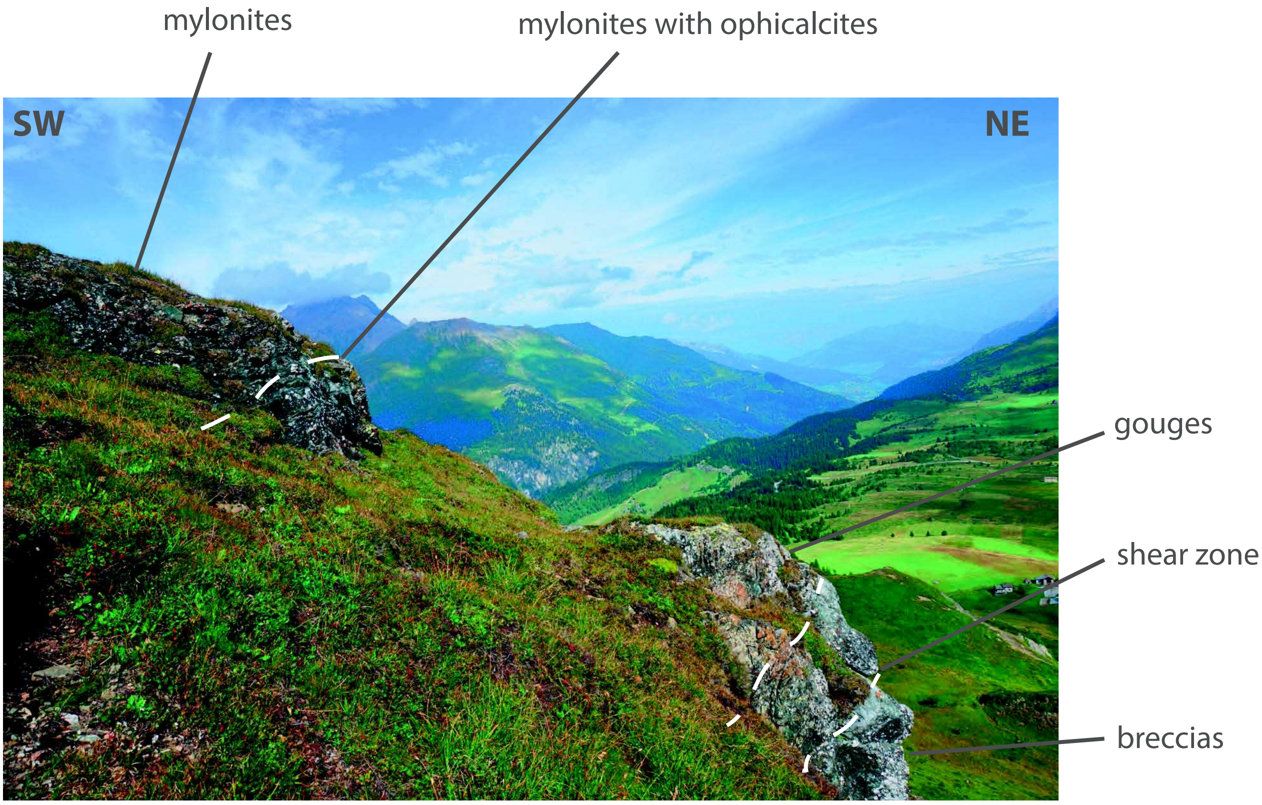
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

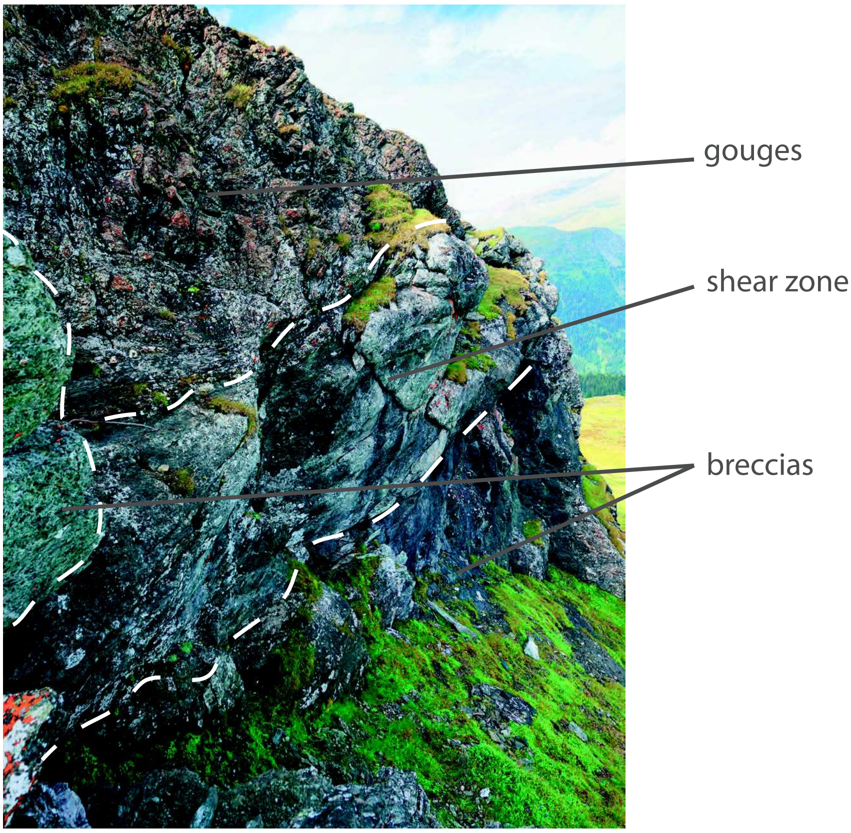
Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

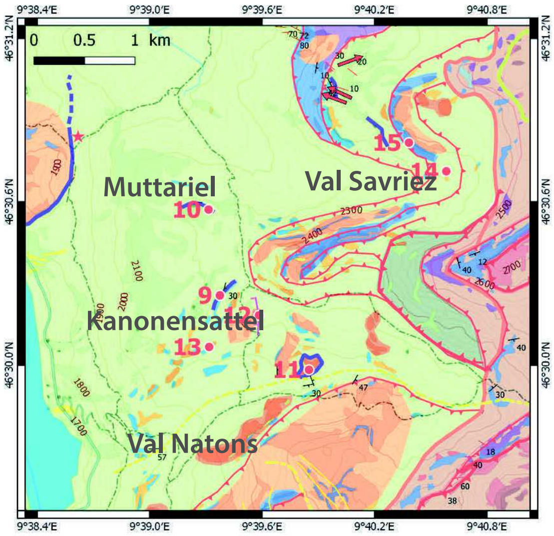
- Normal faults
- Lower Platta det.
- Upper Platta det.


mylonites
mylonites with ophicalcites
SW
NE
gouges
shear zone
breccias

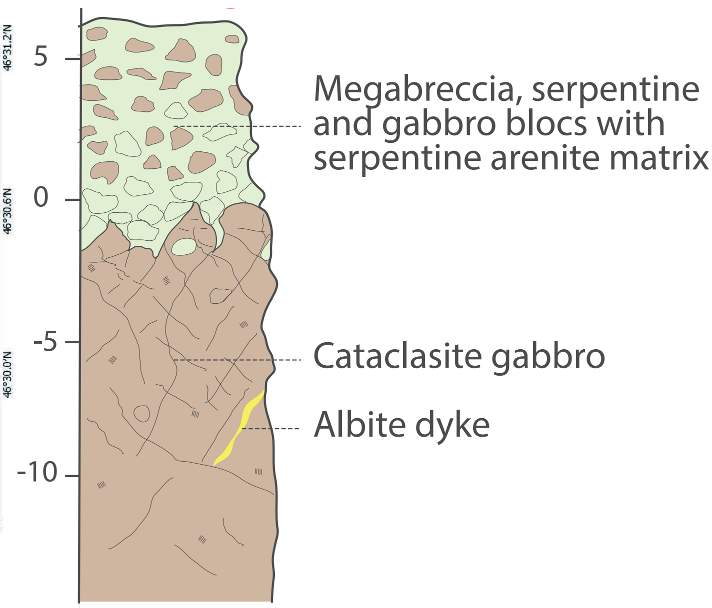

gouges
shear zone
breccias

Annex 1.2.14
Lower Platta unit
Val Nattons, Log 11

Location of Val Nattons area



Val Nattons, Log 11



Lithologies

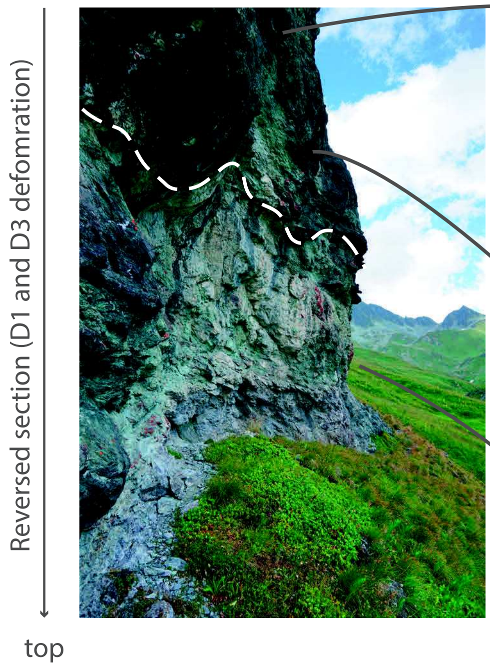
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

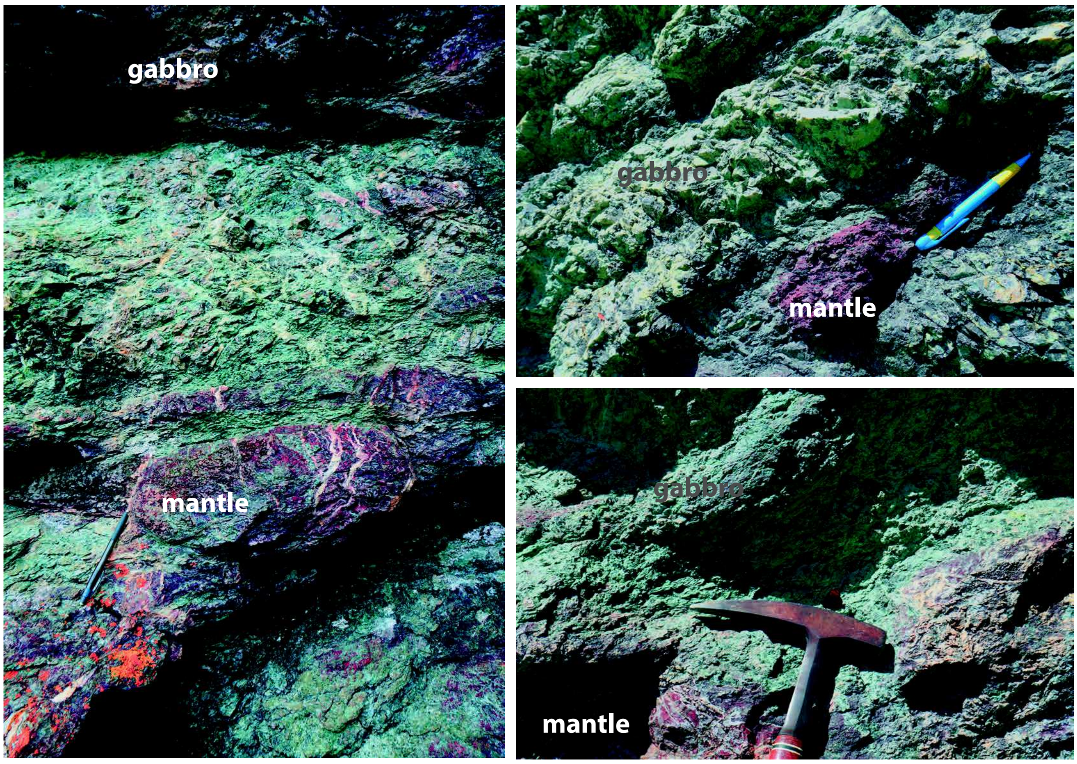
Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.



Gabbro (host rocks)

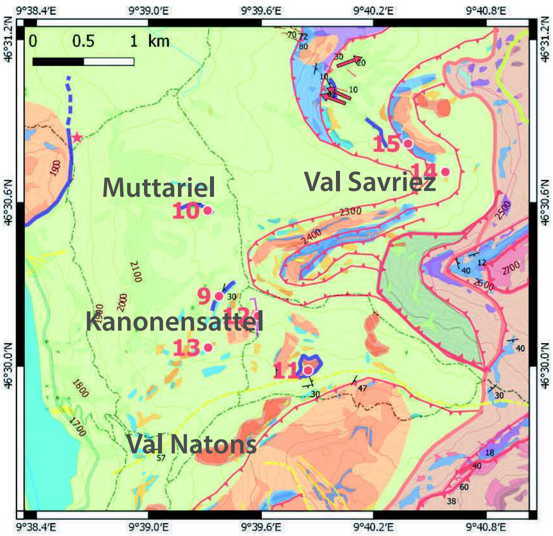
Cataclasited gabbro



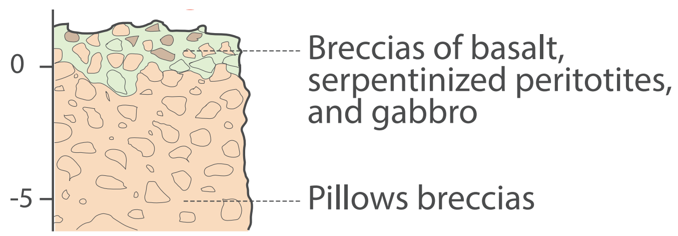
Mega breccias reworking serpentinized peridotites, ophicalcites and gabbro with serpentine arenite matrix

Annex 1.2.15
Lower Platta unit
Val Nattons, Log 12

Location of Val Nattons area



Val Nattons, Log 12



Lithologies

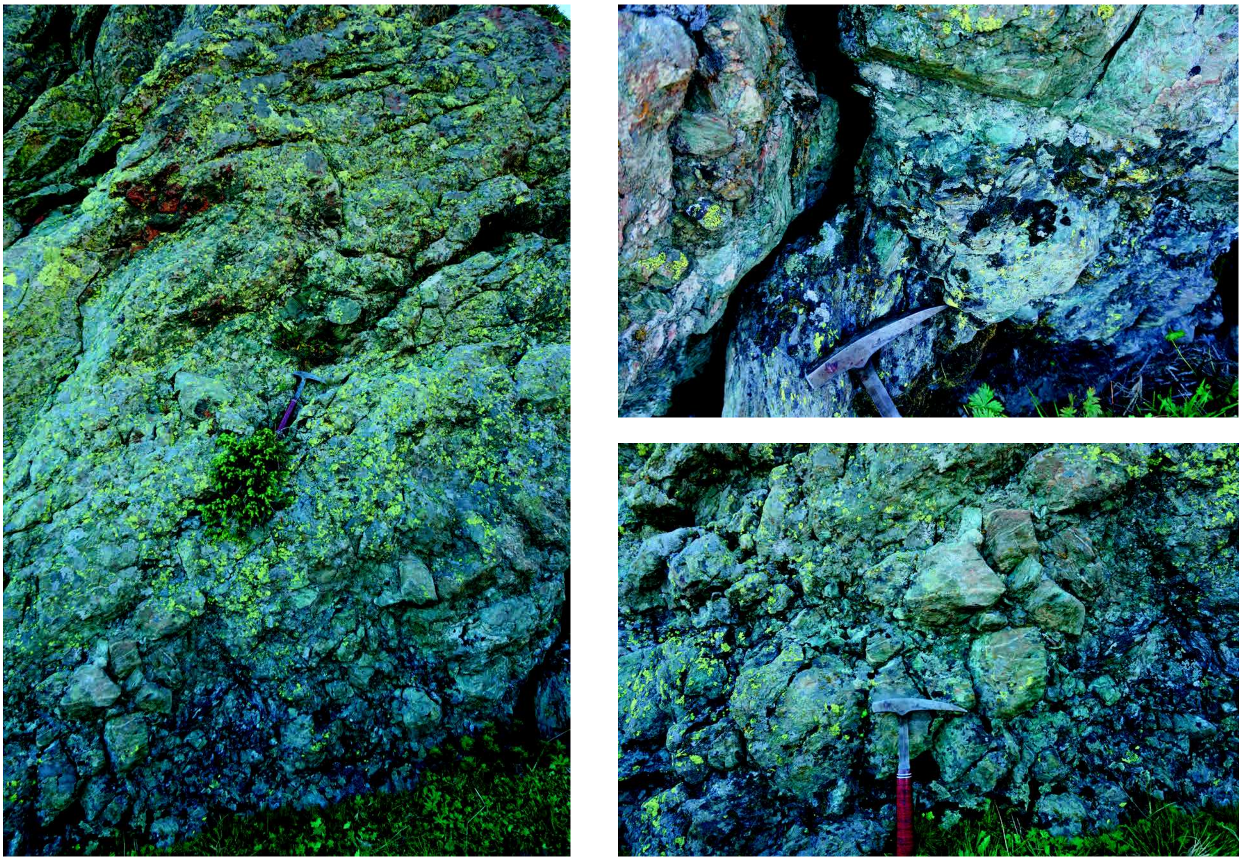
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

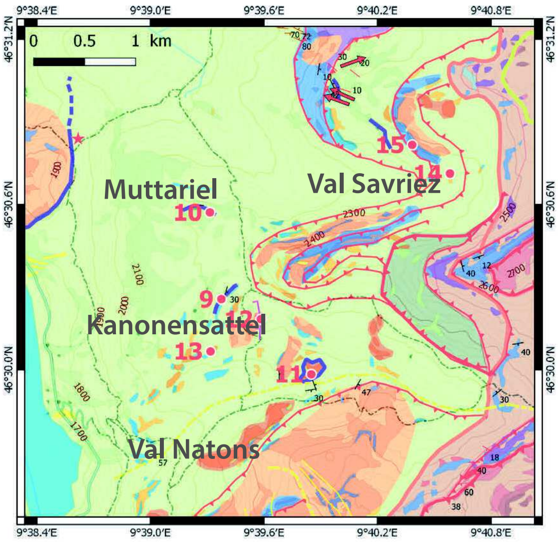
- Normal faults
- Lower Platta det.
- Upper Platta det.



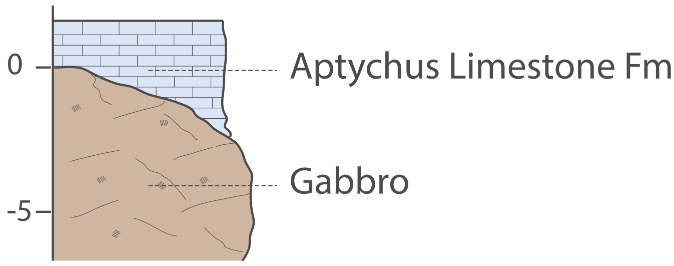
breccias reworking basalt and serpentinised and ophicalcitised peridotites and rare flaser gabbro

Annex 1.2.16
Lower Platta unit
Val Nattons, Log 13

Location of Val Nattons area



Val Nattons, Log 13



Lithologies

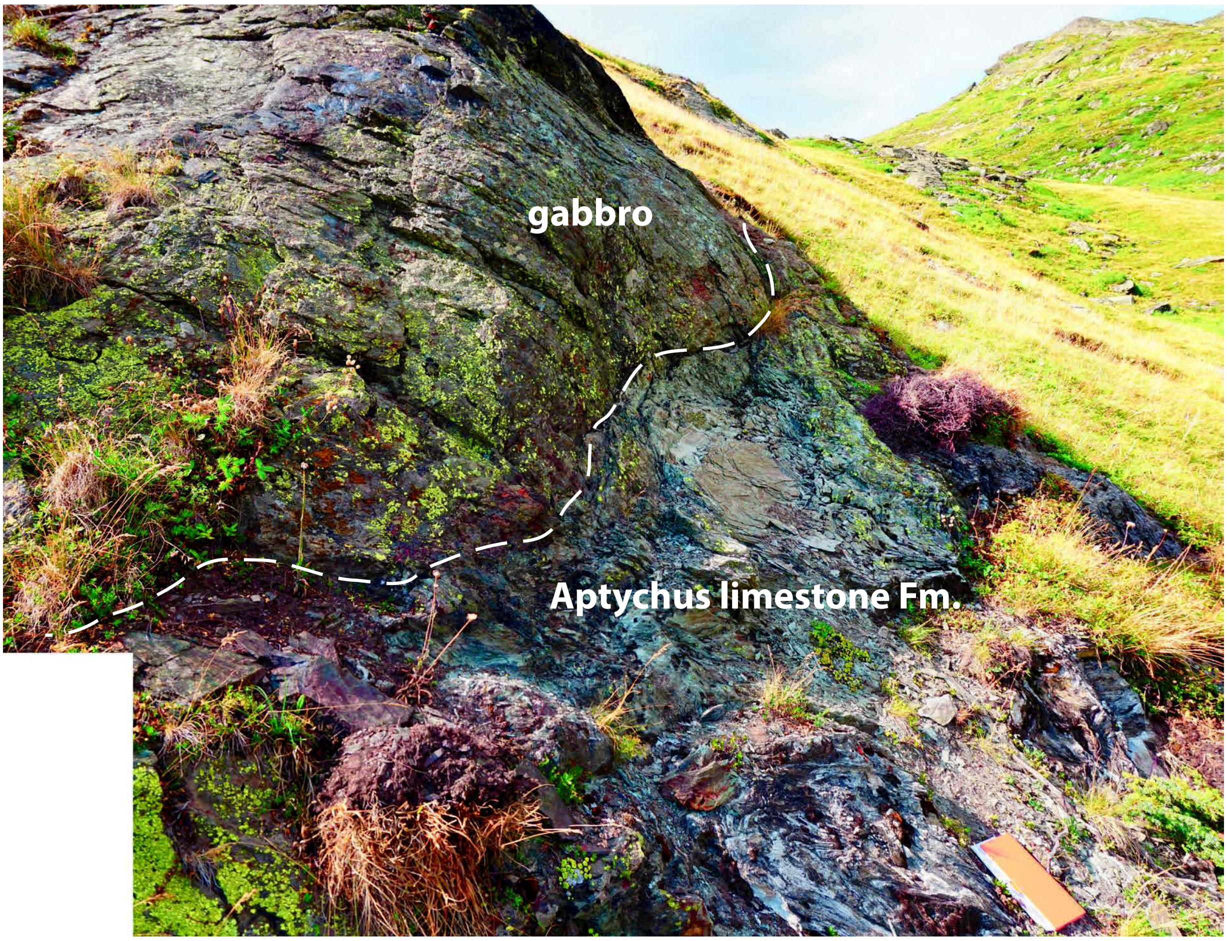
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

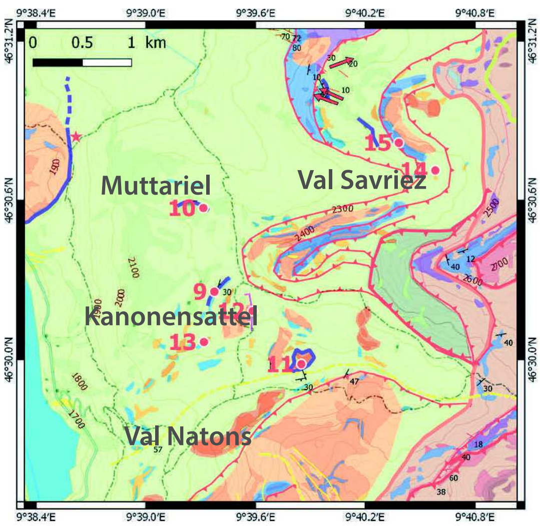
- Normal faults
- Lower Platta det.
- Upper Platta det.

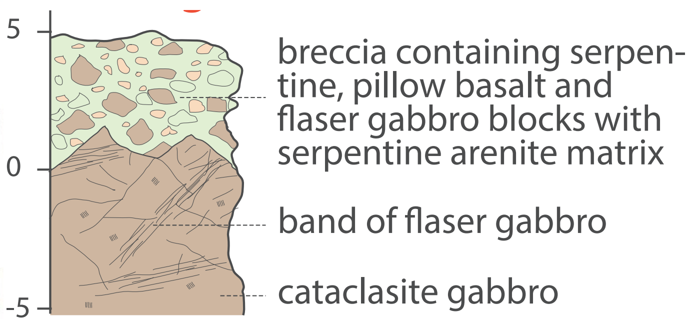

gabbro
Aptychus limestone Fm.

Annex 1.2.17
Lower Platta unit
Val Savriez, Log 14

Location of Val Savriez area

Val Savriez, Log 14





Lithologies

- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

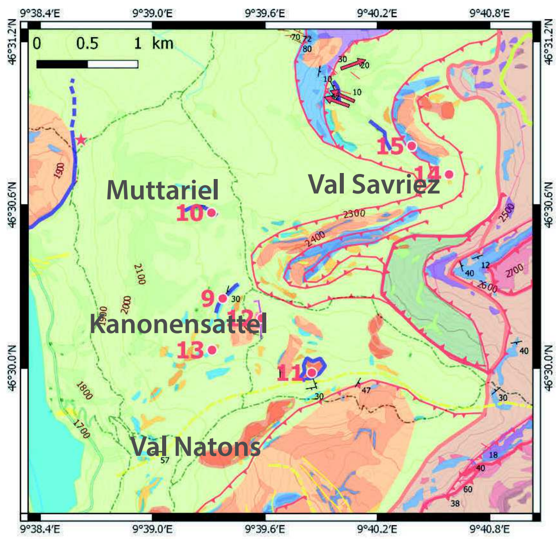
Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.

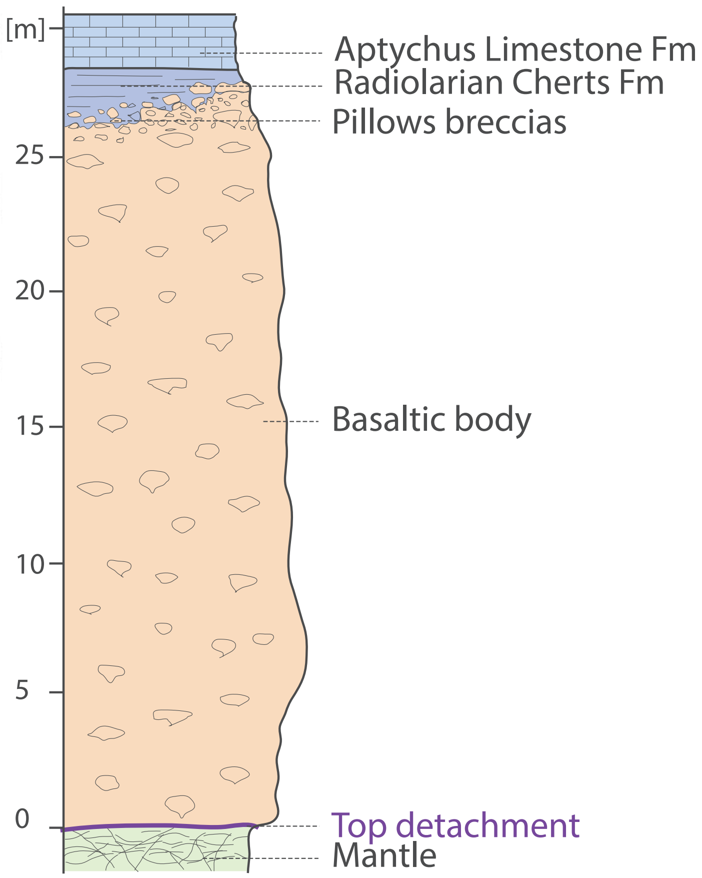
Breccias reworking flaser gabbro, pillows basalt and serpentine with a serpentine arenite matrix

Annex 1.2.18
Lower Platta unit
Val Savriez, Log 15

Location of Val Savriez area



Val Savriez, Log 15



Lithologies

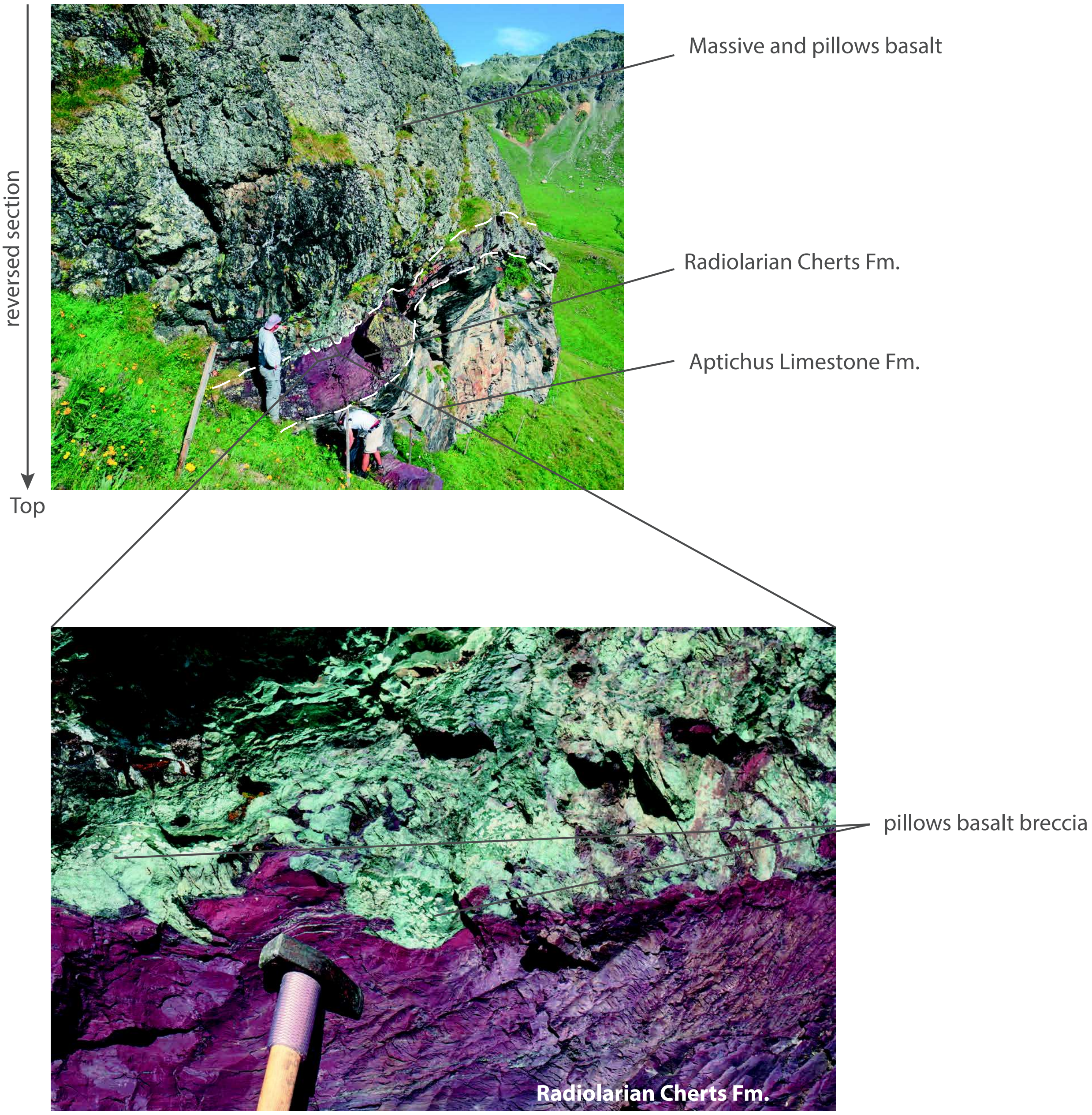
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

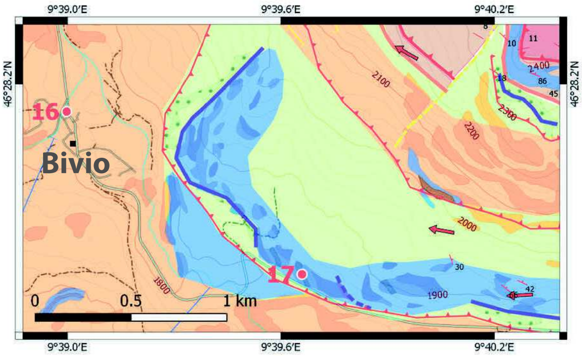
- Normal faults
- Lower Platta det.
- Upper Platta det.



Massive and pillows basalt
Radiolarian Cherts Fm.
Aptichus Limestone Fm.
reversed section
Top
pillows basalt breccia
Radiolarian Cherts Fm.

Annex 1.2.19
Lower Platta unit
Bivio, Log 16

Location of Bivio area



Lithologies

- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

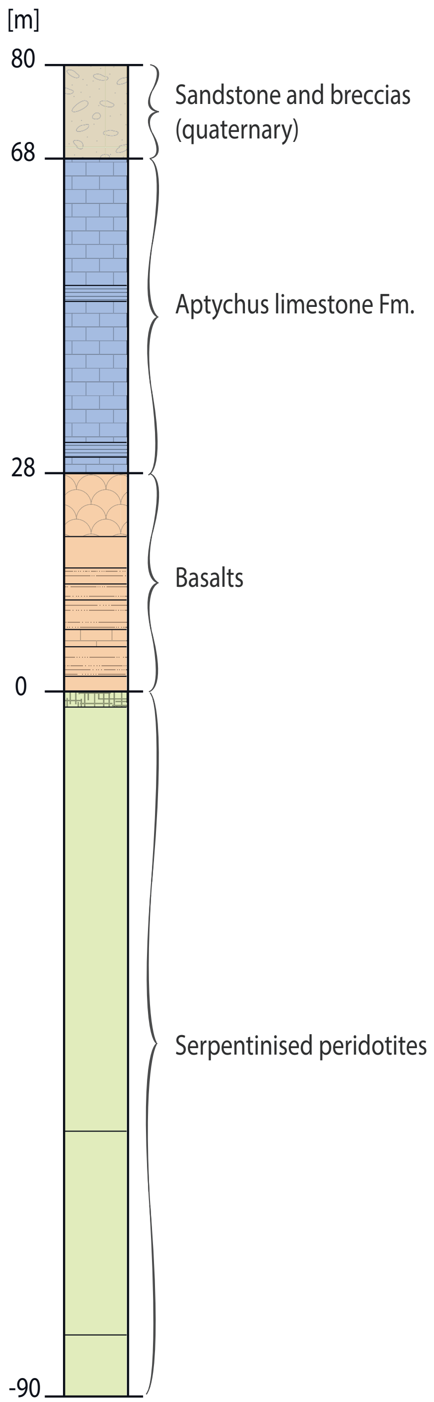
Alpine structures

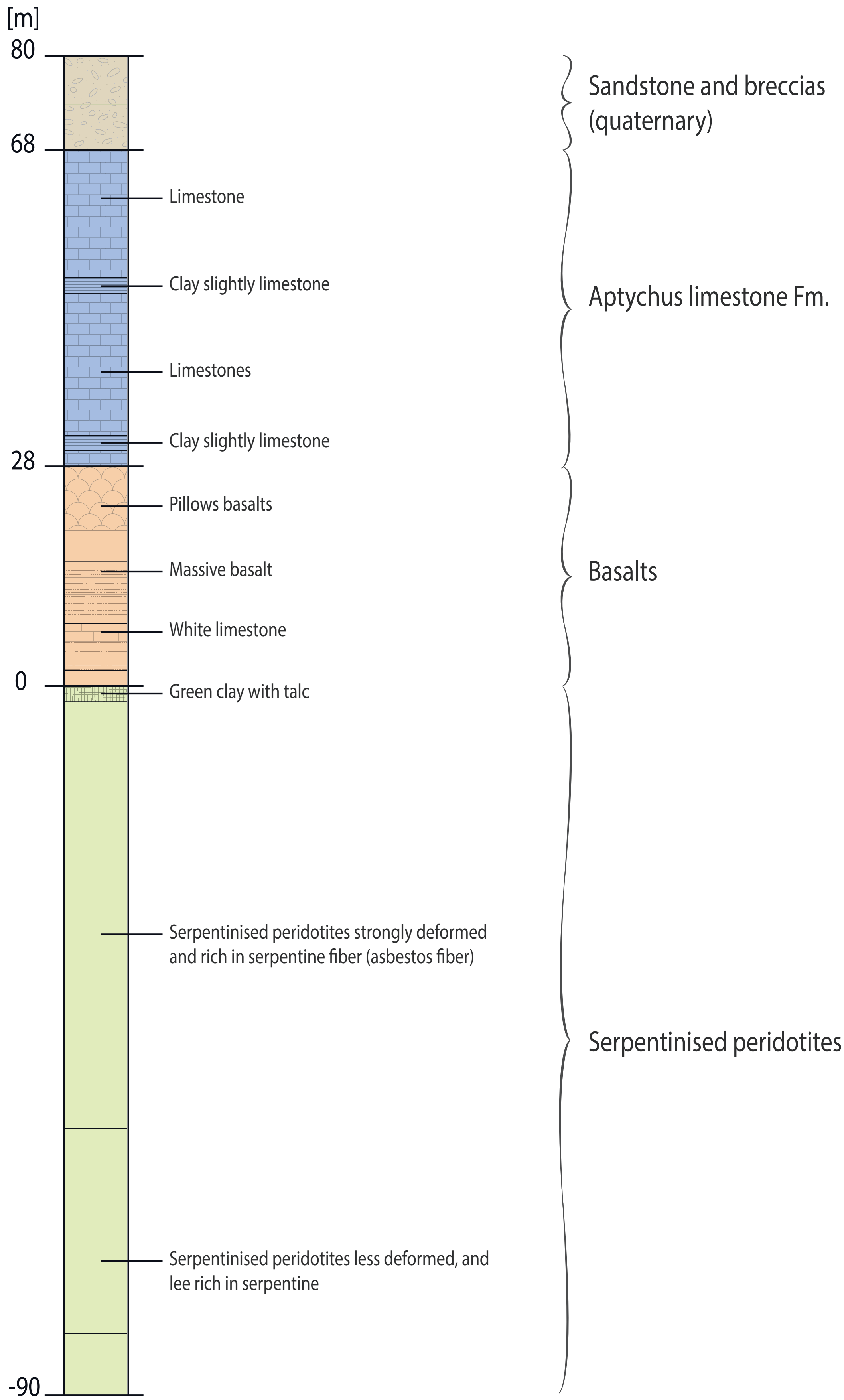
- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.

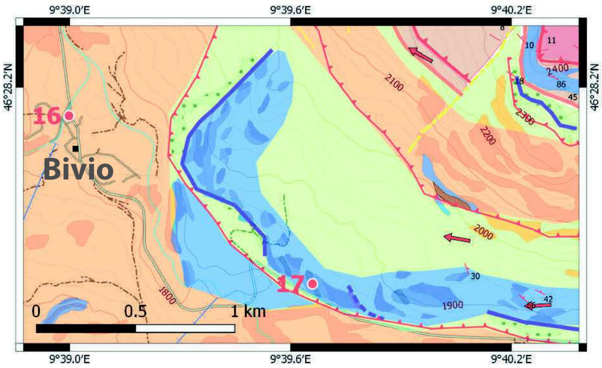
Bivio, Log 16



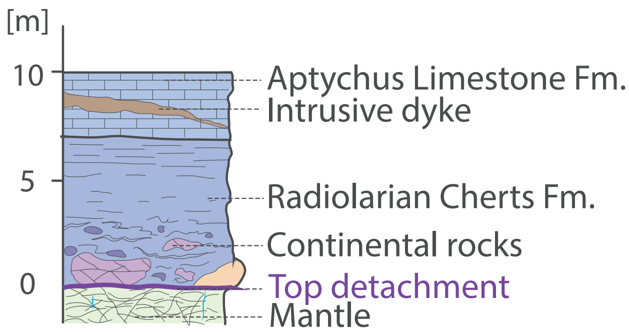

[m]
80
68
28
0
-90
Limestone
Clay slightly limestone
Limestones
Clay slightly limestone
Pillows basalts
Massive basalt
White limestone
Green clay with talc
Serpentinised peridotites strongly deformed and rich in serpentine fiber (asbestos fiber)
Serpentinised peridotites less deformed, and lee rich in serpentine
Sandstone and breccias (quaternary)
Aptychus limestone Fm.
Basalts
Serpentinised peridotites

Annex 1.2.20
Lower Platta unit
South Bivio, Log 17

Location of Bivio area



Bivio, Log 17



Lithologies

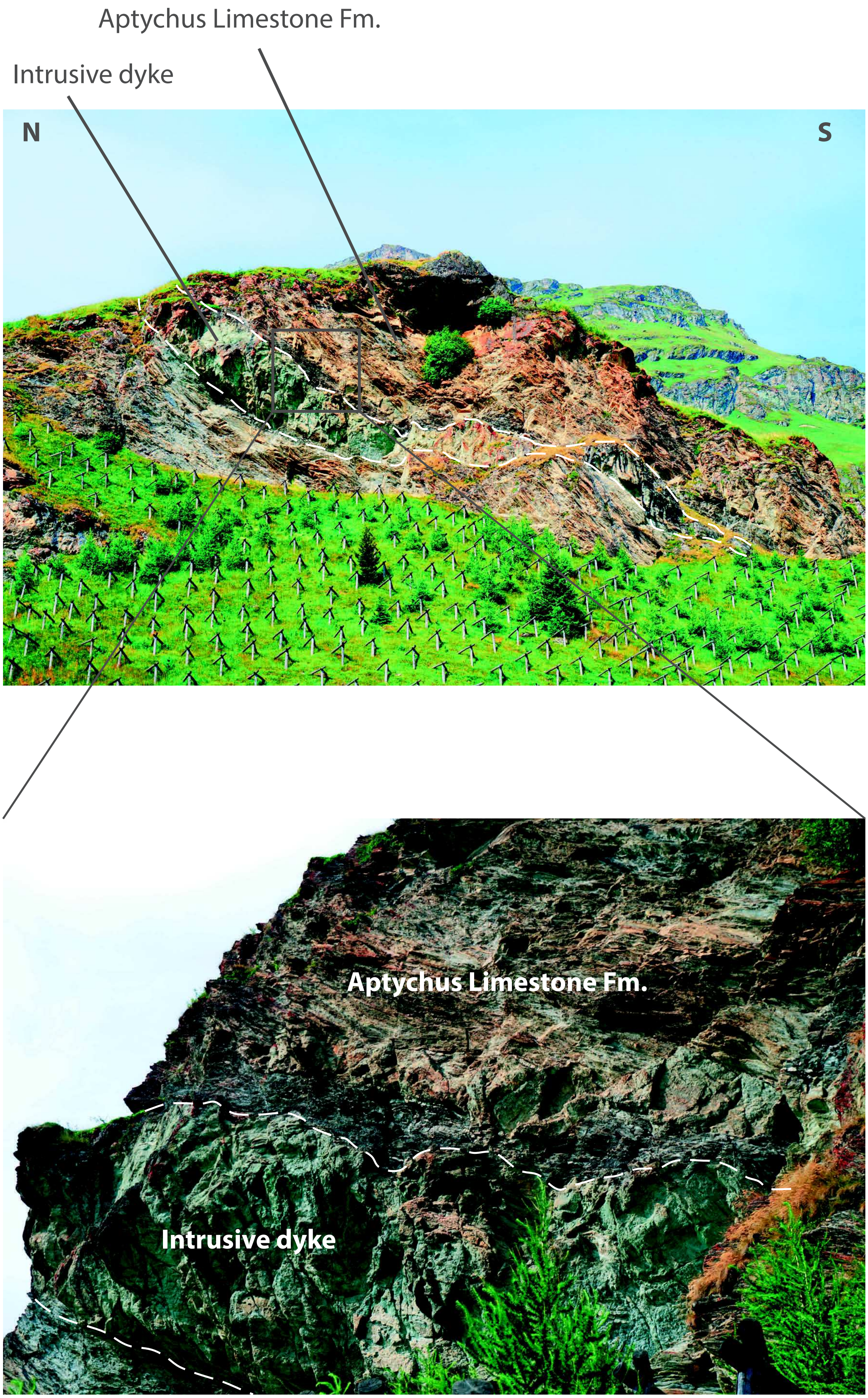
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

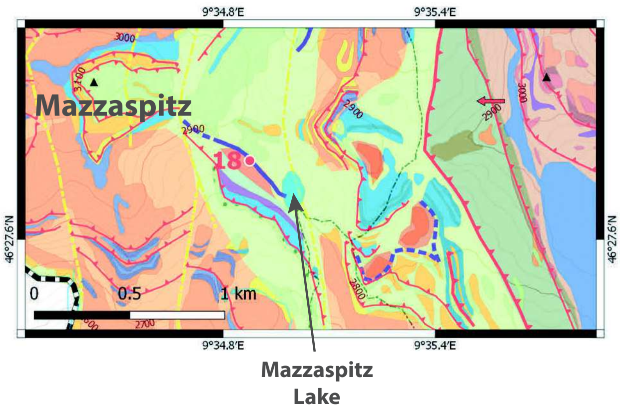
Jurassic structures (Pre-Alpine)

- Normal faults
- Lower Platta det.
- Upper Platta det.

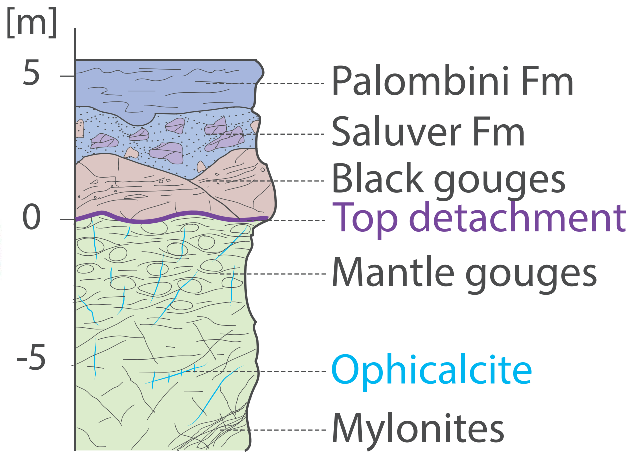

Aptychus Limestone Fm.
Intrusive dyke
N
S
Aptychus Limestone Fm.
Intrusive dyke

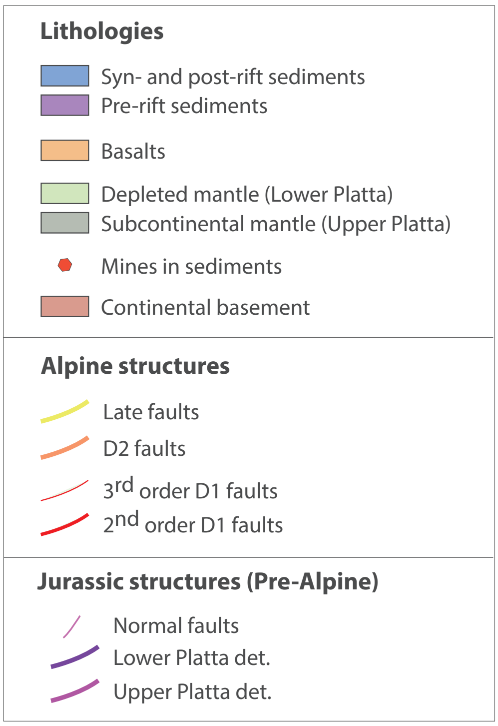
Annex 1.2.21
Lower Platta unit
Mazzaspitz, Log 18

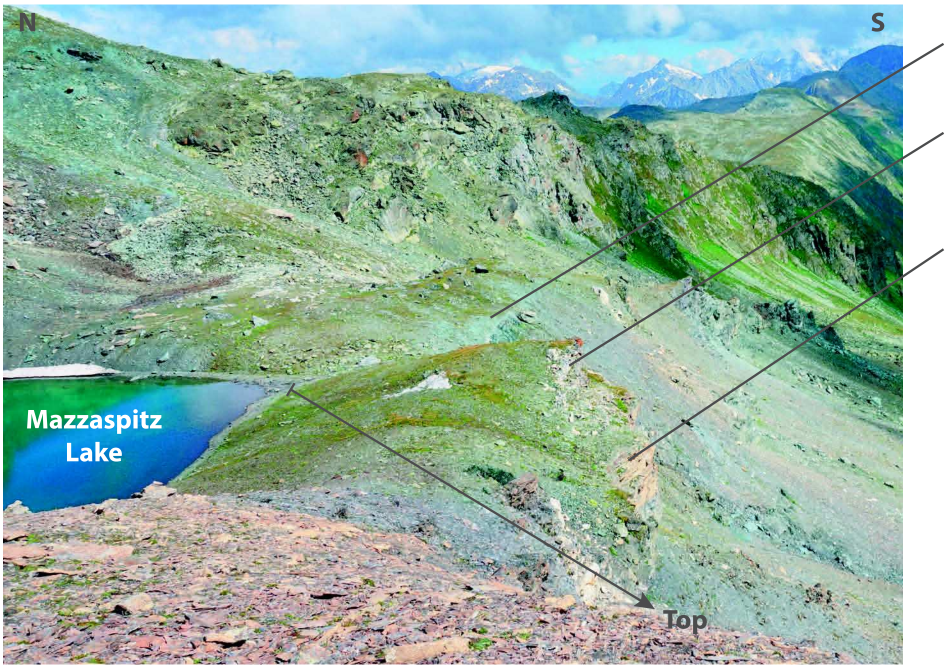
Location of Mazzaspitz area



Mazzaspitz, Log 18

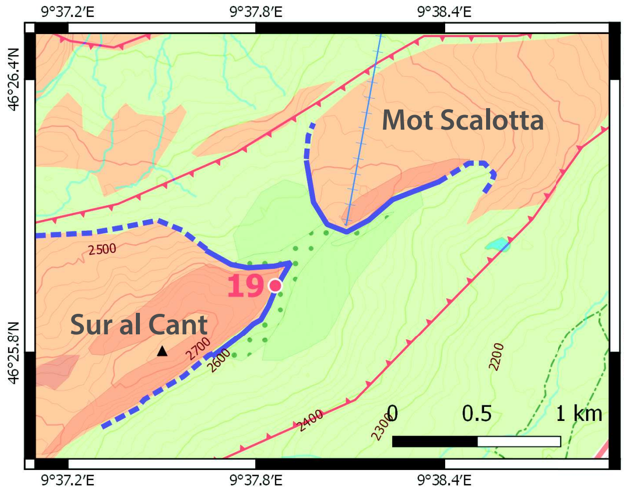




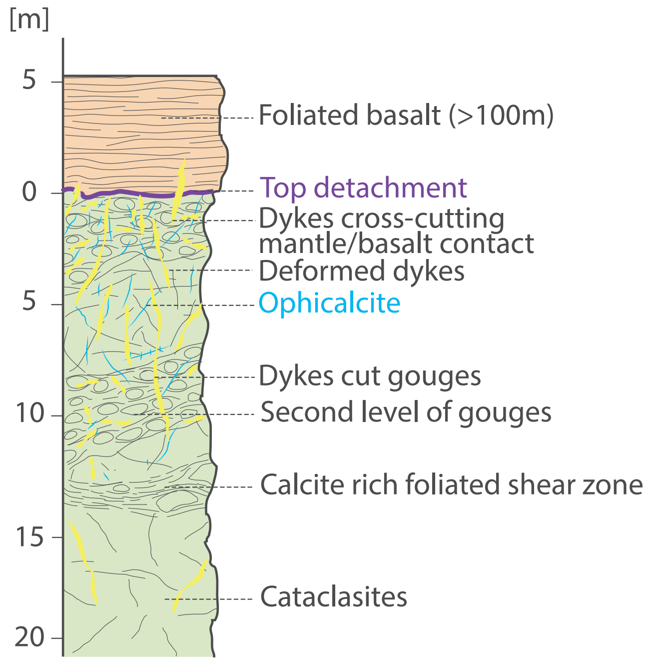

N
S
Mazzaspitz Lake
Top
serpentinite
blocks of dolomites, continental basement and Saluver Fm.
Palombini Fm.

Annex 1.2.22
Lower Platta unit
Sur al Cant, Log 19

Location of Sur al Cant area



Sur al Cant, Log 19



Lithologies

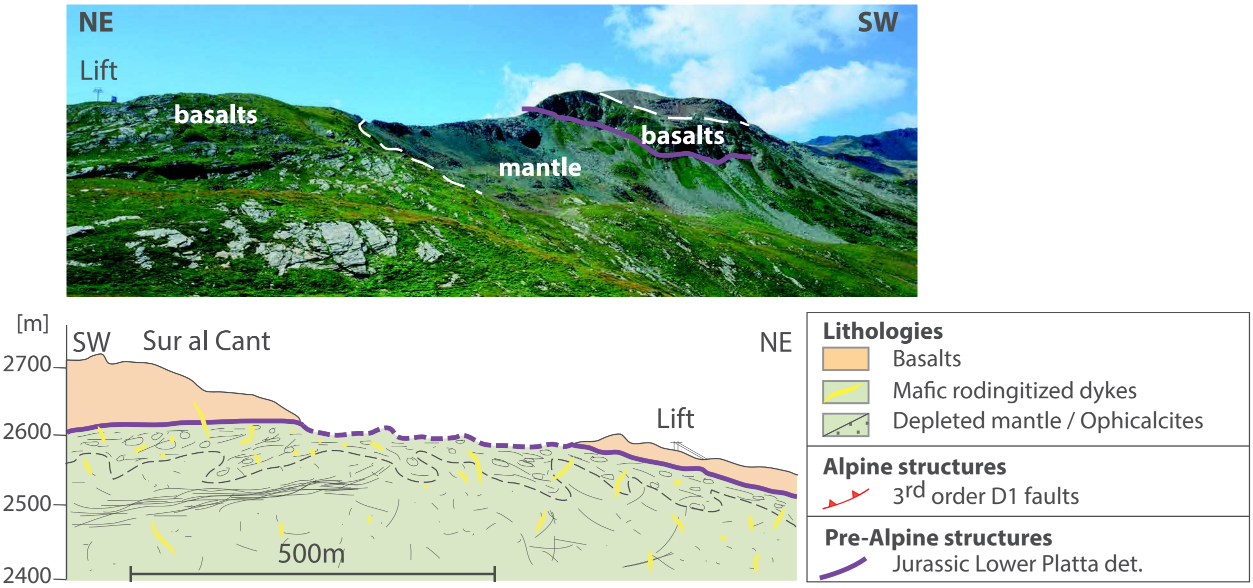
- Syn- and post-rift sediments
- Pre-rift sediments
- Basalts
- Depleted mantle (Lower Platta)
- Subcontinental mantle (Upper Platta)
- Mines in sediments
- Continental basement

Alpine structures

- Late faults
- D2 faults
- 3rd order D1 faults
- 2nd order D1 faults

Jurassic structures (Pre-Alpine)

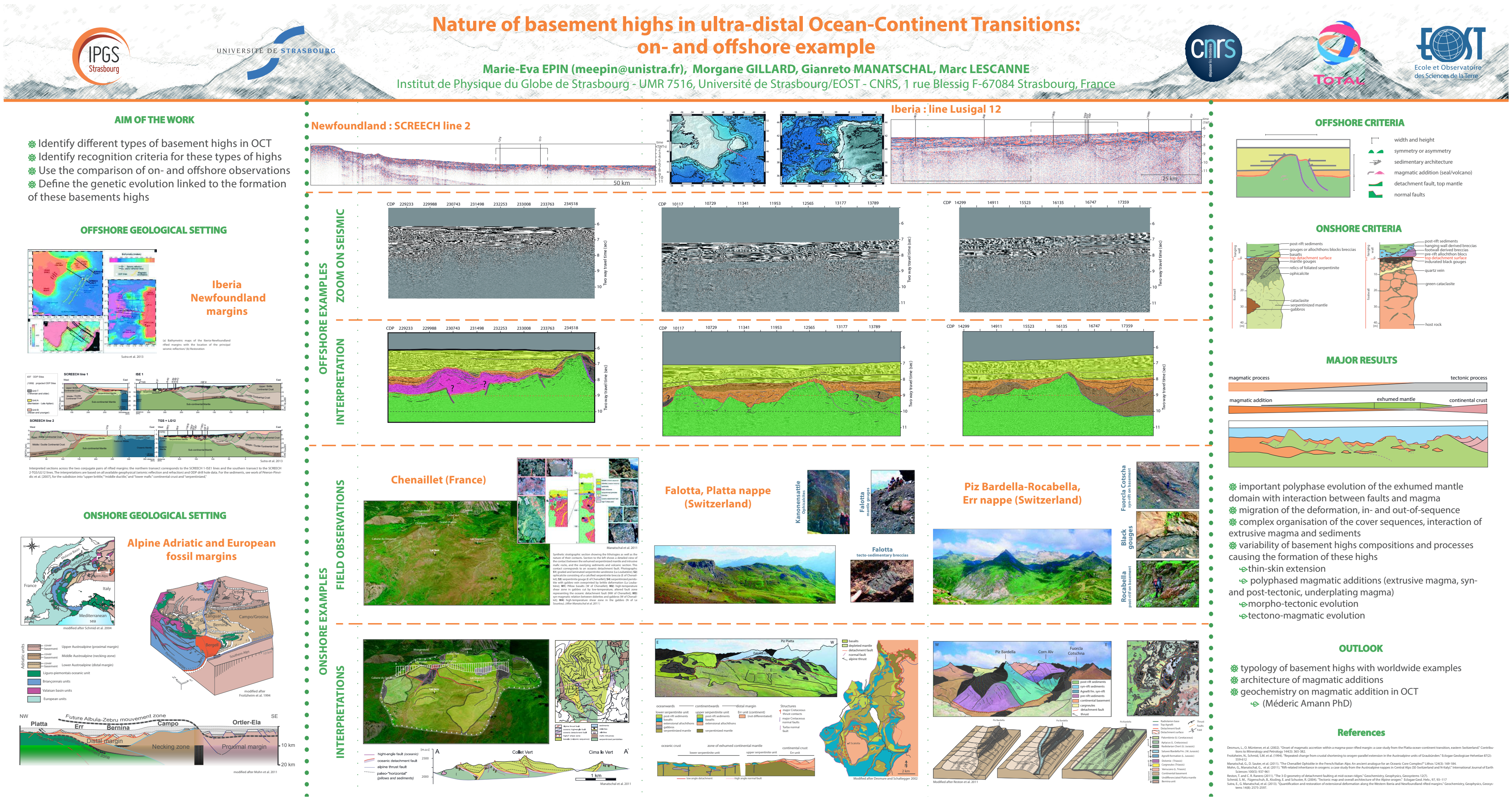
- Normal faults
- Lower Platta det.
- Upper Platta det.


NE
SW
Lift
basalts
basalts
mantle
[m]
2700
2600
2500
2400
SW
Sur al Cant
NE
Lift
500m
Lithologies
Basalts
Mafic rodingitized dykes
Depleted mantle / Ophicalcites
Alpine structures
3rd order D1 faults
Pre-Alpine structures
Jurassic Lower Platta det.


Basalt
serpentinite
serpentinite
Top detachement surface
Contact serpentinite and basalt
Rodingitized
mafic dykes

Annex 2.

Poster prepared for the EGU 2016 - 11669



Annex 3.1.

Birth of an oceanic spreading center at a magma-poor rift system

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Publish in Scientific reports, 2017
DOI:10.1038/s41598-017-15522-2

Introductory paragraph

Oceanic crust is continuously created at mid-oceanic ridges and seafloor spreading represents one of the main processes of plate tectonics. However, if oceanic crust architecture, composition and formation at present-day oceanic ridges are largely described, the processes governing the birth of a spreading center remain enigmatic. Understanding the transition between inherited continental and new oceanic domains is a prerequisite to constrain one of the last major unsolved problems of plate tectonics, namely the formation of a stable divergent plate boundary. In this paper, we present newly released high-resolution seismic reflection profiles that image the complete transition from unambiguous continental to oceanic crusts. Based on these high-resolution seismic sections we show that onset of oceanic seafloor spreading is associated with the formation of a hybrid crust in which thinned continental crust and/or exhumed mantle is sandwiched between magmatic intrusive and extrusive bodies. This crust results from a polyphase evolution showing a gradual transition from tectonic-driven to magmatic-driven processes. The results presented in this paper provide a characterization of the domain in which lithospheric breakup occurs and enable to define the processes controlling formation of a new plate boundary.

Annex 3.2.

Reappraisal of the Magma-rich versus Magma-poor Rifted Margin Archetypes

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2 Department of Earth, Ocean & Ecological Sciences, University of Liverpool, Liverpool L69 3GP, United Kingdom
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(under publication in Geological society special publication)

Abstract

Rifted margins are often classified based on their magmatic budget only. We re-examine the prevailing model that magma-rich margins have excess decompression melting at lithospheric breakup compared with steady state seafloor spreading while magma-poor margins have suppressed melting.

We investigate the magmatic budget related to lithospheric breakup along two high-resolution long-offset deep reflection seismic profiles across the SE Indian (magma-poor) and Uruguayan (magma-rich) rifted margins. Resolving the magmatic budget is difficult and several interpretations are plausible for each case, implying different melting rates and mechanisms to achieve lithospheric breakup. We show that seismic observations of the Uruguayan and other magma-rich margins could be explained not by excess decompression melting compared with steady-state seafloor spreading but rather by a gradual increase in decompression melting with an early onset relative to crustal breakup. The converse, where the onset of decompression melting is late compared with the timing of crustal breakup leads to mantle exhumation and magma-poor margin formation (eg. SE-India).

This work questions the relevance of margin classification based solely on magmatic volumes; considerations on the timing of the onset of decompression melting relative to crustal thinning may be more important than the magmatic budget for unravelling the evolution of rifted margin.

Annex 3.3.

Breaking up continents at magma-poor rifted margins: a seismic vs. outcrop perspective

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1 EOST/IPGS Universitè de Strasbourg, Rue Blessig, 1, F-67084 Strasbourg Cedex (F).
2 Dipartimento di Scienze della Terra e dell'Ambiente, Università degli Studi di Pavia, Via Ferrata, 1, 27100 Pavia (I).

(in prep for Terra Nova)

Abstract

The breakup of continents at magma-poor rifted margins and the subsequent formation of first oceanic crust are complex, yet little understood processes that account for intricate interactions between tectonic and magmatic processes. Whereas high resolution seismic data are able to resolve the complex, first order architecture of Ocean Continent Transitions (OCTs), the direct access to rocks from present-day margins remains exceptional and limited to deep sea drilling. In this study, we combine seismic observations from the East Antarctica margin (GA228) with field observations from the Bracco-Levanto area (Northern Apennine/Italy) representing modern and fossil examples of ultra-distal magma-poor rifted margins, respectively. The combination of detailed structural mapping and petrological studies of rocks from fossil examples with first-order architectural features observed in seismic sections from present day OCTs enables to bridge the different observation scales. Field data suggest that despite mantle rocks are exhumed along major detachment faults, the magmatic budget is not null as magma is present throughout the exhumation process. In addition, extensional detachment faults are truncated by later high-angle normal faults that act as feeders for the emplacement of massive syn-extensional basalts. These observations suggest a polyphase tectonic and magmatic evolution of the ultra-distal margin prior to formation of first oceanic crust that can be studied in detail only by combining seismic and outcrop observations.

UNIVERSITÉ DE STRASBOURG

Ecole et Observatoire des Sciences de laTerre

Marie-Eva EPIN

Morpho-tectono-magmatic evolution and reactivation of ultra-distal magma-poor rifted margins: the fossil Err-Platta Ocean-Continent-Transition (SE Switzerland) and comparison to present-day analogues

Abstract

The aim of this study is to investigate the morpho-structural and magmatic evolution of magma-poor distal rifted margins, as well as their reactivation.

This study is focused on the fossil distal margins of the Alpine Tethys and notably on the distal Adriatic margin. The study of the reactivation of these domains, preserved in the Err and Platta nappes (southeast Switzerland), shows that alpine thrusts (2nd and 3rd order) principally reworked former rift structures.

The Err nappe can be restored as a hyper-extended domain characterized by a system of detachment faults with a complex 3D architecture. This system of detachment faults evolves in-sequence and leads to the continental crust separation and the exhumation of subcontinental mantle. The spatial evolution of these faults seems to be influenced by the occurrence of inherited structures (Permian faults) and pre-rift evaporites that controlled the formation of allochthon blocks.

The Platta nappe corresponds to a subcontinental exhumed mantle domain associated to an increase of syn-tectonic magmatic additions oceanwards. The most distal domain is interpreted as the relic of a dome-shaped structure capped by a detachment fault and crosscut by latter normal faults. These faults facilitated the emplacement of basalts and fluid circulations.

The approach developed in this thesis enabled a better understanding of one example of a distal and ultra-distal magma-poor rifted margin, as well as to discuss processes related to the formation and reactivation of plate boundaries.

Key-words*: Distal magma-poor rifted margins, hyper-extended domains, exhumed mantle domains, 3D architecture, reactivation, Err-Platta nappe, Alps.*

Résumé

Cette thèse a pour but d'étudier l'évolution morpho-structurale et magmatique des marges distales pauvres en magma, ainsi que leur réactivation.

Cette étude est focalisée sur les marges fossiles distales (marge Adriatique) de la Téthys Alpine. L'étude de la réactivation de ces domaines, préservés dans les nappes de l'Err et de la Platta (sud-est de la Suisse), montre que les chevauchements alpins (2ème et 3ème ordre) réactivent principalement d'anciennes structures de rift.

La nappe de l'Err peut ainsi être restaurée et correspond à un ancien domaine de croute hyper-amincie caractérisé par un système de failles de détachement à l'architecture 3D complexe qui évolue en séquence pour amener à la rupture continentale et l'exhumation de manteau sous continental. L'évolution spatiale de ces failles apparait influencée par la présence de structures héritées (failles permiennes) et d'évaporites pré-rift qui contrôlent la formation de blocs allochtones.

La nappe de la Platta correspond à un domaine de manteau sous continental exhumé, associé à de plus en plus d'additions magmatiques syn-tectoniques dans les parties les plus distales. Le domaine le plus distal est interprété comme la relique d'une structure en dôme coiffée par une faille de détachement et recoupée par la suite par des failles normales qui favorisent la mise en place de basaltes et la circulation de fluides.

L'approche utilisée dans cette thèse a permis de mieux contraindre un exemple d'architecture de marge distale pauvre en magma et de discuter plus généralement des processus responsables de la formation et de la réactivation des limites de plaque.

Mots clefs*: Marges distales pauvres en magma, domaines hyper-étirées, domaines de manteau exhumé, architecture 3D, réactivation, nappe d'Err-Platta, Alpes*