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Autor: Manatschal, Gianreto / Nievergelt, Peter

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A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland)

GIANRETO MANATSCHAL[1] & PETER NIEVERGELT[2]

Key words: Austroalpine, South Penninic, Alpine tectonics, rifting tectonics, continent-ocean transition, low-angle detachment faults, mantle exhumation

ABSTRACT

Kinematic inversion of the Alpine deformation in the Lower Austroalpine Err nappe and the Upper Penninic Platta nappe in the eastern Central Alps allows one to reconstruct the continent-ocean transition of a segment of the Mesozoic Tethys that is characterized by a rift-related detachment system. The age of the low-angle detachment system is constrained by the following observations: 1) the detachment faults truncate high angle normal faults and associated tilted blocks comprising Triassic dolomite, 2) syn-rift sediments of post-Early-Toarcian age seal the fault planes, and 3) fault rocks derived from these detachment faults occur as clasts in the syn-rift sediments. Hence, the detachment faults had to be active after or during tilting of the blocks and the formation of the Middle Jurassic depositional basins but had to be exhumed at the sea floor before the deposition of the youngest syn-rift sediments and the sedimentation of the upper Middle to Upper Jurassic Radiolarite Formation which is the first one deposited on both continental and oceanic basement.

In the Err nappe, the Middle Jurassic detachment system is defined by at least two top-to-the-west low-angle detachment faults. One of them has a displacement of more than 10 km, and the investigation of the fault rocks indicates that this detachment fault was active in an upper crustal level (< 300°C). The detachment system forms a break-away in the east and cuts down towards the west into the lithospheric mantle. Uplift and westwards stepping of low-angle normal faulting explain the oceanward decreasing size of the hanging wall blocks and the oceanward decreasing proportion of continental basement within these blocks. The emplacement of extensional allochthons of upper crustal composition on top of tectonically exhumed serpentinized mantle lithosphere, both covered by pillow basalts and sealed by post-rift sediments is related to top-to-the-west displacement along this detachment system.

The extensional top-to-the-west transport direction, detachment faults cutting down into deeper crustal levels towards the west, the rift-related isostatic movements, inferred from the sedimentary evolution, and the lack of rift-related volcanic activity suggest that the former segment of this southern margin of the Tethys ocean was a non-volcanic and sediment-starved lower plate margin with a main detachment system dipping towards the west, beneath the European continent.

ZUSAMMENFASSUNG

Die kinematische Inversion der Alpinen Deformation in der unterostalpinen Err-Decke und in der oberpenninischen Platta-Decke in Graubünden ermöglicht eine Rekonstruktion des Kontinent-Ozean-Überganges eines Segmentes der mesozoischen Tethys. Dieser Kontinent-Ozean-Übergang ist gekennzeichnet durch ein Abschersystem, das während des Riftings angelegt wurde.

Das Alter des flachen Abschersystems ist durch folgende Beobachtungen festgelegt: 1) die flachen Abscherflächen schneiden sowohl die steilen Abschiebungsbrüche als auch deren Kippschollen ab, welche triassische Dolomite enthalten, 2) synrift-Sedimente mit einem post-früh-Toarcian Alter überlagern direkt die Bruchflächen der flachen Abscherflächen, und 3) die Tektonite von den flachen Abscherflächen findet man auch als Klasten in den synrift-Sedimenten. Aufgrund dieser Beobachtungen nehmen wir an, dass mindestens eine der flachen Abscherflächen am Meeresboden freigelegt wurde während gleichzeitiger Ablagerung der synrift-Sedimente, aber nach dem Kippen der Kippschollen und somit auch nach der Bildung der ersten mitteljurassischen Becken.

In der Err-Decke besteht das mitteljurassische Abschersystem aus mindestens zwei westvergenten flachen Abschiebungsflächen. Eine davon, die Err-Abscherfläche, weist einen Versatz von mindestens 10 km auf, und die Untersuchung der Tektonite zeigt, dass die Err-Abscherfläche in einem erdoberflächennahen Krustenbereich aktiv gewesen ist (< 300°C). Das Abschersystem bildete Brüche aus, die im Osten die Oberfläche erreichten und gegen Westen in den lithosphärischen Mantel reichten. Die synrift-Hebung der Abscherflächen und das West- d.h. Ozeanwärtsschreiten der neu ausgebildeten Abschiebungsflächen erklären, weshalb die Grösse der Kippschollen und das Verhältnis zwischen kontinentalen Grundgebirgsgesteinen und mesozoischen Sedimenten in den Kippschollen gegen Westen, d.h. gegen den Ozean hin abnehmen. Die Platznahme der Kippschollen auf der tektonisch freigelegten, serpentinitisierten Mantellithosphäre, beide mit oberjurassischer Kissenlava und postrift-Sedimenten versiegelt, erfolgte entlang den Abscherflächen.

Die Transportrichtung (top-Westen), das Hinunterschneiden der Abschiebungsflächen gegen Westen in tiefere Krustenbereiche und die isostatischen Bewegungen während des Riftings, die in den Sedimentablagerungen gespeichert sind, zeigen, dass dieses Segment des südlichen Kontinentalrandes des mesozoischen Tethys-Ozeans einen amagmatischen, «lower plate» Kontinentalrand darstellt mit einem Hauptabscherhorizont, der gegen Westen unter den europäischen Kontinent einfiel.

[1] Danish Lithosphere Centre, Øster Volgade 10 L, DK–1350 København K, Present address: Geologisches Institut, ETH Zentrum, CH–8092 Zürich
[2] Institut für Mineralogie und Petrographie, ETH Zentrum, CH–8092 Zürich

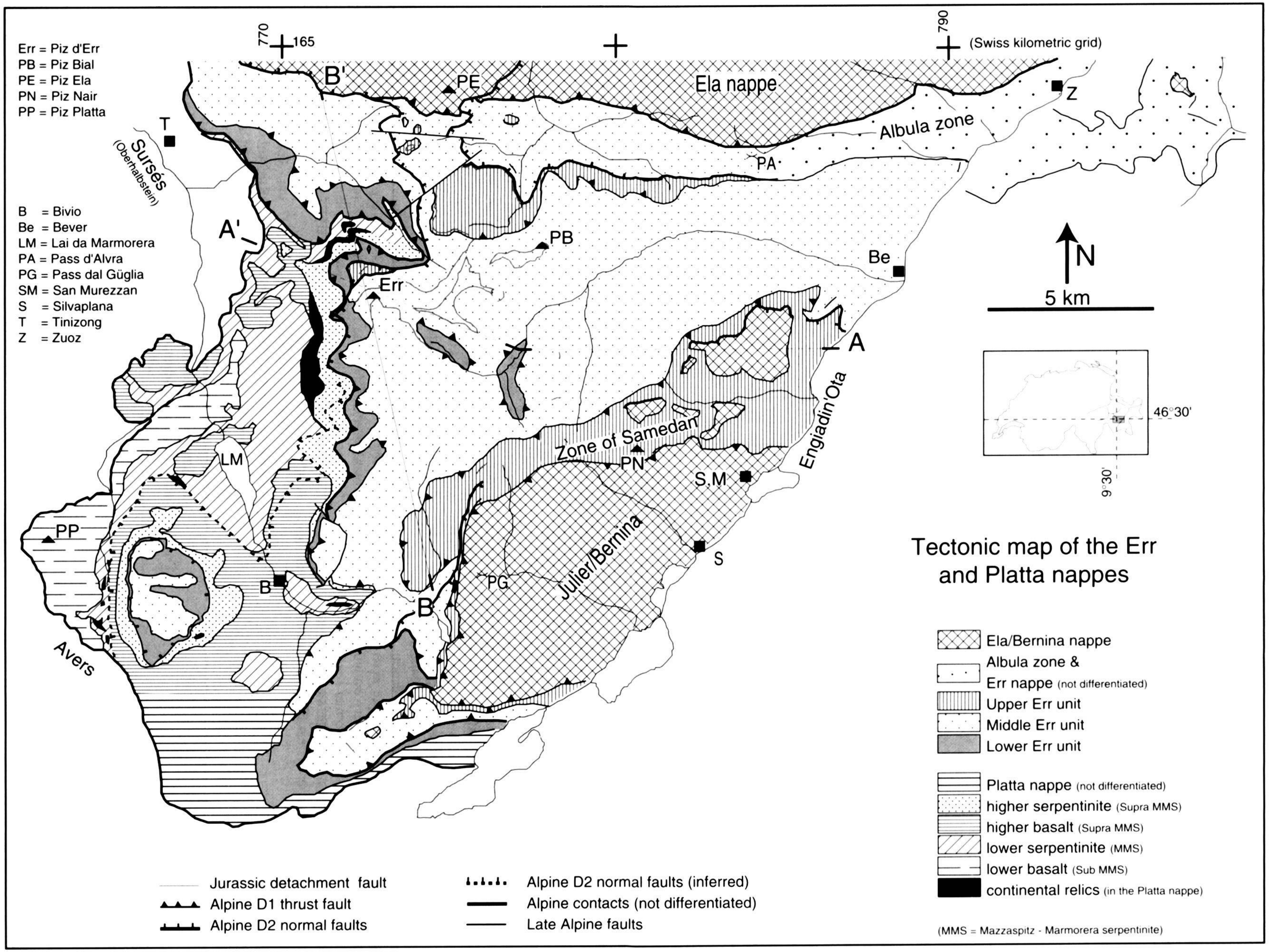


Fig. 1. Tectonic map of the Err and Platta nappes subdivided into different subunits. The subdivision of the ophiolitic Platta nappe simply refers to the position above or below the Mazzaspitz-Marmorera serpentinite.

1. Introduction

The transition from continental to oceanic crust along passive continental margins is still poorly known, as the deeper levels of modern passive continental margins are usually buried below thick sedimentary successions and therefore are not directly accessible to observation. However, seismic investigations along passive continental margins have helped to recognize some of their architecture. In particular, deep sea drilling along the Iberian margin (ODP Leg 103: Boillot et al. 1988 and ODP Leg 149: Sawyer et al. 1994) combined with seismic data has facilitated a better understanding of the relations between tectonics, sedimentation and exhumation of mantle rocks along a sediment-starved, non-volcanic margin. Today, there exists a large amount of offshore data from continental margins. In spite of all this work, the mode of rifting, simple shear (e.g. Wernicke 1985, Lister et al. 1986) versus pure shear (e.g. McKenzie 1978), and the geometry and kinematics of fault systems along passive continental margins are still highly debated. There remain open questions like: How does the lithosphere behave during rifting and breakup? What is the resulting geometry of a continent-ocean transition? What is the relation between continental basement, oceanic crust, exhumed mantle lithosphere and related syn- and post-rift sediments? What happens when a passive continental margin becomes involved in active margin evolution? These questions are of fundamental interest for the understanding of plate tectonics and the unravelling of orogenic belts.

In contrast to undeformed margins, inverted fossil margins in many mountain belts are well exposed and easily accessible for study. Where kinematic inversion is possible, fossil margins yield information about processes of rifting and drifting. In the Alps two segments of the southern margin of the Jurassic Piemont-Liguria ocean are relatively well preserved: the South Alpine and the Austroalpine-Upper Penninic segment. The two are now separated by the Tertiary Insubric line and its Cretaceous predecessors (Laubscher 1991). In the Southern Alps, the proximal parts of the continental margin can be studied and reconstructed with some confidence (e.g., von Bistram 1903, Wiedenmayer 1963, Bernoulli 1964, Gaetani 1975, Kälin & Trümpy 1977, Winterer & Bosellini 1981, Bernoulli et al. 1990, Handy & Zingg 1991, Bertotti 1991 and Bertotti et al., 1993), but the distal parts of this margin are strongly overprinted by Alpine tectonics, obscuring the original relations with the Penninic oceanic crust.

The Austroalpine-Upper Penninic segment in eastern Switzerland (Grischun or Graubünden) was interpreted already by Trümpy (1975) and Dietrich (1976) as a relic of a former Jurassic passive continental margin. However, a better understanding of Alpine tectonics combined with the knowledge of modern margins was needed to reconstruct the former continent-ocean transition in the Err and Platta nappes in Sursés (Oberhalbstein).

The aim of this paper is to summarize the relevant field observations and data collected during a Ph.D. study (Manatschal 1995) and to use these data and observations together with those of many others made over more than half a century to propose a reliable reconstruction of a former continent-ocean transition in the Err and Platta paleogeographical domains. We shall discuss temporal and geometric relations between sediments, continental basement, mantle and oceanic rocks and present evidence for a low-angle detachment system related to rifting and break-up.

2. Regional setting

The Lower Austroalpine Err nappe and the Upper Penninic Platta nappe are located in the southeastern part of Switzerland between Avers-Pass d'Alvra (Albula Pass) and Engiadin'Ota (Oberengadin) (Fig. 1). These two tectonic units belong to a stack of nappes that formed during oblique east-west directed convergence between Adria and Europe in Late Cretaceous time leading to the closure of the Piemont-Liguria segment of Tethys (e.g., Laubscher 1970, Trümpy 1975, Dietrich 1976, Weissert & Bernoulli 1985, Froitzheim & Eberli 1990, Froitzheim & Manatschal 1996). The relics of oceanic lithosphere and continental crust forming the Platta and Err nappes represent remnants of the Piemont-Liguria ocean and of the Apulian continental margin.

The Austroalpine-Upper Penninic nappe pile in the studied area was formed under conditions of deep burial diagenesis to greenschist metamorphic facies (Trommsdorff & Dietrich 1980, Trommsdorff 1983, Früh-Green et al. 1990, Ferreiro Mählmann 1995, 1996) and was overprinted by several "post-nappe" deformation phases (e.g., Froitzheim et al. 1994 and references therein). Today, the following major units or "nappe systems" can be distinguished (Fig. 1, 2):

1) The Ela/Bernina system is formed by the Julier and Bernina basement nappes and by the detached sediments of part of the Zone of Samedan (Piz Padella and Piz Schlattain), of the eastern Albula Zone and of the Ela nappe (Upper Austroalpine after Spicher [1980], Lower Austroalpine after Schmid & Froitzheim [1993]). The Ela/Bernina system south of Pass d'Alvra comprises crystalline basement rocks with a locally reduced Permo-Triassic to Upper Cretaceous sedimentary cover. Characteristic are alkaline granites of post-Variscan age and Liassic sedimentary breccias without crystalline basement clasts.
2) The Err system comprises the Err nappe, most of the Zone of Samedan and the Murtiröl-Val Vaüglia imbricates. The Err nappe can be divided into lower, middle and upper tectonic units (Manatschal 1995): a Lower, Middle and Upper unit. The Err nappe s.l. is characterized by post-Variscan granitoids and Permo-Triassic to Lower Cretaceous sediments.
3) The Platta nappe comprises mainly remnants of oceanic lithosphere and post-rift sediments. However, it also contains slivers of continental basement with Mesozoic sediments attached. In the Platta nappe, individual thrust faults

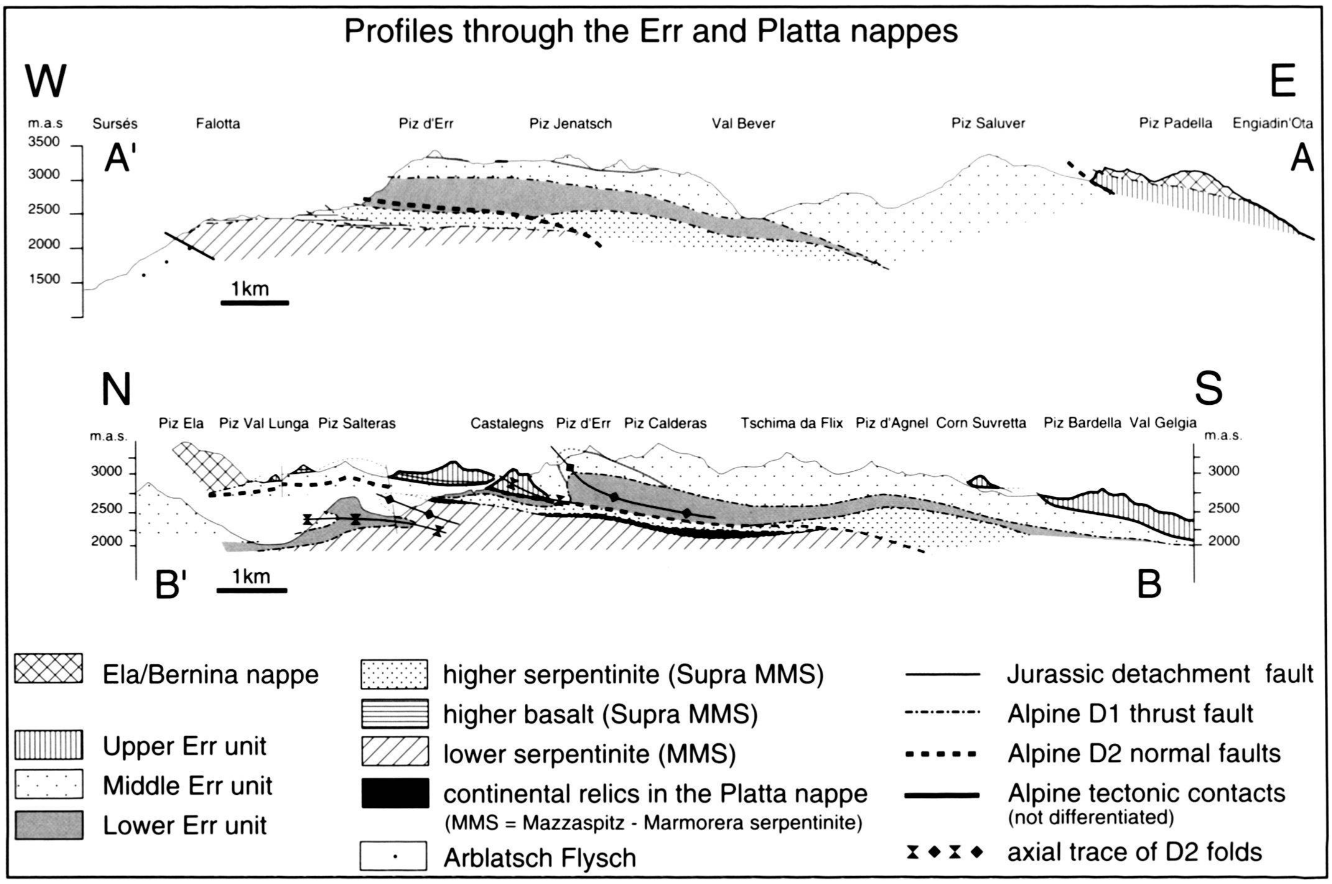


Fig. 2. Reconstructed profiles through the Err and Platta nappes (traces in Fig. 1).

are difficult to trace over large areas. The Mazzaspitz-Marmorera-Serpentinite (=MMS) (Dietrich 1969, 1970), a serpentinite body traceable throughout the northern and middle part of the Platta nappe, allows one to distinguish sheets which are in a tectonically deeper position (Sub-MMS) and sheets in a higher position (Supra-MMS). The ophiolites of the Arosa Zone in the north and the Malenco-Forno-Lizun Ophiolites in the south may have experienced a similar ocean floor history and early Alpine tectonic evolution as the Platta nappe but were much more affected by Tertiary deformation.

These three ophiolitic units, together with the Austroalpine nappes are part of an "orogenic lid", a pile of nappes formed during the Late Cretaceous top-to-the-west convergence that was transported towards the north during the Early Tertiary as a coherent package over Middle- and Lower-Penninic units (e.g. Milnes 1978, Laubscher 1983, Liniger & Nievergelt 1990, Schmid et al. 1990).

Ring et al. (1988, 1989), Hsü & Briegel (1991) and Dürr (1992) interpreted the Late Cretaceous Err-Platta boundary as a mélange structure generated during subduction of the Upper Penninic below the Austroalpine units. However, detailed mapping (e.g. Cornelius 1932, Stöcklin 1949, Heierli 1955, Dietrich 1969, Finger 1978) and a structural analysis of the area between Val d'Err and Bivio (Liniger 1992, Handy et al. 1993, Froitzheim et al. 1994, Manatschal 1995) reveal no evidence for a chaotic mélange type structure. The stratigraphically defined units are not randomly oriented rock bodies, embedded in a strongly deformed matrix, but rather suggest an imbricate fan (in the sense of Boyer & Elliott 1982) with normal-sequence thrusting and some well-defined thrusts, consisting of "oceanic crust" and exhumed mantle rocks which were eventually welded to the continental Err nappe in Late Cretaceous time.

3. Stratigraphy of the Err nappe

3.1 Basement and pre-rift sediments

The crystalline basement of the Err nappe is formed by late syn- to post-Variscan intrusive and extrusive rocks (e.g. Cornelius 1935, Staub 1948, Mercolli 1982, von Quadt et al. 1994) emplaced in and on top of polymetamorphic gneiss and schist.

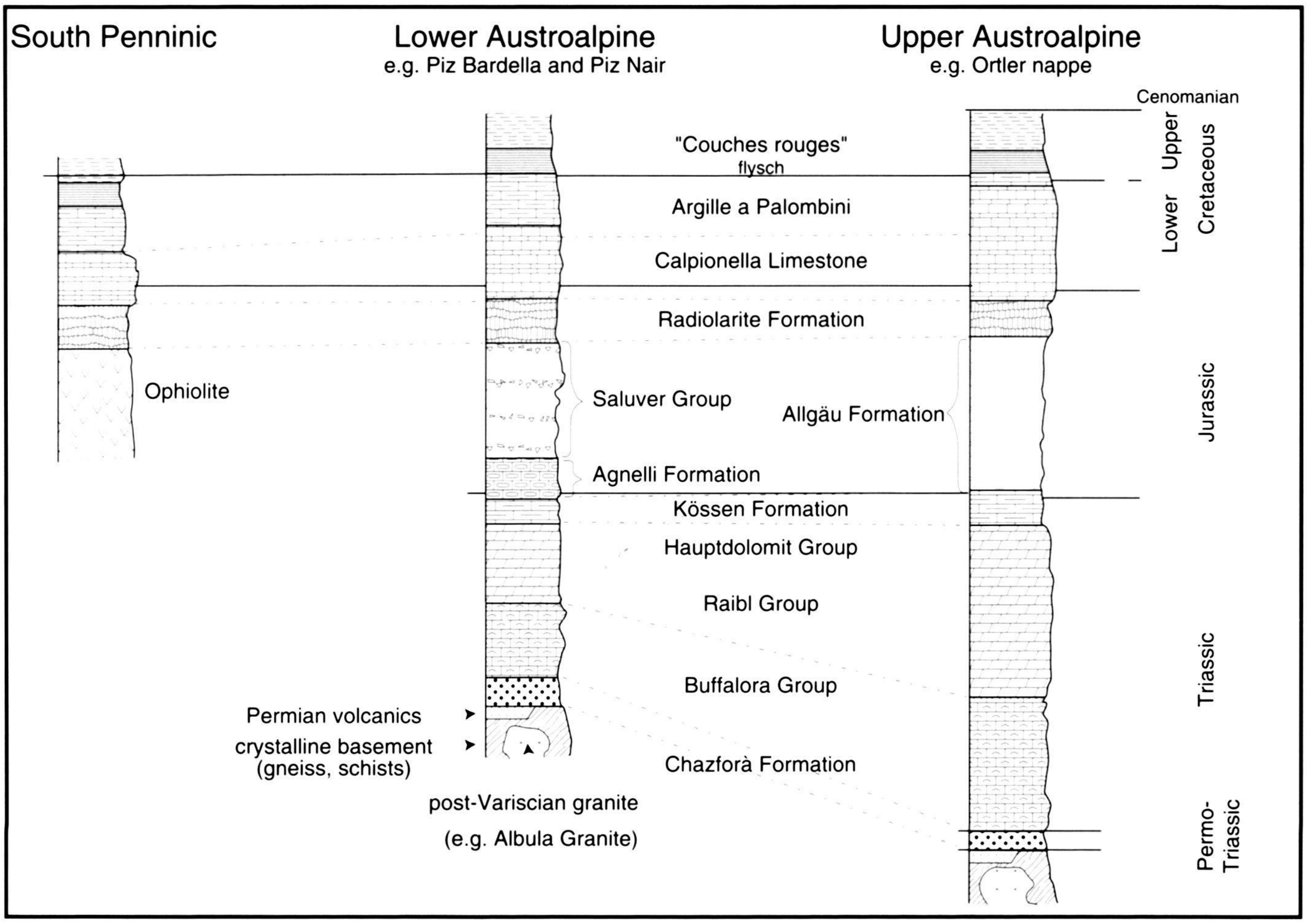


Fig. 3. Composite lithostratigraphic sections of the South Penninic and Austroalpine sequences in Grischun (modified after Winkler [1988]).

The Err basement lacks the alkaline suite and the alkaline extrusive rocks found in the Julier-Bernina basement (Spillmann & Büchi 1993), but contains calc-alkaline rocks (granophyre) which are missing in the Bernina basement (Cornelius 1935). This different distribution of rock types in the Err and Bernina basement allows one to distinguish between a source area located in the Bernina domain and another one located in the Err domain for some of the crystalline-bearing Mesozoic sedimentary breccias. Within the Err basement, the Albula Granite is the most common rock type. It is never stratigraphically overlain by Permo-Triassic sediments and all observed contacts between Albula Granite and Permo-Triassic sediments are tectonic, suggesting that the Albula Granite was probably exhumed after the deposition of the latter sediments during rifting. This is also supported by the lack of clast of Albula Granite in the lowermost crystalline bearing Jurassic sedimentary breccias in the Err nappe (Cornelius 1935, Finger 1978).

A Permian volcanic assemblage stratigraphically overlies gneisses and granophyres. It consists of rhyolites (e.g. Neir-Porphyroid of Cornelius [1935]) with intercalations of rhyodacites (e.g. "violette Sprenkelschiefer" of Cornelius [1935]) and dacites to andesites (e.g. Vairanaschiefer of Cornelius [1935]) and is part of a calc-alkaline series (Mercolli 1982, 1989, and Fig. 4 in Handy et al. 1993).

A sequence of pre-rift Permo-Triassic to Liassic sediments, unconformably overlies polymetamorphic basement rocks and non-conformably overlies Permian volcanics. The sequence starts with continental clastics (Chazforà Formation) which are overlain by sandstone and siltstone with interbedded dolomites (Fuorn Formation). Dolomites interbedded with limestone, cornieule or shale (Buffalora Group, Raibl Group, Hauptdolomite Group) dominate the Ladinian to Norian deposits (Naef 1987) (Fig. 3). Fossiliferous limestones, interbedded with shales, marls and dolomites (Kössen Formation, Rhaetian) overlie the massive dolomites of the Hauptdolomite Group and are overlain by massive siliceous limestone of the Agnelli Formation. These limestones contain layers and nodules of chert, fissure fillings and hardgrounds with ferro-manganese crusts and encrusted ammonites, indicating a Sinemurian age (*Paltechioceras* sp.) for the limestone (Finger 1978)

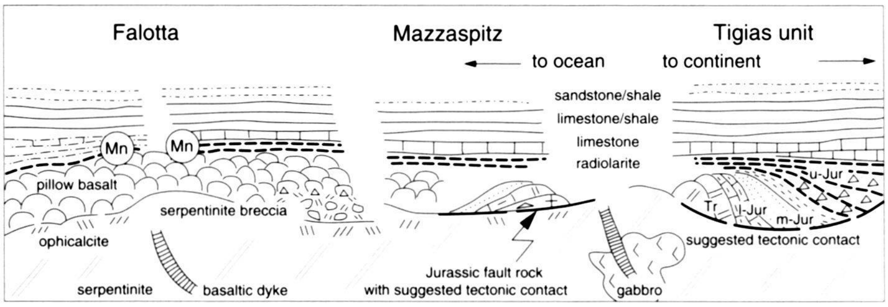


Fig. 4. Schematic stratigraphic relationships between oceanic lithosphere (serpentinites, gabbros, basalts), post-rift sediments and relics of continental crust in the South Penninic Platta nappe.

and an Early Pliensbachien age (pers. com. Heinz Furrer) for the hardground. The Agnelli Formation is interpreted to have been deposited on a submarine high which extended over the whole Lower Austroalpine Err domain during the Early to Middle Liassic. At that time, the Central Austroalpine domain was affected by high-angle normal faulting and accompanying sedimentation of mass flow and turbiditic deposits of the Allgäu Formation (Furrer et al. 1985, Eberli 1987, 1988, Furrer 1993, Conti et al. 1994).

3.2 Syn-rift sediments

Sedimentary breccias with a variable amount of matrix and intercalated hemipelagic background sediments, sandy limestones and shales conformably overlie the top of the Agnelli Formation or unconformably overlie the older sediments or metamorphic basement rocks (Finger 1978). The very local distribution and the strong variability in composition and texture, typical for syn-rift sediments, have led to different local names for these sediments, such as Saluver Formation (Finger 1978), Bardella Formation (Finger 1978), Salteras Series (Stöcklin 1949) and Salamun Breccia (Stöcklin 1949). In this study, the name "Saluver Group" (Furrer et al. 1985) is used for these sedimentary breccias and sandstones which are often particularly rich in crystalline basement clasts. Characteristic for the sedimentary breccias of the Saluver Group are a general up-section change from pure carbonate to carbonate/crystalline breccias (Stöcklin 1949) and the occurrence of one or more thinning- and fining-upward cycles (Finger 1978). The age of most of the breccias in the Lower Austroalpine units is badly constrained but the observation that these breccias stratigraphically overlie a hardground of Early Pliensbachien age (pers. com. Heinz Furrer) and are themselves overlain by radiolarian cherts of the upper Middle to Upper Jurassic Radiolarite Formation (Baumgartner 1987) makes a Middle Jurassic age for them most likely. The fact that in some places younger strata, sometimes even Lower Cretaceous Argille a Palombini, onlap the breccias and appear to interfinger with them (e.g. Fuorcla Mulix, see below) suggests that some of the breccias might also be younger. Since the post-rift sediments of the Err nappe are stratigraphically and sedimentologically similar to the ones of the Platta nappe, they are discussed together in the next chapter.

4. Stratigraphy of the Platta nappe

4.1 Ophiolites

Massive basalts, pillow lava and breccia and hyaloclastites represent the extrusive part of the ophiolite suite of the Platta nappe (Steinmann 1905, Cornelius 1935, Dietrich 1969, 1970). With higher strain and grade of metamorphism towards the south, the primary extrusive structures are gradually obliterated (Dietrich 1969). Gabbro is rare and is intrusive together with basaltic dikes in serpentinite. Some gabbros are undeformed (e.g. Val Natons), whereas others are strongly foliated and exhibit a clear stretching lineation and asymmetric fabrics indicating non-coaxial shear under high-temperature conditions (at least 400 to 500°C). Plagioclase and pyroxene ribbons suggest crystal plastic deformation mechanisms, active during the deformation of these rocks. Since Alpine metamorphism in the area is only of greenschist facies (Trommsdorff 1983), a pre-Alpine age for these gabbroic mylonites is strongly suggested.

Ultrabasic rocks are represented by lizardite-chrysotile-serpentinite north of Bivio and antigorite bearing lizardite-chrysotile-serpentinite south of Bivio, indicating an increase in Alpine metamorphism from north to south (Trommsdorff & Evans 1974, Trommsdorff 1983). Unaltered relics of peridotites were not described, but from microscopic as well as from geochemical data spinel lherzolites and harzburgites are presumed to be the protoliths of the serpentinites (Dietrich 1969, Trommsdorff & Evans 1974, Burkhard & O'Neil 1988).

The serpentinites are intruded by gabbros and the latter are cut by basaltic dikes (see Fig. 4). These cross cutting relationships clearly indicate that the serpentinites are the oldest rocks of the system. They form a kind of basement, into which gabbros intruded and on top of which pillow lavas and pillow breccias were deposited.

The serpentinites in the Platta nappe are overlain in some places by ophicalcites which are covered by post-rift sediments (Dietrich 1970) or by pillow lava. These ophicalcites often show a red matrix of carbonate containing only clasts of serpentinites. Well preserved structures like geopetal sedimentary fabrics described by Bernoulli & Weissert (1985) from the Arosa Zone (Totalp) were not reported from the ophicalcites of the Platta nappe.

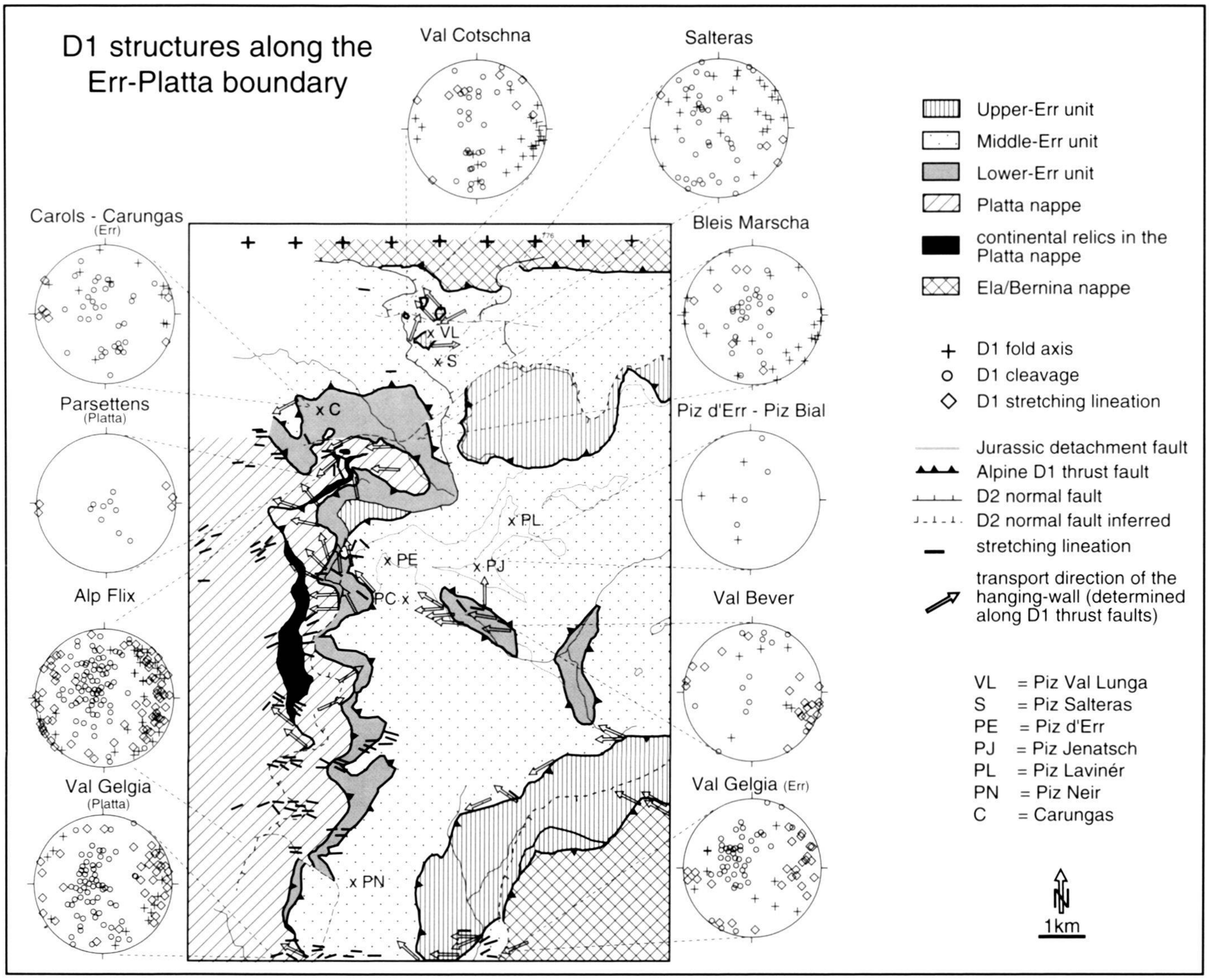


Fig. 5. D1-structures along the Err-Platta boundary between Val d'Err and Bivio.

4.2 Post-rift sediments

The first sediments found on both continental and oceanic basement, defining the base of the post-rift sedimentary sequence, belong to the upper Middle to Upper Jurassic Radiolarite Formation (Baumgartner 1987). They are composed of thin bedded, siliceous shales and cherts (Fig. 3). The whole formation is usually not thicker than 40 m in the Austroalpine units and about 1 to 5 m in the ophiolitic cover sequences. Because of the polyphase Alpine deformation, undisturbed stratigraphic contacts with the underlying lithologies are rare. In the Radiolarite Formation of the Platta ophiolitic cover, Dietrich (1970) described angular clasts of dolomite, gneiss, schist, spinel and serpentinite in sedimentary breccias. Coarse grained detritus originating from a continental as well as from an oceanic source in breccias of the Radiolarite Formation in the Tigias unit, which is characterized by an Austroalpine Mesozoic sedimentary sequence (see later and Fig. 17), suggests a close proximity of the Platta and Err domains in Late Jurassic time.

Light-colored micritic limestones with intercalations of shales (Calpionella Limestone or Aptychus Limestone), about 30 to 40 m thick in the Err and about 5 m in the Platta nappe, followed by calcareous slates, dark siliceous shales and calcarenites alternating with dark grey limestones (Argille a Palombini, = Emmat Series of Finger [1978], Neocomschiefer of Stöcklin [1949] or Roccabella-Schiefer of Dietrich [1970]), about 20-120 m thick in the Err nappe and up to 30 m in the Platta nappe, overlie the Radiolarite Formation. Dietrich (1969) found planktonic foraminifera (*Hedbergella* sp, *Planomalina* sp., *Schackoina* sp., questionable *Globigerinoides* *and Clavihedbergella* sp.) within the Argille a Palombini yielding an Aptian to Albian age for the youngest dated rocks in the Platta ophiolitic sequence.

4.3 Remnants of Lower Austroalpine within the Platta nappe

Slivers of continental basement overlain by pre- and syn-rift sediments (Triassic dolomite and sedimentary breccias and sandstones of the Saluver Group) are typically associated with the serpentinites in the Platta nappe (Dietrich 1969). Some of these slivers preserve internal structures, whereas others are strongly overprinted by Alpine deformation. According to the first workers in the Platta nappe (e.g. Cornelius 1935) these slivers were assumed to form the relics of the country rocks into which the ophiolites intruded. In light of plate tectonics, the ophiolites were no longer interpreted as intrusions, and the Lower Austroalpine rocks within the Platta ophiolitic nappe were assumed to be: either continental blocks lying within an ophiolitic mélange formed during subduction of the Tethys ocean beneath the Austroalpine units (Ring et al. 1988, 1989, Hsü & Briegel 1991) or extensional allochthons of continental basement emplaced on exhumed mantle lithosphere during the Middle Jurassic break-up of the Piemont-Liguria ocean along a west dipping low-angle detachment fault (Manatschal 1995, Froitzheim & Manatschal 1996).

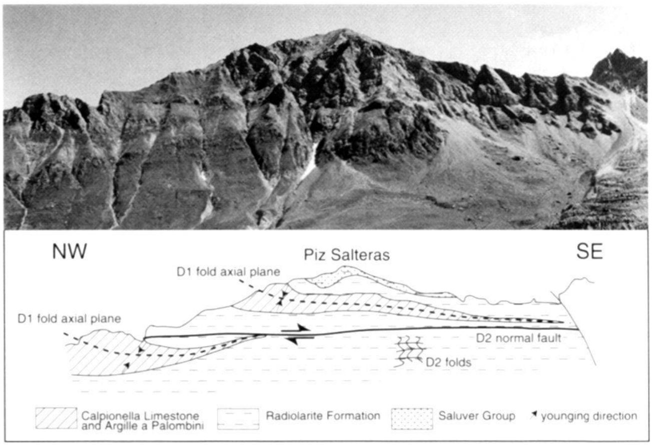


Fig. 6. Relation between isoclinal D1-folds, D2-folds and a D2-normal fault in the southwest face of Piz Salteras.

5. Alpine Deformation

5.1 Introduction

To reconstruct the original geometry of the continental margin and to understand the mode of deformation associated with its evolution, Alpine deformation must be kinematically inverted. With this in mind, the Alpine structures observed along the Err-Platta boundary between Val d'Err and Val Gelgia (Julier) are discussed below. For a discussion of the Alpine structures of the entire Lower Austroalpine nappe complex in eastern Switzerland, the reader is referred to a comprehensive synthesis in Froitzheim et al. (1994).

5.2 Trupchun phase (D1)

The main Alpine deformation in the Platta and Err nappes resulted from the Trupchun phase (= D1) (Froitzheim et al. 1994). During this tectonic phase which may be related to Late Cretaceous E-W directed convergence between the European and the Apulian plate (Handy et al. 1993), the South Penninic Platta nappe and the Lower Austroalpine Err nappe were involved in top-to-the-west to northwest-directed nappe transport. This is documented by stretching lineations, shear sense indicators in the main shear zones, and W to NW facing D1 folds in the Err and Platta nappes (see Fig. 5).

D1 structures in the Err and Platta nappes are: 1) mm to km-scale folds showing an isoclinal, strongly non-cylindrical sheath fold geometry with a penetrative axial plane schistosity. This schistosity is defined by newly grown illite, chlorite and opaque minerals, and 2) thrust faults separating the nappes. Whereas the isoclinal folds are mainly observed in the syn- and post-rift sediments, the thrust faults are most common within the competent basement rocks. D1 structures formed at low metamorphic grade (lowest greenschist facies or even lower) in a shallow crustal level. This is shown by micro structures in quartz-bearing fault rocks and by illite crystallinity and vitrinite reflectivity data of Ferreiro Mählmann (1995, 1996). Fission track data on zircons from the Err nappe show that the temperatures never exceeded the partial annealing zone (between 200° and 250°, Hurford & Green 1982) during Alpine deformation (Eggenberger 1990, Manatschal 1995).

Most of the thrust faults are complicated polyphase structures. Along the Julier thrust fault, separating the Err from the Bernina nappe (Fig. 5), s-c fabrics indicate a top-to-the-west shear sense (north of Piz Julier, 778.750/152.150, 2700 m.a.s). Handy et al. (1993) found evidence for a reactivation of this fault plane as a top-to-the-east normal fault during D2 and possibly also as a top-to-the-north thrust during D3. The thrust fault which separates the Ela from the Err nappe was described as a D1-thrust fault, folded during a later stage of D1 and overprinted by D2-folding (Froitzheim et al. 1994). West of Piz d'Ela this thrust fault is cut by a D2 normal fault (Fig. 1 and 7).

E-W-trending transpressive zones such as the Albula Zone and the Zone of Samedan (Fig. 1) are mainly formed by steep to moderately dipping structures. For their interpretations see Froitzheim et al. (1994) and Handy et al. (1993). In the area discussed here, bounded to the north and to the south by these zones, Alpine deformation is localized in shear zones or within the pre-rift sediments. Due to the localization of Alpine deformation, relics of pre-Alpine structures within the basement rocks and the pre-rift sediments in the Err nappe survived Alpine deformation.

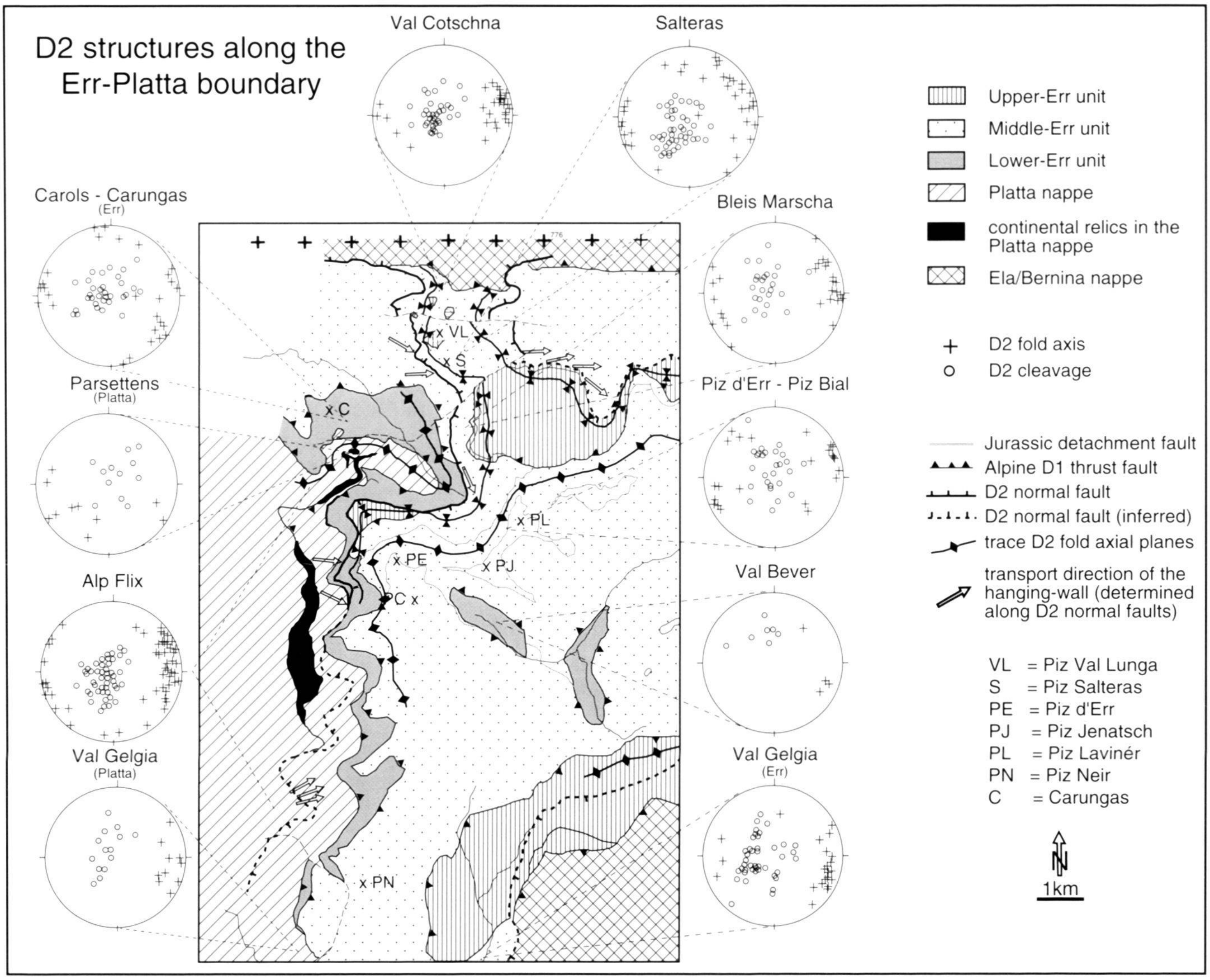


Fig. 7. D2-structures along the Err-Platta boundary between Val d'Err and Bivio.

5.3 Ducan-Ela phase (D2)

E- to SE-directed normal faults and cogenetic recumbent folds of the Ducan-Ela phase overprinting the previously formed nappe pile in the Lower Austroalpine in Grischun (Froitzheim 1992, Liniger 1992, Handy et al. 1993, Froitzheim et al. 1994) are interpreted to result from Late Cretaceous collapse of a previously overthickened crust (Froitzheim 1992).

In the Err and Platta nappes, this deformation phase is characterized by large- to small-scale east-west trending folds with sub-horizontal axial planes and southeast-dipping normal faults cutting the nappe pile (Fig. 2, 6, 7). The large-scale D2-fold north of Piz d'Err can be followed from Piz d'Err in the west to the Pass d'Alvra in the east (see Fig. 1 and 7). Large scale D2-folds can also be traced from the Err into the Platta nappe. In the area of Parsettens in Val d'Err, a D1-thrust fault separating the Err nappe from the Platta nappe is folded by a large-scale D2-fold. Smaller D2 folds folding the Err-Platta contact were also observed in Val Gelgia. Between Pass d'Ela in the north and Sursès in the south a fault plane could be mapped which exhibits a top-east-to-southeast shear sense (Fig. 7). This fault cuts down towards SE into deeper levels of the D1-nappe stack, and is only weakly overprinted by later D3-deformation. Using these criteria, this fault is interpreted as a D2-normal fault. The amount of displacement along this normal fault can be estimated from the offset of the Lower Err unit/Supra MMS boundary (Fig. 2). It is between 1 and 2 km. This normal fault is well preserved and only weakly overprinted in the area of Piz Salteras (Fig. 6). Here, the normal fault cuts older D1 folds, and D2 fold axial planes are subparallel to the normal fault. In the Zone of Samedan, Handy et al. (1993) observed several top-east normal faults, which were also ascribed to the Ducan-Ela phase.

5.4 *The Blaisun phase (D3) and younger structures*

The youngest pervasive deformation phase in the Austroalpine and Upper Penninic nappes north of Engiadin' Ota, the Blaisun phase (D3), weakly overprints older Late Cretaceous structures. This phase is interpreted to be the result of Eocene collision tectonics (Handy et al. 1993, Froitzheim et al. 1994) resulting in the 'en bloc' thrusting of the Upper Penninic and Austroalpine nappe stack toward the north over the Middle to Lower Penninic nappes.

In the study area, the Blaisun phase is documented by large scale, upright, open folds as well as by many small scale chevron-type to flexural-slip and flexural flow type folds on a m-scale. The fold axes are sub-horizontal and strike constantly east-west. The folds show a gradual northwards increase in wave length from about 300 m in the Val Gelgia area to a few kilometers in Val d'Err. In Val d'Err, the fold axial planes form a weak solution cleavage and change their dip direction from north to south over a distance of a few kilometers; in the area of the Val Gelgia, the same fan-shape geometry can be observed on an outcrop scale. South of Pass da Sett (Septimer Pass) only north-dipping axial planes were described by Liniger (1992), Spillmann (1993), and Tietz (1993). Further south in the Val Malenco, crystallization of new minerals along D3 cleavage planes (here the main cleavage) indicates upper green schist facies conditions (Hermann & Müntener 1992).

The base of the Platta nappe, which is not considered in this study, is defined by a prominent east dipping normal fault, the Turba mylonite zone (=TMZ). The TMZ (Liniger 1992, Nievergelt et al. 1996) can be followed from Mulegns in Sursès to the Val Bregaglia where it is cut by the Bregaglia granodiorite. Therefore the TMZ is older than the Bregaglia granodiorite intrusion, dated at 30 Ma by von Blanckenburg (1992). A lower age bracket for the TMZ is given by the cross-cutting relationship with pre-TMZ structures (Liniger 1992) in the Arblatsch Flysch and in the Avers Schiefer (e.g. D1 structures of Liniger [1992]) which are dated at 45 to 35 Ma (Schreurs 1993, 1996). At Piz Platta, Liniger (1992) observed two sets of north-south-striking normal faults: an older set that is restricted to the hanging-wall of the TMZ and kinematically linked to this fault zone (syn-TMZ) and a younger one cross cutting the TMZ (post-TMZ).

Post-Blaisun deformation phases (F4 and later phases of Liniger [1992]) form E-W and N-S trending faults with a displacement of about 20 to 100 m. These structures are of minor tectonic importance. The most significant faults related to theses phases are the Septimer fault and the Lunghin fault further south (e.g. Liniger 1992).

5.5 *Implications of the Alpine structures*

The analysis of the Alpine structures in the area between Val d'Err and Val Gelgia suggests a similar tectonic evolution for the Platta and the Err nappes during Late Cretaceous and Tertiary convergence. The displacement during the top-to-the-west or northwest imbrication of the Err and Platta nappes during D1 was accommodated along several fault planes and is in the order of a few tens of kilometers (Manatschal 1995). The amount of displacement along wrench faults in the Albula Zone and a possible one in the Zone of Samedan, resulting from a transpressive component, is difficult to estimate. Later Alpine phases (D2 and younger phases) overprint the formed stack of units as shown by D1 thrust faults folded by D2 folds, as well as by the observation that a D2 normal fault can be traced from the Err nappe into the Platta nappe. Therefore, we suggest that the Err-Platta contact was severely affected by D1 and locally also by D2 and later deformation. The overprint by D2 and younger deformation phases increases towards deeper levels of the Platta nappe and towards the adjacent areas south of Val Güglia and north of Val d'Err. However, this contact still retains vestiges of earlier passive margin structures. Consequently, the pre-Alpine transition from the distal continental margin (Err nappe) to the oceanic crust (Platta nappe) was affected in the studied area above all by east-west directed movements during Late Cretaceous time. During later north-south shortening the upper part of the Platta nappe was already welded to the Austroalpine units and the contact was only weakly overprinted by younger Alpine structures. Probably this is only valid for the area between Val d'Err and Bivio. North of Val d'Err, the Austroalpine-Upper Penninic boundary may interfere with the northern continuation of the Tertiary Turba Mylonite Zone and south of Val Gelgia this contact becomes progressively more complex, due to the increasing Tertiary metamorphism and strain, related to back folding (Liniger 1992).

6. Kinematic inversion of the Err and Platta nappes

The idea of kinematic inversion is expressed by the equation: pre-Alpine geometry = present day situation – Alpine deformation. Even if this equation represents a strong simplification, it shows clearly that the understanding of Alpine tectonics and related structures is a pre-requisite to reconstruct the original geometry of fossil continental margins.

The kinematic inversion here proposed is based on the today generally accepted tectonic evolution of the Lower Austroalpine and Upper Penninic nappes in Grischun (e.g. Liniger 1992, Spillmann 1993, Handy et al. 1993, Froitzheim et al. 1994, Manatschal 1995), implying that the former continent-ocean transition was mainly affected by east-west directed movements (only valid for the area between Val d'Err and Bivio, see above). Consequently, a first order kinematic inversion of the Alpine structures and a palinspastic reconstruction of the former continent-ocean transition, recorded in the Err

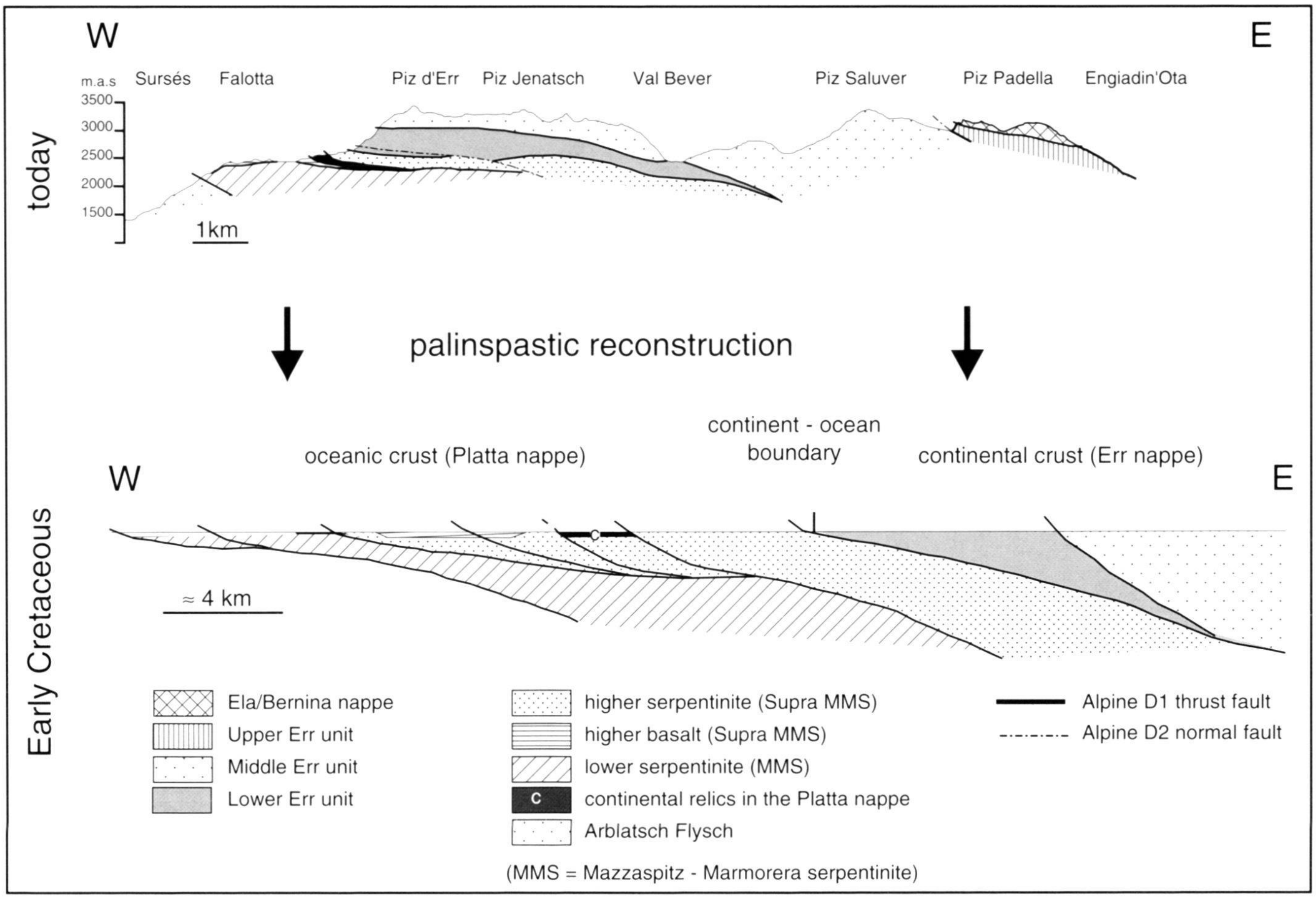


Fig. 8. Palinspastic reconstruction of an east-west oriented profile across the Err and Platta nappes placing the Alpine tectonic units into their pre-Alpine position.

and Platta domains, can be derived in an east-west directed profile using the simple tectonic rule "the higher a thrust sheet lies in the nappe pile, the more continent-wards it was originally located" (Fig. 8). In the following, we will discuss the preserved rifting structures of the former continent-ocean transition in the Err and Platta domains.

7. Jurassic tectonics

7.1 Introduction

Froitzheim and Eberli (1990) described segments of Jurassic detachment faults in the area of Piz d'Err, Piz Val Lunga and Val Bever. In addition, we found several other relics of rift-related detachment faults in the continental Err nappe as well as in the ophiolitic Platta nappe. An overview of all known outcrops is given in figure 9. Before discussing these outcrops, we shall give a short overview of the fault rocks and the timing of the detachment faults, both essential for understanding these structures. Later, we integrate the local observations described below to reconstruct the ocean-continent transition and discuss the original geometry and evolution of this margin.

7.2 Fault rocks related to Jurassic detachment faults

The preserved segments of low-angle detachment faults in the Err and Platta nappes are characterized by black and green fault rocks and leucocratic bodies. The fault rocks associated with the low-angle detachment faults can be distinguished from Alpine fault rocks in the studied area on the basis of their fabrics and their mineralogical and chemical composition (Manatschal 1995).

The green fault rocks have conglomerate- or breccia-like fabrics and consist exclusively of clasts from the footwall (Albula Granite and gneiss). Albitization of the K-feldspar and saussuritization of plagioclase accompanied cataclasis in the green fault rocks and led to strain softening.

The fabric of the black fault rocks is matrix-supported and scale-independent. The clasts (green fault rocks and rocks from leucocratic bodies, see below) are derived mainly from the footwall, are rounded or elongated and are embedded in a phyllosilicate-rich matrix. Hanging wall clasts (gneiss, Triassic dolomite) are less common. The chemical composition of the black fault rocks is very distinct and can be used to distinguish them from the neighbouring rocks and from Alpine fault rocks

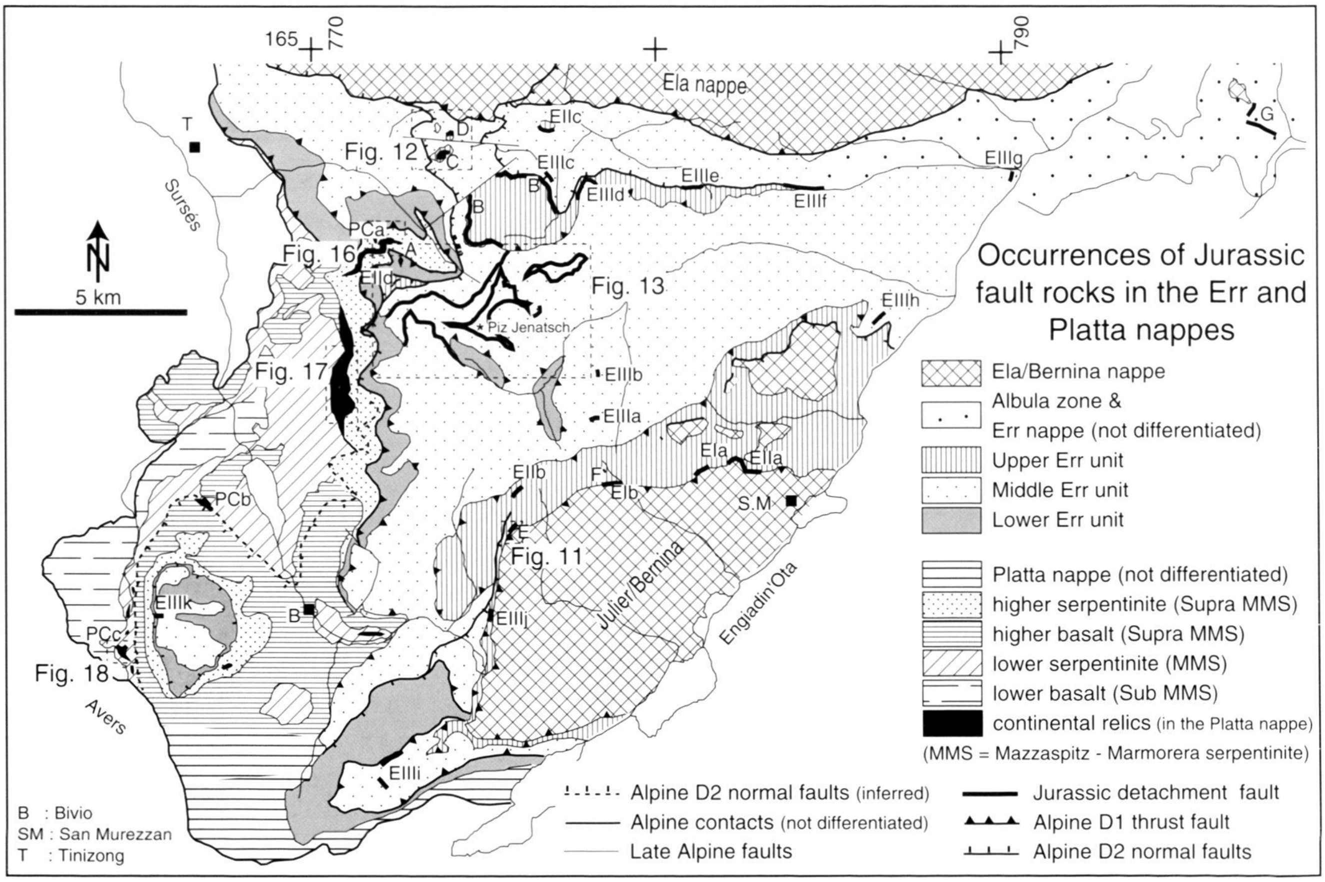


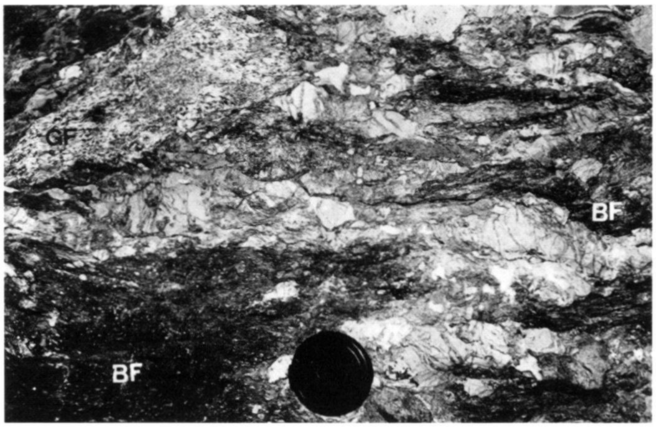
Fig. 9. Tectonic map of the Err and Platta nappes showing all localities where relics of Jurassic fault rocks were found (list of the localities below). A: Castalegns north ridge (772.30/159.00, 2690 m.a.s); B: Piz Bleis Marscha – Val Tschitta; C: Piz Val Lunga (773.7/161.9, 3078 m.a.s); D: Cuetschens (774.0/162.6, 2850 m.a.s); E: Fuorcla Cotschna (775.8/151.1, 2740 m.a.s); F: Val Suvretta (Gianda Cuolms) (778.70/152.75, 2620 m.a.s); G: Val Vaüglia – Murtiröl; EIa: South of Piz Nair (781.05/153.10; 2690 m.a.s.); EIb: Base of Julier thrust fault in the Val Suvretta (778.75/152.10, 2700 m.a.s); EIIa: Muot da San Murezzan (782.45/153.40; 2480 m.a.s); EIIb: Fuorcla Marguns (776.15/152.80; 2860 m.a.s); EIIc: Murtels da Fallò (776.00/162.80; 2520 m.a.s); EIId: Castalegns (772.05/158.15; 3021 m.a.s); EIIIa: North of Fuorcla Suvretta (778.00/153.95; 3030 m.a.s); EIIIb: North ridge of Piz Bever at Pkt. 2956 (778.35/155.75; 2956 m.a.s.); EIIIc: Foras d'Nes (776.25/161.50; 2280 m.a.s); EIIId: Murtel Trigd (778.00/161.00; 2400 m.a.s); EIIIe: Crap Alv – Lai da Palpuogna (780.00/161.10 to 781.00/161.10); EIIIf: Piz Mez, Pass d'Alvra (785.15/161.00; 2570 m.a.s); EIIIg: Acla Albertini (La Punt) (789.75/161.30; 1810 m.a.s); EIIIh: Crap Sassella (Alp Muntatsch, Samedan) (786.10/157.35, 2150 m.a.s); EIIIi: Grevasalvas (772.00/143.85; 2850 m.a.s and 771.85/144.45; 2580 m.a.s); EIIIj: La Veduta (Pass dal Güglia) (774.95/148.96; 2240 m.a.s); EIIIk: Southern ridge of Piz Scalotta (765.60/148.70; 2950 m.a.s); PCa: Castalegns north ridge (772.00/159.50, 2580 m.a.s); PCb: Alp da Starschagns (767.00/152.00; 2290 m.a.s); PCc: Southeast of Mazzaspitz (764.55/148.90; 2820 m.a.s)

(Manatschal 1995). The black fault rocks are always accompanied by the green fault rocks in the Err and Platta nappes. The contacts between these tectonites are sharp and a clear overprinting relationship exists between these two rock types. Clasts of green fault rocks in the black fault rocks and injections of the black fault rocks in the green fault rocks clearly demonstrate that the black fault rocks post-date the green fault rocks at the outcrop scale.

Leucocratic bodies consisting of pure recrystallized quartz and albite often cut across the green fault rocks, but are truncated by the low-angle detachment faults and reworked in the black fault rocks. Based on these overprinting relationships the leucocratic bodies have to be formed simultaneous with the detachment faults. They are interpreted to result from the retrograde breakdown reaction of feldspar to phyllosilicates during cataclasis, resulting in a surplus of quartz.

7.3 Age constrains for the low-angle normal fault system in the Err nappe

The low-angle normal faults in the Err nappe truncate high angle normal faults and tilted blocks comprising Triassic dolomites (Fig. 10c), and are sealed by syn-rift sediments of post-Early-Toarcian age (Fig. 10b). Therefore, tectonic activity along the low-angle normal faults must post-date tilting of the blocks during formation of depositional basins but syn-date deposition of the late syn-rift sediments. The occurrence of clasts of green and black fault rocks derived from the low-



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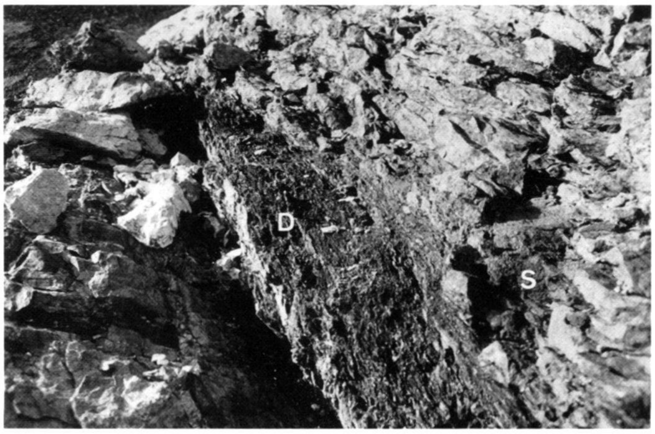

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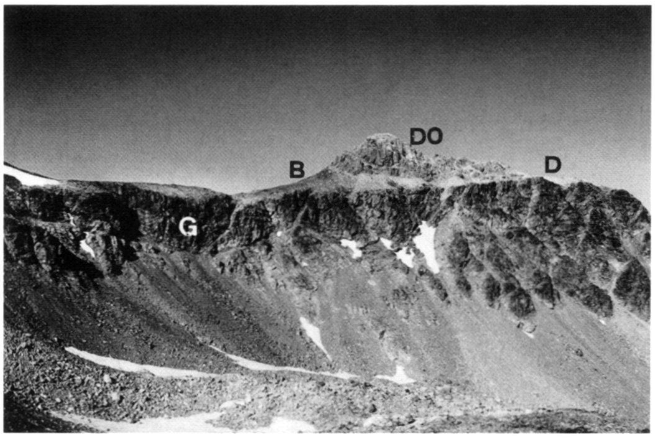

c

Fig. 10. Age constraints for the detachment system in the Err nappe: (a) Clasts of black fault rocks (BF) and green fault rocks (GF) in sedimentary breccias of the Middle Jurassic Saluver Group. (Piz Salteras, Val d'Err [773.95/161.40; 3080 m.a.s]) (b) Sealing of the detachment fault (D) (represented by black fault rocks) and foliated tectonic breccias by sandstones and breccias of the Middle Jurassic Saluver Group (S) at Fuorcla Cotschna (775.95/151.15, 2880 m.a.s). (c) A tilted block consisting of Middle Triassic dolomites (DO) and crystalline basement rocks (B), cut by a low-angle detachment fault (D), and (G) Albula Granite forming the footwall. (P. 3060 east of Piz Lavinér).

angle normal faults in the late syn-rift sediments (Froitzheim & Eberli 1990) (Fig. 10a) supports this interpretation and documents exhumation of the low-angle normal fault(s) during rifting at the sea floor.

7.4 Outcrops preserving remnants of the continent-ocean transition

In the following, outcrops preserving remnants of rift related structures and cataclastic rocks are described according to their Alpine tectonic position, starting with outcrops in the highest, most continentward units and ending with those in the deepest, oceanic units. A complete list of Jurassic fault rock occurrences is given in text of figure 9.

7.4.1 Fuorcla Cotschna (Fig. 11)

In the outcrops between Muot Cotschen and Fuorcla Cotschna (775.80/151.10; 2740 m.a.s), belonging to the Upper Err unit, Albula Granite is overlain by sheared and strongly foliated crystalline basement rocks, accompanied by anastomosing zones of black fault rocks (cf. Handy et al. 1993, see their Fig. 5B and 5C). These Jurassic fault rocks are overlain by weakly foliated syn-rift sediments of the Saluver Group, onlapping the fault rocks with an angle of about 20 to 30° (Fig. 10b). At their base, the syn-rift sediments comprise breccias containing basement clasts and sandstones which are overlain by carbonate-rich breccias and olistoliths. At some places, the matrix of the breccias and sandstones is black and its chemical composition is similar to that of the black fault rocks from the Jurassic detachment faults (Manatschal 1995). Upsection, a change from carbonate to crystalline basement clast-dominated breccias occurs, and, at places, there is an abrupt change from pure crystalline to pure carbonate breccia layers. Generally, the syn-rift sediments fine upward and grade into strongly folded red cherts and shales of the Radiolarite Formation. Within the Radiolarite Formation, olistoliths consisting of reworked slivers of breccias from the Saluver Group can be found together with mass flow deposits composed of reworked crystalline basement and Triassic carbonates. As shown in the map and the profile in figure 11, the outcrop of Fuorcla Cotschna is under- and overlain by Alpine shear zones, which may have overprinted some of the Jurassic structures. However, the observed field relations clearly indicate a pre-Alpine age for most of the observed structures in the basement of Muot Cotschen (Handy et al. 1993).

7.4.2 Piz Val Lunga and Cuetschens (Fig. 12)

The western ridge of Piz Val Lunga (773.7/161.9, 3078 m.a.s) exposes one of the best preserved sections across a former Jurassic low-angle normal fault. The original footwall, now the summit of Piz Val Lunga, consists of weakly deformed Albula Granite. Only a few meters away from the detachment, the cataclastic overprint is very strong, as shown by the occurrence of green fault rock. The fault plane itself is made up of black fault rock. The former hanging wall is formed by Triassic dolomites, presumably of Ladinian or Norian age. Rims of dedolomitized, sparitic calcite can be observed along the contact between the black fault rocks and the dolomites. The Triassic dolomite is stratigraphically overlain by a syn-rift breccia of the Saluver Group with a strongly tectonized contact to the topographically underlying Argille a Palombini. This contact is interpreted as a D1 thrust fault.

In a south-north directed section, the klippe of Cuetschens (774.0/162.6, 2850 m.a.s) north of Piz Val Lunga contains Albula Granite separated by remnants of black fault rocks from slices of gneiss, sandy dolomite of the Fuorn Formation, Triassic dolomite and syn-rift sedimentary breccias of the Salteras Group. This succession may represent a relic Jurassic detachment fault zone that is strongly overprinted by Alpine deformation. The assumed Jurassic detachment fault is truncated by a presently flat-lying Alpine D1 thrust fault at an angle of about 60°. This indicates that at least one of the two faults was not

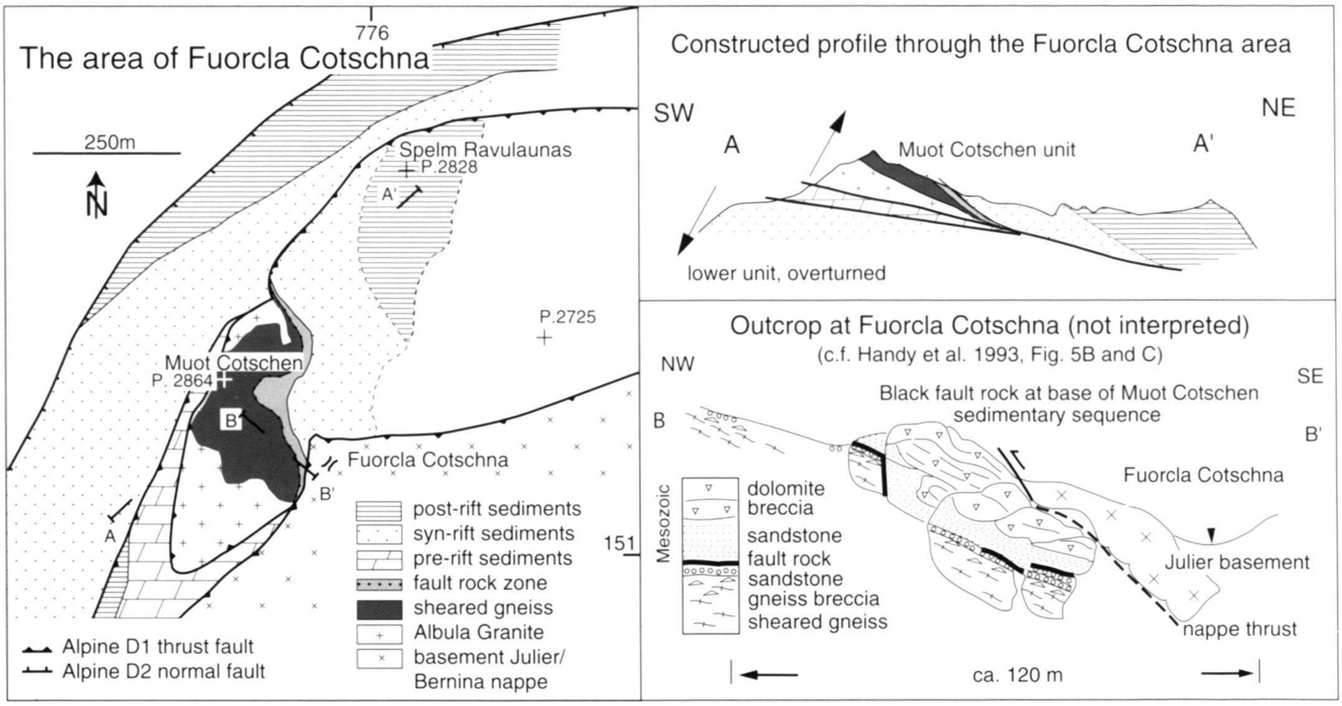

Fig. 11. Geological map and simplified profile of the area of Fuorcla Cotschna, after Cornelius (1932), Finger (1978), Handy et al. (1993) and own observations. Locality E in Fig. 9.

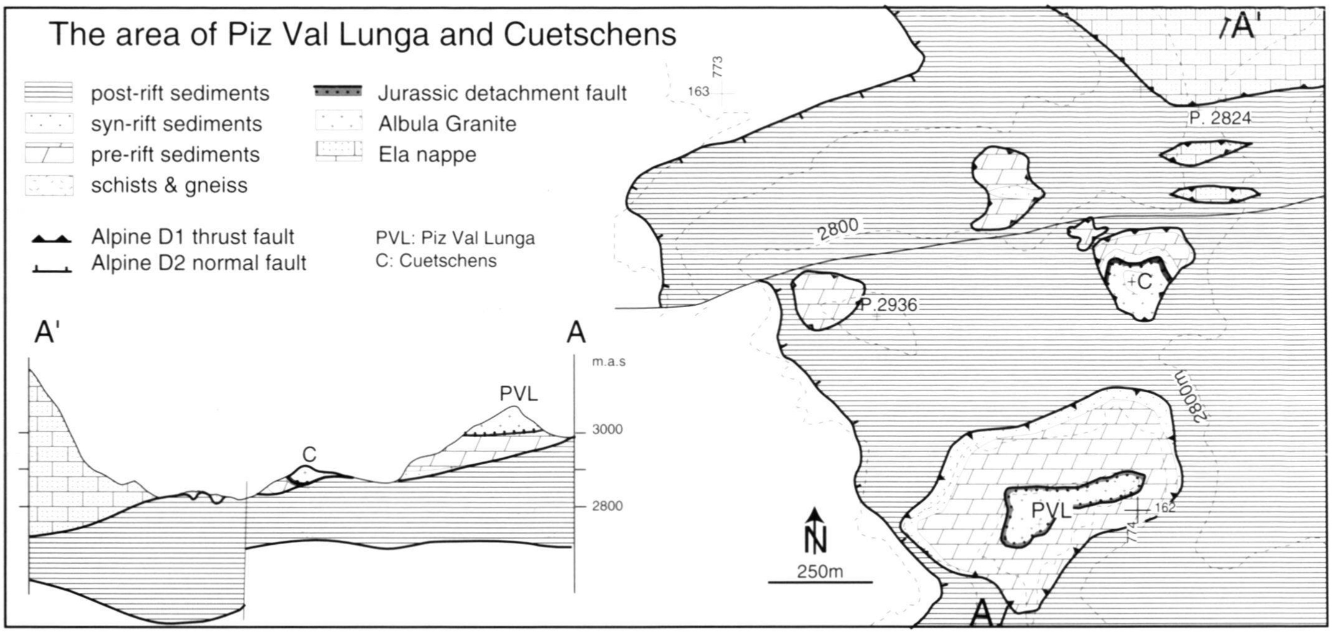

Fig. 12. Geological map and profile from Piz Val Lunga to Cuetschens, compiled after Cornelius (1932), Stöcklin (1949) and own observations. Locality C and D in Fig. 9.

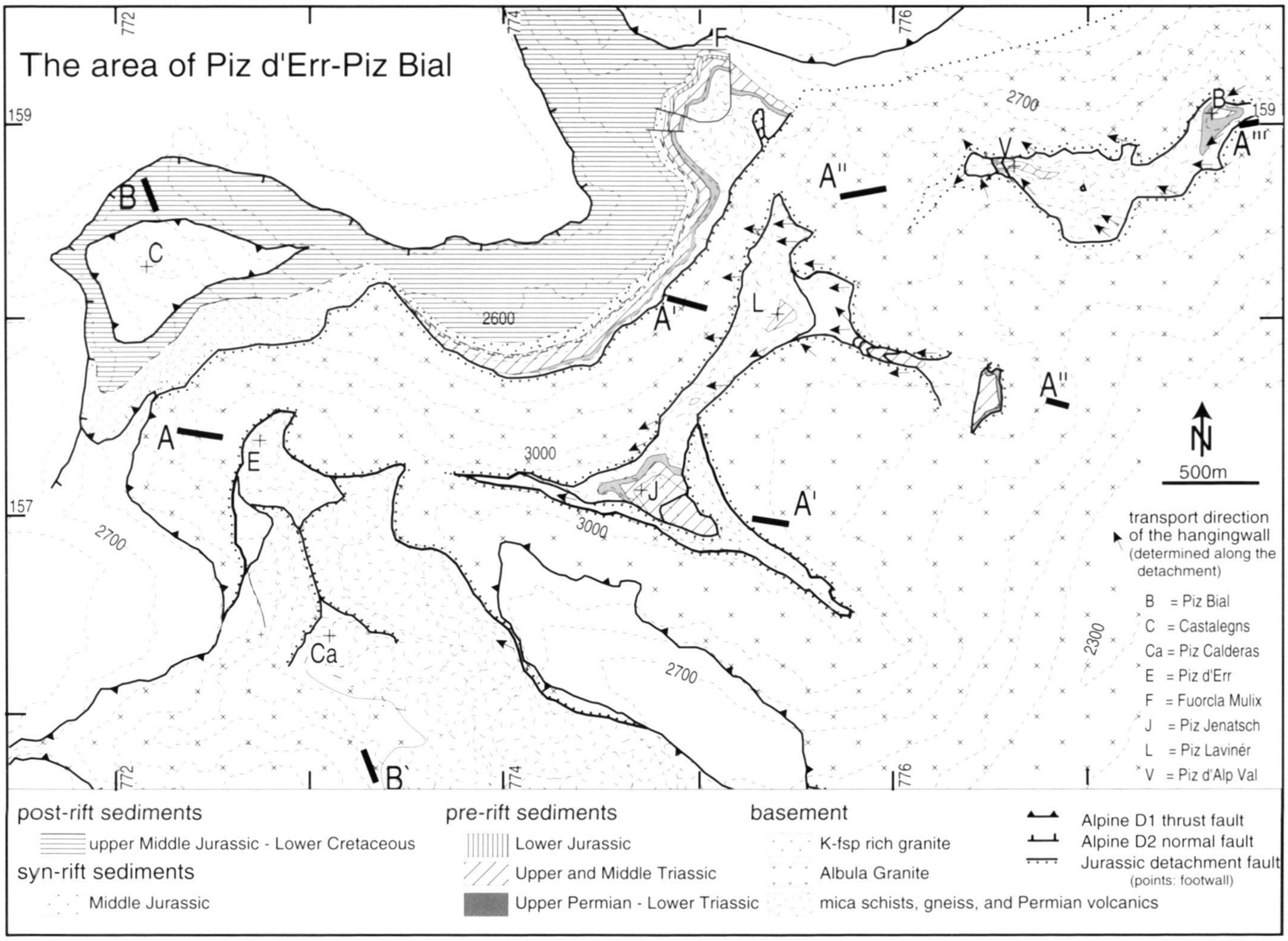

Fig. 13. Geological map of the area of Piz d'Err – Piz Bial. For location, see Fig. 9.

horizontal when thrusting occurred. The high angle between the two fault planes may also explain why the Jurassic fault plane was not strongly reactivated during Alpine nappe transport. The outcrops of Piz Val Lunga and Cuetschens belong to the Upper Err unit and are interpreted together with the zone of Piz Bleis Marscha (Fig. 9) as the overturned limb of a west-facing D1 fold.

7.4.3 The zone of Piz d'Err, Piz Bial, Val Bever (Fig. 13)

In the area of Piz d'Err, Piz Jenatsch, Piz Lavinér, Piz d'Alp Val and Piz Bial a rift-related Jurassic low-angle detachment system is well preserved and only weakly overprinted by later Alpine deformation (Froitzheim & Eberli 1990). Detailed mapping allowed us to follow one fault over a distance of 6 km before it is cut by D1 thrust faults (Fig. 13). Locally, two stacked detachment faults are observed, the upper Jenatsch detachment and the lower Err detachment (Figs. 13, 14, 15).

The footwall of the Jenatsch detachment, which is only observed in the Piz Jenatsch – Piz Calderas area, characteristically contains cm long, reddish K-feldspar bearing granite and gneiss. In contrast, the footwall of the Err detachment in the studied area only contains Albula Granite. Except from the uppermost 200 m, the footwall of the low-angle detachment faults is in general very weakly deformed.

The hanging wall of the Err detachment is formed by gneiss and schist stratigraphically overlain by Permian to Lower Jurassic sediments, which are unconformably overlain by Middle Jurassic to Lower Cretaceous syn- and post-rift sediments (Fig. 13). In the zone of Piz d'Err-Piz Bial-Val Bever a few klippen of hanging wall blocks showing complicated internal structures lie on top of the Err detachment. In the following, these klippen are described, going from east to west, parallel to original Jurassic transport direction.

Piz d'Alp Val-Piz Bial klippe (Fig. 14c)

This klippe is formed by gneiss and mica schists stratigraphically overlain by Permo-Triassic sediments. The internal geometry of the klippe is dominated by east dipping, high-angle normal faults and west-side-down rotated hanging wall blocks. The normal faults strike north-south and their vertical displacements are of the order of 50 m. North of Piz d'Alp Val, these normal faults are cut by the Err detachment. Angular relationships within the Triassic dolomites and between the Mesozoic sediments and the basement at Piz Bial are the result of small-scale, low-angle faults. At P. 3033 east of Piz d'Alp Val, crystalline basement lies on top of Permo-Triassic sediments. The relations at this outcrop may reflect later Alpine thrusting.

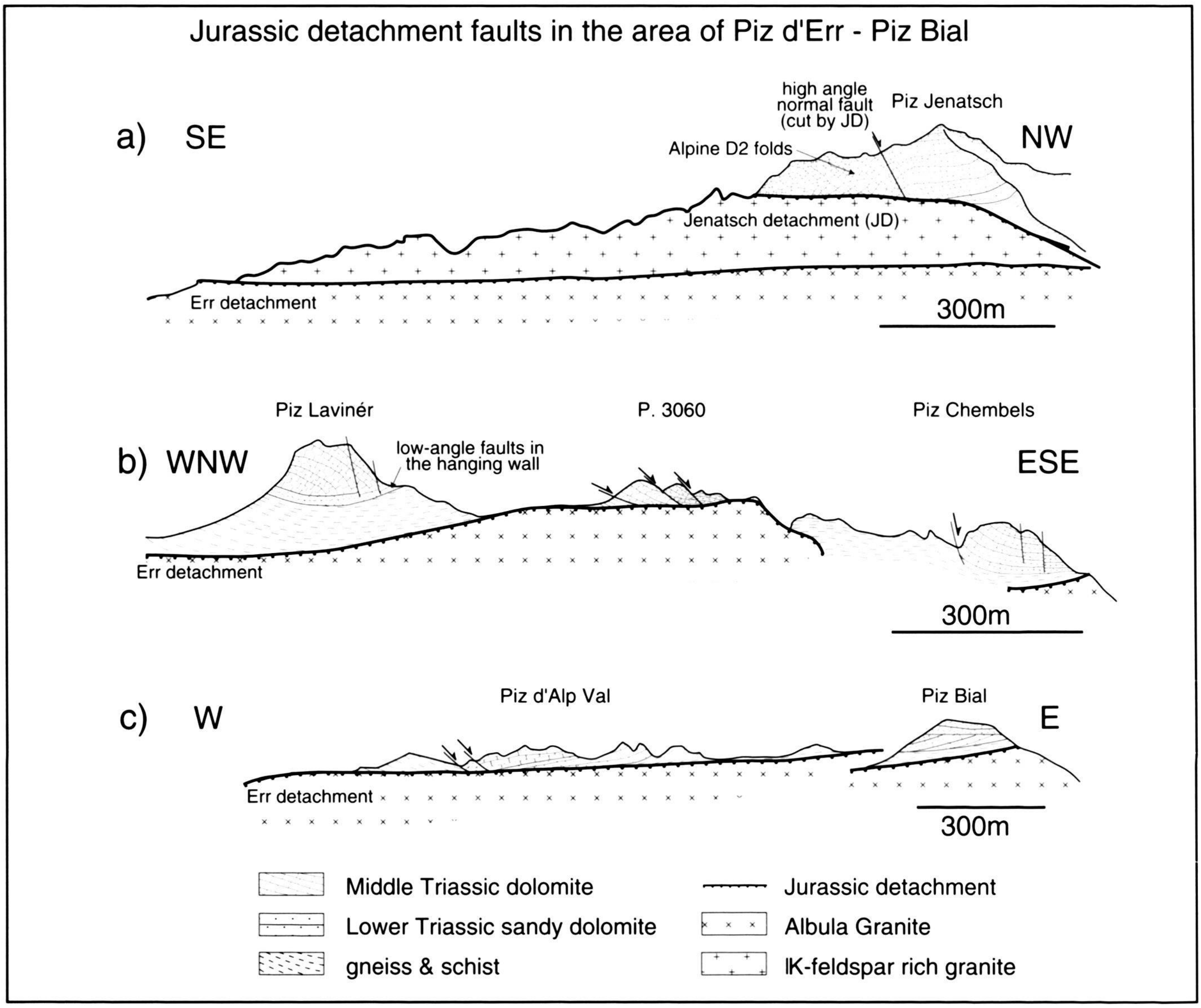

Fig. 14. The Jurassic low-angle normal fault system in the area of Piz Bial, Piz Lavinér and Piz Jenatsch: (a) view of Piz Jenatsch from northeast showing the relationship between high-angle and low-angle normal faults and between the Err (dE) and the Jenatsch (dJ) detachment, after Stöcklin (1949), (b) view of the ridge Piz Lavinér – Piz Chembels from southwest (modified after Cornelius [1950] and Froitzheim & Eberli [1990]), (c) E-W directed profile across the klippe of Piz d'Alp Val – Piz Bial (modified after Stöcklin, 1949).

Piz Lavinér-P. 3060-Piz Chembels klippe (Fig. 14b)

In a WNW – ESE trending section through the Piz Lavinér-P. 3060-Piz Chembels klippe, the Err detachment separates granite (Albula Granite) in the footwall from gneiss and schists, stratigraphically overlain by Permo-Triassic sediments in the hanging wall. At Piz Lavinér and P. 3060, the sedimentary rocks in the hanging wall dip east-southeast and become younger in the same direction. This geometry indicates east-side-down tilting of the hanging wall. In the hanging wall blocks, at least two generations of structures can be observed. A first generation of mainly east dipping high-angle normal faults is cut by a second generation of top-to-the-west low-angle faults (Figs. 13, 14 and 15). Between P. 3060 and Piz Chembels, the fault rocks marking the detachment, dip towards the east and are found again in the southeast ridge of the Piz Chembels, separating the Albula Granite from slivers of gneiss and Triassic dolomite.

Jenatsch klippe (Fig. 14a)

Along the NE side of Piz Jenatsch, two low-angle detachment faults are observed. The lower detachment can be correlated with the detachment observed at Piz d'Err (Fig. 15) and at Piz Lavinér-Piz Bial (Err detachment); the upper detachment is the Jenatsch detachment. These two low-angle faults separate three blocks. The block overlying the upper detachment consists of augengneiss in the northwest, stratigraphically overlain by Permo-Triassic sediments to the southeast. The bedding of these sediments forms a low angle with the Jenatsch detachment. Additionally, several low-angle faults, sub-parallel to bedding, occur within the sediments (e.g. Fig. 14b). Further toward southeast, the sediments are cut by a steeply dipping, northeast-southwest trending fault. Sediments on the southeastern side of this fault form a steep angle with the Jenatsch detachment and are affected by recumbent Alpine D2 folds. Since this fault cuts the Middle Triassic dolomites and is truncated by the Jenatsch de-

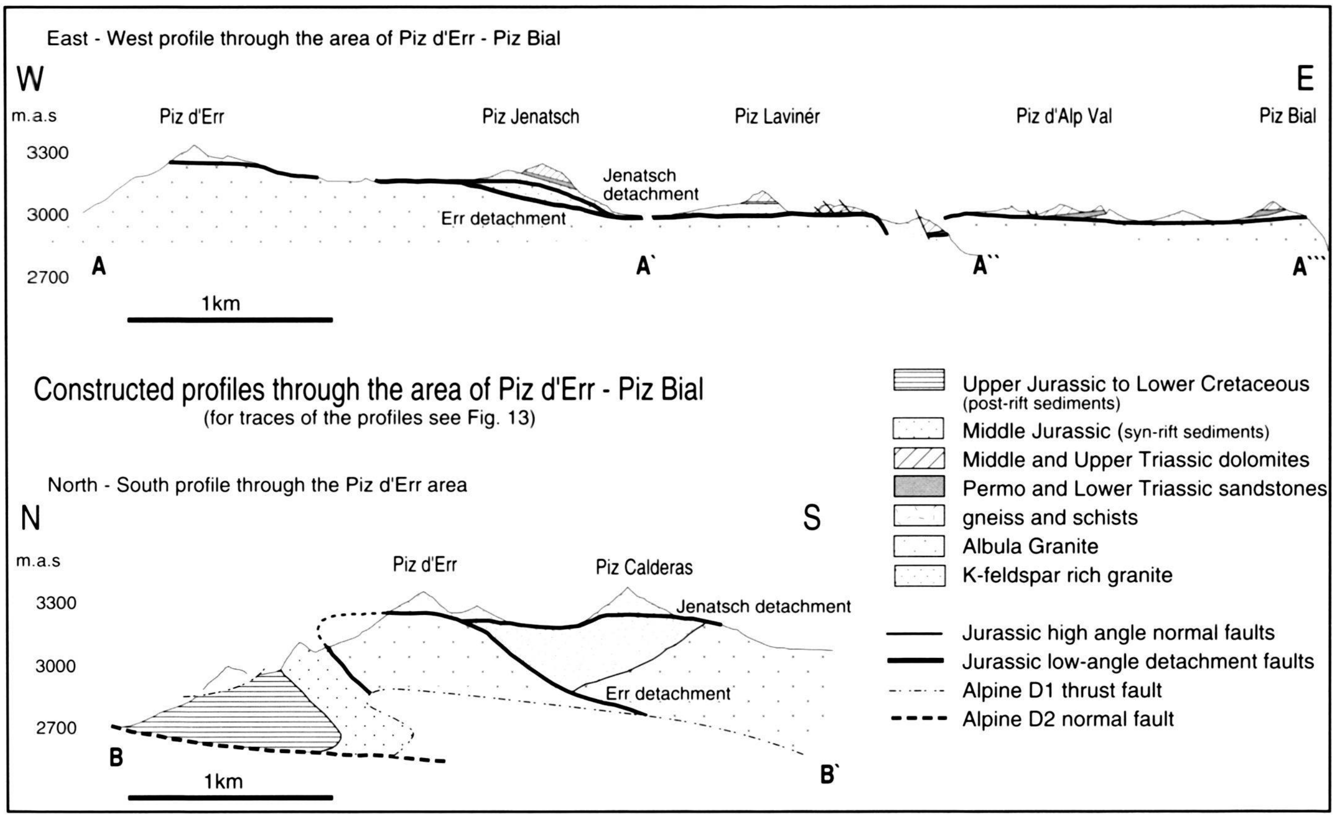

Fig. 15. Profiles normal and parallel to the transport direction of the Jurassic detachment faults in the area of Piz d'Err – Piz Bial. For the traces of the profiles see Fig. 13.

tachment, its age has to post-date the deposition of the Middle Triassic dolomites and to pre-date the minimum age of the Err detachment, which is Middle Jurassic.

Between the Jenatsch and the Err detachment in the southeast ridge of Piz Jenatsch (Fig. 14a), a granite with red K-feldspar phenocrysts up to 4 cm long is exposed. Similar rocks are found at Pass d'Alvra in the footwall of a Jurassic low-angle normal fault (see outcrop EIIIf in Fig. 9).

Since the ridge between Piz Jenatsch and Piz Lavinér shows a continuous section of gneiss which is stratigraphically overlain by Permo-Triassic sediments, the Jenatsch detachment cannot cut this mountain ridge. Therefore, the Jenatsch detachment must join the Err detachment towards the north somewhere beneath the glacier. Towards the west, at the col between Piz d'Err and Piz Calderas, the Err detachment cuts the Jenatsch detachment (Fig. 15, N-S profile).

Piz d'Err and the area southwest of Val Bever (Fig. 13)

In the area of Piz Calderas, the hanging wall of the Err detachment is formed by granite and orthogneiss. Intrusive contacts between granite and orthogneiss are observed in the area of Vadret da Calderas (773.50/155.80, 3140 m.a.s). These rocks form the footwall of the Jenatsch detachment, which can be observed in the col between Piz d'Err and Piz Calderas. The hanging wall of the Jenatsch detachment in the area of Piz Calderas consists of orthogneiss. In the area of Tschima da Flix and Piz d'Agnel this orthogneiss is overlain by Permian volcanics. The contact between the basement rocks and the volcanics is tectonically overprinted. East of Piz Surgonda, the Permian volcanics are stratigraphically overlain by Lower Triassic sandstones of the Chazforà Formation and Middle Triassic dolomites (Cornelius 1932).

North of Piz d'Err-Piz Bial (Fig. 13)

North of the zone of Piz d'Err-Piz Bial in uppermost Val d'Err, the hanging wall of the Jurassic detachment is overturned and forms the so-called "Err Mittelschenkel" of Cornelius (1950). This structure is well exposed at Fuorcla Mulix (F in Fig. 13) where one of the best preserved stratigraphic sequences through the Permo-Triassic to Lower Cretaceous sediments of the Lower Austroalpine can be studied (Cornelius 1935, Stöcklin 1949, Naef 1987). The profile starts with a gneiss that is truncated at the base by the Jurassic detachment. The gneiss is overlain along a stratigraphic contact by Permian to Lower Jurassic sandstones, dolomites and limestones forming the pre-rift sediments, followed by breccias of the Saluver Group representing the syn-rift sediments and then by Lower Cretaceous post-rift sediments, the slates and limestones of the Argille a Palombini Formation. The Upper Jurassic Radiolarite Formation and the Calpionella Limestones are missing in this section. A chert-rich conglomerate occurs at the boundary between the Err Breccia and the Argille a Palombini which is 2 to 3 m thick, characteristically dark and contains clasts of chert, gneiss and dolomite. The clasts lie in a clay-rich carbonate matrix containing Cu-ore minerals such as malachite and chalkopyrite (Stöcklin 1949) and remains of radiolarian skeletons. This contact between the Err Breccia and the Argille a Palombini is interpreted by Lozza (1990) as a stratigraphic horizon that can be traced from Fuorcla Mulix to the northwest ridge of Piz d'Err.

In the Piz d'Err northwest ridge, the Err breccia is separated from the Albula Granite by Jurassic fault rocks and some strongly deformed slivers of metamorphic basement rocks and of Triassic dolomite. Thus, the pre-rift sediments wedge out between Fuorcla Mulix and the Piz d'Err northwest ridge over a distance of 3 km (Fig. 13). In contrast to the pre-rift sediments, the syn-

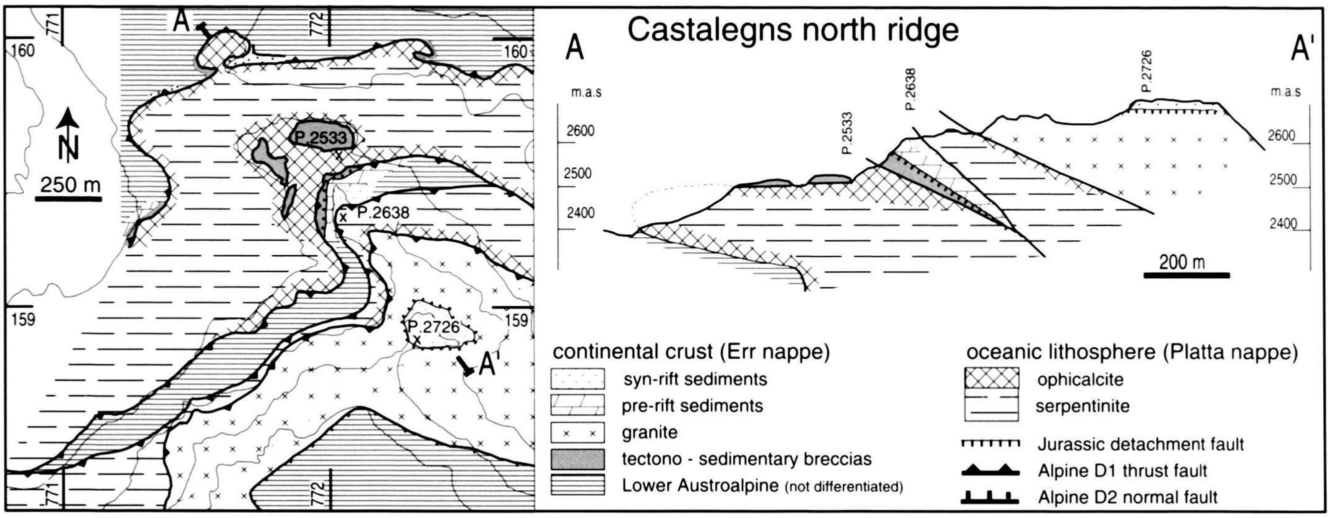

Fig. 16. Geological map and profile of the Castalegns north ridge, compiled after Cornelius (1932) and own observations. Locality PCa in Fig. 9.

and post-rift sediments can be traced from Fuorcla Mulix to the Err northwest ridge, documenting an unconformity between the pre- and the syn-rift sediments.

Along the east side of Val d'Err the post-rift sediments can be followed within the same tectonic unit towards the north. West of Piz Bleis Marscha, the Argille a Palombini are accompanied by radiolarian cherts and limestones. Original stratigraphic contacts are overprinted by Alpine tectonics. In the area of Piz Salteras (Fig. 5 and 6) these post-rift sediments are in stratigraphic contact with the Salteras Series (= Saluver Group, Middle Jurassic). Therefore, it is assumed that the Err Breccia and the Salteras Series in Val d'Err are in stratigraphic contact with the same post-rift sediments. Within the Salteras Series of Piz Salteras, clasts of the characteristic Jurassic black and green fault rocks are found together with clasts of Albula Granite (Fig. 10a; see also Froitzheim & Eberli 1990, their Fig. 5d). These clasts document that the Jurassic detachment must have been exhumed at the sea floor during sedimentation of the Salteras Series and that the source of the black fault rocks (i.e., an exhumed Jurassic detachment) could not have been too far away, as the clay-rich black fault rocks were not destroyed during transport. These relationships are consistent with a submarine swell-basin geometry during the Middle to Late Jurassic with the Err Breccia deposited near a high, lapping onto an exhumed detachment fault, and with the Salteras Series forming more distal deposits containing clasts of the eroded detachment fault. The observation that clasts of Jurassic fault rocks and of Albula Granite are rare in the syn-rift sediments suggests that there was no substantial erosion of the detachment fault.

7.4.4 Castalegns north ridge (Fig. 16) and small outcrops east of Sursés

Fragments of the former continent-ocean boundary overprinted by Alpine deformation are found in the imbricated and folded Lower Err unit and the Supra Mazzaspitz-Marmorera serpentinites along the Castalegns north ridge (772.30/159.00, 2690 m.a.s). The Lower Err unit consists in this area of a porphyric granite, which can be followed from Val d'Err to the Err west ridge in the area of Alp Flix.

At P. 2726 (Fig. 16), a thin discontinuous layer of strongly tectonized crystalline rocks with anastomosing zones of black fault rocks forms the top of porphyric granite and is overlain with a depositional contact by crystalline breccias containing clasts of gneiss, schist and granite. Up-section, the breccias grade over two meters into a brown breccia with crystalline basement and carbonate clasts which is overlain by a coarse-grained sandstone. Laterally, the breccia wedges out and the sandstone directly overlies the tectonized porphyric granite.

At P. 2638 (Fig. 16), a sliver of continental rocks imbricated during D1 thrusting between serpentinites, contains sedimentary breccias with crystalline basement clasts and anastomosing shear zones with black fault rocks. This tectonized basement unit is overlain by a stratigraphically and tectonically reduced sequence of Permian volcanics, sandy dolomite (Lower Triassic), massive dolomite (Middle and/or Upper Triassic), and breccia with crystalline basement and carbonate clasts accompanied by sandy shale (Saluver Group; Middle Jurassic).

At P. 2533 (Fig. 16) along the same ridge, serpentinite grades into ophicalcite and is overlain along an Alpine tectonic contact by a crystalline breccia. This breccia contains clasts of Albula Granite and gneiss. The clasts range in width from several tens of metres- to some cm. At some places fracture fillings within the breccia can be observed. They consist of sparse, rounded crystalline-basement clasts floating in a matrix of limestone or red clay. These structures are cut by the main Alpine cleavage, which in this area is related to D1. Therefore the formation of these fractures filled by sediments has to predate the first Alpine deformation phase and may be related to Jurassic rifting.

At Cuolm da Bovs NW of Castalegns (771.4/159.7; 2400 m.a.s) a sliver of Austroalpine rocks is surrounded by serpentinite. This sliver contains crystalline breccias, formed by gneiss and Albula Granite, overlain by a crystalline/dolomite bearing sedimentary breccia of the Saluver Group, cherts alternating with shales of the Radiolarite Formation and shale-rich limestones of the Argille a Palombini. The strong Alpine deformational overprint makes it impossible to find original stratigraphic contacts, but the transition from a crystalline-bearing breccia to syn- and post-rift sediments is similar to that observed in the better preserved outcrops of the Castalegns north ridge.

7.4.5 Tigias unit

East of Tigias on Alp Flix (770.8/154.9; 2200 m.a.s) (Fig. 17), the biggest and best preserved Lower Austroalpine sliver within the Platta nappe can be observed (Cornelius 1932, 1950). This sliver lies in the same tectonic zone as the slivers of the Castalegns northwest ridge and Cuolm da Bovs. A complete stratigraphic section from Triassic dolomite to the Lower Cretaceous Argille a Palombini and flyschoid series of unknown age is observed, forming an isoclinal Alpine fold. In the Middle to Upper Jurassic radiolarian cherts (Radiolarite Formation), sedimentary breccias with clasts of gneiss, pillow basalts and grains of spinel are observed. This mixed detritus of oceanic and continental

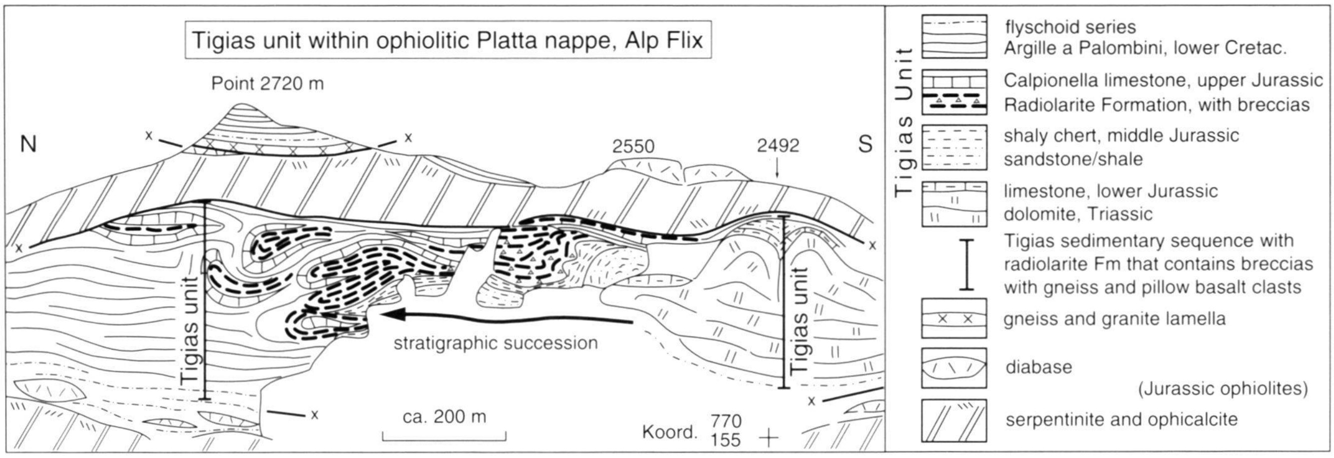

Fig. 17. Schematic view of the Tigias unit at Alp Flix, representing a relic of continental crust within the Platta nappe. For location, see Fig. 9.

provenance documents the proximity of the lower Austroalpine continental margin sequences and oceanic crust (Platta domain). Towards the south, this sliver wedges out and only a few boudins of crystalline rocks and dolomite can be followed at the top of the Mazzaspitz-Marmorera serpentinite south of Ava da las Tigias.

7.4.6 Area of Alp da Starschagns and area east of Mazzaspitz

West of Alp da Starschagns (767.00/152.00; 2290 m.a.s), a sliver of continental basement can be traced over a distance of about 400 m. The contacts to the adjacent serpentinites and pillow basalts are overprinted by Alpine deformation. In a southeast-northwest oriented profile across this sliver, cataclastically deformed granite and gneiss comparable to the green fault rocks contain anastomosing shear zones consisting of black fault rocks. These fault rocks are surrounded by shales, sandstones and sedimentary breccias of the Saluver Group and the Argille a Palombini. The contacts between the different lithologies are strongly overprinted by Alpine deformation.

In the area southeast of Mazzaspitz (764.55/148.90; 2820 m.a.s), a sliver containing Lower Austroalpine sediments lies between serpentinites and ophicalcites (Fig. 18). The contacts with the ophiolites are tectonic (Dietrich 1969). The sliver strikes northwest-southeast and wedges out toward both ends. In its current orientation, the top of the overturned sliver consists of sheared and foliated basement rocks bearing a strong affinity to the Jurassic fault rocks. These fault rocks are overlain by sandstones and sedimentary breccias of the Saluver Group containing only carbonate clasts. These syn-rift sediments are separated from the strongly folded post-rift sediments by a 2 m thick, almost continuous horizon of cornieule and dolomite. The post-rift sediments comprise cherts and shales of the Radiolarite Formation, recrystallized limestones of the Calpionella Limestone, and shales and limestones of the Argille a Palombini.

7.4.7 Other Austroalpine blocks in the Platta nappe

Most rocks of Austroalpine provenance in the Platta nappe are small boudins of Triassic dolomites (Falotta [769.45/157.60; 2270 m.a.s], Flüeseen [765.55/146.95; 2680 m.a.s]), sedimentary syn-rift breccias of the Saluver Group (Ruina Spliatsch [767.90/154.10; 1589 m.a.s]) or slivers of crystalline basement rocks (Plang Tguils [767.50/147.40; 2520 m.a.s]). At several places these slivers could also represent olistoliths or debris flows within the Argille a Palombini, as for example south of Barscheinz along the Pass dal Güglia road (770.75/148.20, 1730 m.a.s). All these relics of continental crust and related sediments in the Platta nappe are accompanied by serpentinites, which are assumed to belong to the same serpentinite body, the Mazzaspitz-Marmorera serpentinite.

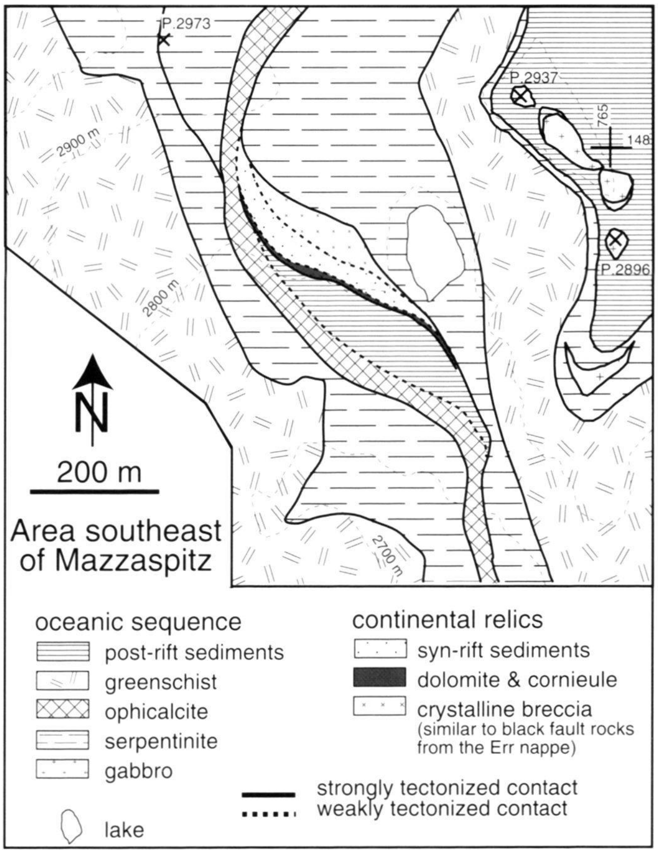

Fig. 18. Geological map of the area southeast of Mazzaspitz in the Platta nappe. Locality PCc in Fig. 9.

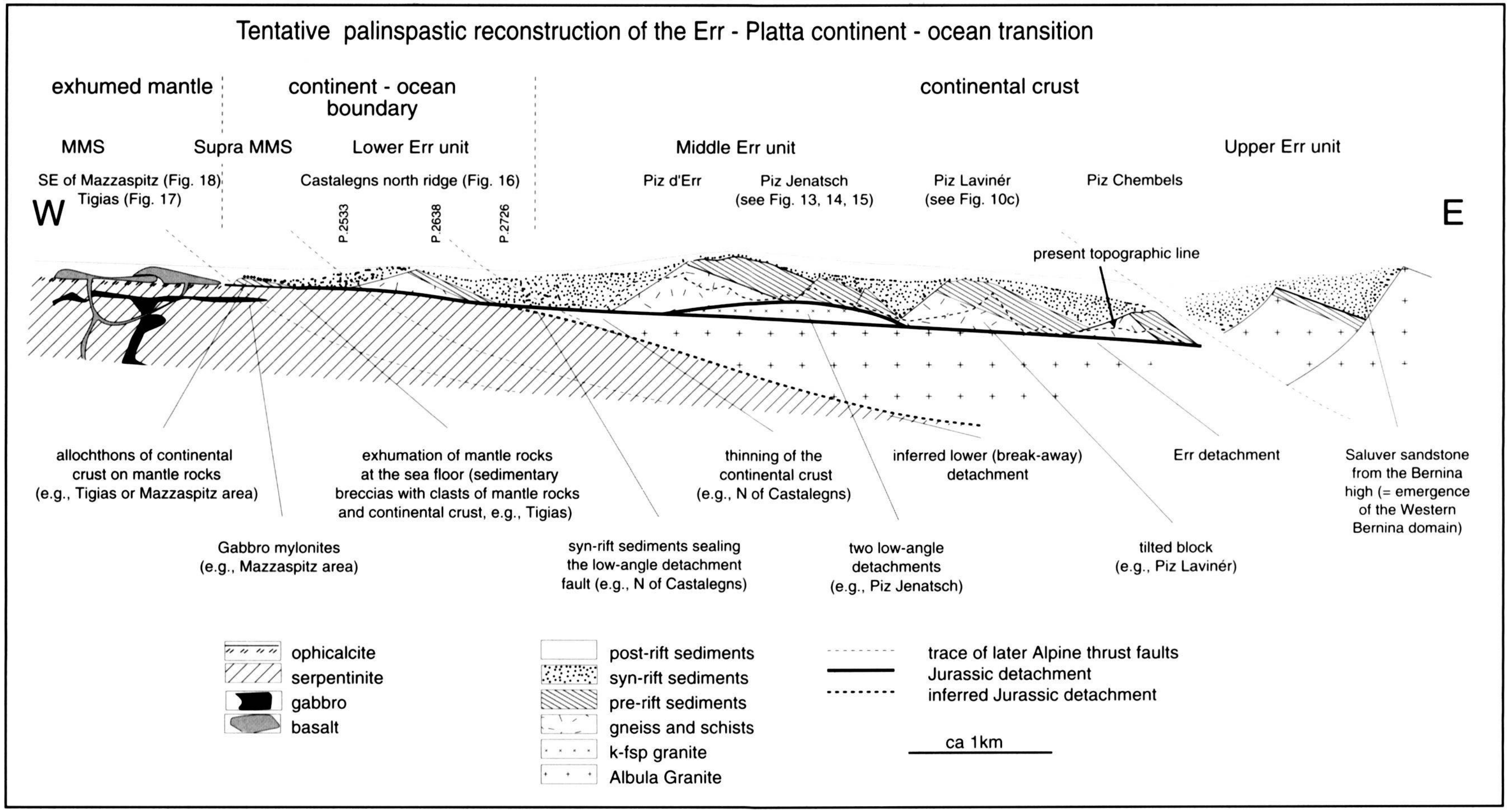

Fig. 19. Tentative palinspastic section showing the observed relationships between sediments, detachment faults and exhumed mantle rocks along the ocean-continent transition in the Err and Platta domains.

8. Discussion

8.1 The low-angle detachment system

8.1.1 The detachment structures

The reconstructed continent-ocean transition of the Err and Platta domains (Fig. 19) is characterized by a low-angle detachment system that accommodated top-to-the-west displacement. This detachment can be traced over a reconstructed distance of at least 35 km parallel to the transport direction from the continental basement of the Err domain to the oceanic Platta domain. Over the entire area observed, no noticeable change in the metamorphism of the footwall rocks and no crystal plastic, dynamic recrystallization in quartz in the fault rocks is observed, indicating that detachment faulting occurred in the upper crust at temperatures below 300°C and was active at a low angle. The inference of a primary low-angle is also supported by the low angle between the syn-rift sediments and the detachment fault observed at Muot Cotschen (Figs. 10b and 11) and at P. 2726 of the Castalegns north ridge (Fig. 16).

In the area of Piz Jenatsch in the Middle Err unit, a very characteristic small intrusion of a granite with up to 4 cm long red K-feldspar megacrysts was found in the hanging wall of the Err detachment. The same rock type occurs again in the footwall of the Err detachment south of the Pass d'Alvra (see outcrop EIIIf and Piz Jenatsch in Fig. 9). These two outcrops can be connected by an east-west striking line parallel to the transport direction (Manatschal 1995) along the Err detachment (Fig. 13). The distance between these two outcrops today is 11 km. Assuming that the two outcrops originally belonged to the same granite body, which is very likely since there are no other outcrops of this rock type known in the area, this distance may be taken as an estimate for the displacement along this Jurassic detachment fault.

Excellent outcrop conditions and the weak Alpine tectonic overprint in the area of Piz d'Err-Piz Bial-Val Bever allow us to reconstruct the 3D-geometry of the Jurassic detachment with some confidence. This reconstruction shows that high-angle normal faults are very common. Most of them have a limited amount of displacement (< 50 m), which may be related to accommodation problems during block tilting. The clockwise (e.g. Piz Lavinér [Fig. 14b]) and anticlockwise tilting (e.g. Piz d'Alp Val [Fig. 14c]) (looking northwards) of the Mesozoic sediments indicates that block tilting in the hanging wall was not uniform. Therefore the tilt of hanging wall blocks is difficult to use as a kinematic indicator for the master fault as proposed by Brun et al. (1985). In the area of Piz d'Err-Piz Bial, where the Alpine overprint is weak, a top-to-the-west shear sense was determined for the low-angle detachment system using s-c fabrics, shear bands, asymmetric clasts and joint-fault relationships observed in the black fault rocks and in the neighbouring rocks (Fig. 13).

In the area of Piz Jenatsch-Piz Bial two low-angle detachment faults can be observed (Fig. 13, Fig. 14a, Fig. 15). Both cut high-angle normal faults and tilted blocks. Assuming that these high-angle normal faults rooted, as generally assumed, in a detachment fault, a third detachment fault had to be present at depth (Fig. 20). This inferred detachment must have been active in a deeper crustal level, must have predated the activity along the observed detachment faults, and may have been connected to a break-away along the boundary between the Err and Bernina domain (further discussion of the break-away, see below).

8.1.2 The footwall structures

In the area of Murtiröl-Val Vaüglia (see G in Fig. 9) gneiss in stratigraphic contact with pre-rift sediments forms the footwall of the fault system. Towards the west in the area of Piz d'Err – Piz Bial (Fig. 13), the footwall is formed by a massive, weakly deformed Albula granite which shows intrusive contacts with the latter gneiss and does not show stratigraphic contacts with pre-rift sediments. The continental basement appears to become thinner and strongly brecciated towards the continent-ocean transition. In the Platta nappe, characteristic Jurassic fault rocks, representing relics of a Jurassic detachment fault, overlie serpentinites and mylonitized gabbro. This serpentinite is assumed to originate from spinel lherzolite and harzburgite (Burkhard & O'Neil 1988). The mylonitized gabbro contains a fabric defined by dynamically recrystallized plagioclase and pyroxene ribbons formed during dynamic recrystallization processes stable at much higher temperatures (> 700°C in the case of pyroxene) than those ever reached during Alpine orogeny in the northern Platta nappe (< 450°C according to Trommsdorff 1983). From the observed cross-cutting relationships (Fig. 4) it is likely that the gabbro intruded into mantle peridotite, and mylonitization occurred during initial uplift, prior to serpentinitization of the peridotite and exhumation of these rocks at the sea floor in the footwall of the detachment faults. Lower crustal rocks were not observed, either in the footwall or as clasts in the syn-rift breccias.

8.1.3 The hanging wall structures

The hanging wall of the detachment system is characterized by mainly clockwise rotated (looking to the north) tilted blocks. The size of these tilted blocks and the amount of basement rocks involved in the hanging wall of the low-angle detachment faults decrease from east towards west, i.e. towards the ocean, parallel to the Jurassic transport direction. Fragments of continental basement as well as pre- and syn-rift sediments in the Platta nappe are accompanied by characteristic fault rocks, similar to those observed along the Jurassic detachment faults in the Err nappe. These fragments are always associated with the Mazzaspitz-Marmorera-serpentinite (= MMS), a prominent serpentinite body that can be traced in the northern and middle part of the Platta nappe (Dietrich 1969, 1970) (Fig. 1). In analogy with the tilted blocks in the Err nappe, these slivers are interpreted as extensional allochthons emplaced during Jurassic time along a low-angle detachment fault on top of exhumed mantle lithosphere (Froitzheim & Manatschal 1996). This is well shown east of Tigias on Alp Flix (Figs. 17, 19 and 20), where one such fragment is stratigraphically overlain by the Middle to Upper Jurassic Radiolarite Formation con-

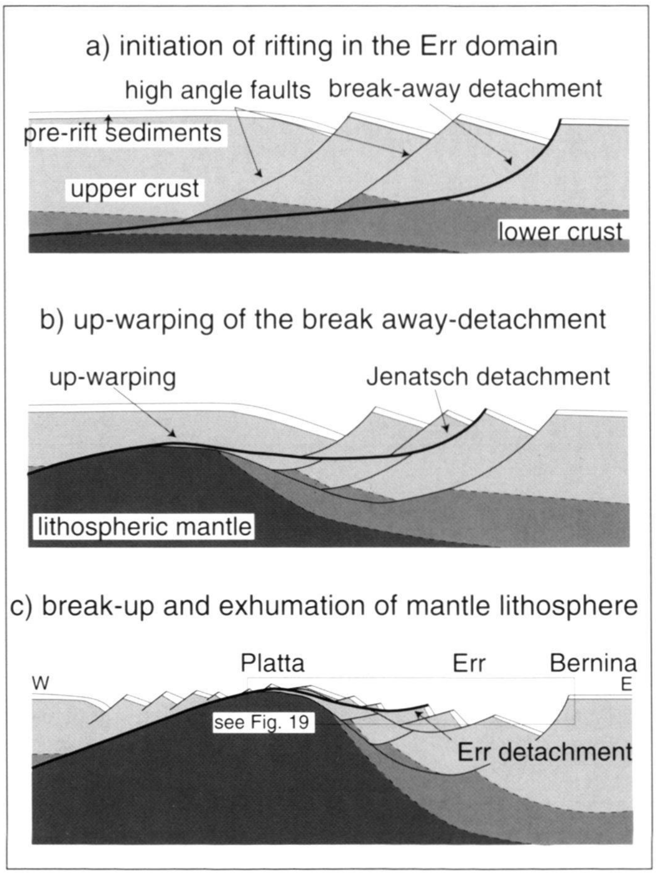

Fig. 20. Model to explain the geometry and evolution of the detachment system from initial rifting to break-up.

taining clasts of gneiss and ophiolitic detritus. This suggests that continental crust (e.g., Err domain) and mantle rocks (e.g., Platta domain) were juxtaposed during Middle to Late Jurassic time. Pillow lava or post-rift sediments in stratigraphic contact with underlying ophicalcite and serpentinite in the Platta nappe and Arosa Zone (Bernoulli & Weissert 1985) as well as in the Western Alps (Lemoine et al. 1987) are direct evidence of exhumed mantle rocks.

8.2 Relation between syn-rift sediments and the low-angle detachment faults

Syn-rift sediments can be found today in different tectonic levels in direct contact with the Jurassic detachment within the Err nappe. The outcrops of Fuorcla Cotschna (Fig. 11), Piz Nair (outcrop EIa in Fig. 9) in the upper Err unit, and Murtiröl-Val Vaüglia (G in Fig. 9, see also Roesli [1927]) may be related to Jurassic exhumation of the detachment faults along the break-away (Froitzheim & Manatschal 1996). The outcrops of Castalegns north ridge (Fig. 16) and Mazzaspitz (Fig. 18) may represent examples where an exhumed low-angle detachment fault along the ocean-continent boundary was directly sealed by syn-rift sediments. An additional possibility, namely that already deposited syn-rift sediments were truncated by low-angle normal faults, may be a good explanation for the outcrops of Cuetschens (Fig. 12) and Foras d'Nes (outcrop EIIIc, Fig. 9).

8.3 The geometry of the continent-ocean transition

The top-to-the-west transport direction, the predominantly west-side-down rotation of the hanging wall blocks and the proposed occurrence of a break-away along the border between the Err and Bernina domains (Froitzheim & Manatschal 1996) suggest a west-dipping detachment system. However, the decrease in size of the hanging wall blocks and the gradual disappearance of continental basement in the transport direction, the exhumation of top-to-the-west detachment faults in the most distal part of the margin along the ocean-continent boundary (e.g. Castalegns north ridge, Fig. 16), and the observation that the high-angle normal faults are truncated by the low-angle detachment faults (see Fig. 20c) are not compatible with a west-dipping listric fault geometry of the detachment and associated faults alone (see Fig. 20a). In this case, one would expect that both, the size of the hanging wall blocks and the ratio between basement rocks and pre-rift sediments should increase in transport direction.

To explain our observations, we use a modified model proposed by Lister and Davis (1989) for metamorphic core complexes. This model, shown in Fig. 20, assumes a polyphase evolution of an extensional system from initial rifting (Fig. 20a) to final break-up (Fig. 20c). Rifting is suggested to initiate along a listric, top-to-the-west normal fault, the so called break-away detachment which acted in deeper crustal levels as basal shear zone for the tilted blocks (Fig. 20a). Due to up-warping of the footwall and rotation of the active detachment faults into mechanically unfavourable positions, new detachment faults formed (e.g., the Jenatsch detachment in Fig. 20b and Err detachment in Fig. 20c). This process which links horizontal extension with vertical uplift can explain all the observations mentioned above. The up-warping of the detachment near the continent-ocean boundary is assumed to be related to local isostatic rebound during extension (cf. experiments of Brun et al. 1994). Possible driving forces for the isostatic rebound are the unloading of the footwall during movement along the detachment faults and serpentinization of the mantle peridotites during uplift and final exhumation at the sea floor. Therefore, we assume that exhumation of the Platta "ocean" is related to a detachment system showing a "core complex" type geometry (e.g. Wernicke 1992). In using this analogy, we emphasize that only the geometric relationships are meant, since we are aware that the tectonic settings of metamorphic core complexes and continental margins are very different.

8.4 Evolution of rifting in the Austroalpine-South Penninic domains in Grischun

The onset of rifting along the European-Apulian margin is marked in the Briançonnais in the Western Alps (Lemoine et al. 1986) and in the Central Austroalpine domains (Furrer et al. 1985, Eberli 1988, Conti et al. 1994) by subsidence and rift-basins bounded by high-angle normal faults leading to a thinning of the continental crust. At that (Late Triassic/Early Jurassic) time, the Err domain evolved into a submarine high onto which thin, hemipelagic limestone were deposited (Furrer et al. 1985). Initiation of near-surface faulting and basin formation in the Err domain post-dates the early Toarcian (Finger 1978), after rifting activity declined east of the Bernina domain (Eberli 1988). This second rifting phase is characterized by: 1) initiation of near-surface faulting and basin formation in the Err domain and simultaneous declining of rifting activity east of the Bernina domain, 2) relative uplift of the eastern Bernina domain and simultaneous subsidence of the Err domain and 3) change in tectonic style from symmetrical high-angle faulting to strongly asymmetric and localized low-angle detachment faulting that accommodated most of the extensional strain.

The most prominent structure active in the final stage of rifting is a low-angle detachment fault system. It forms a breakaway in the east (western Bernina domain), and cuts down towards the west beneath the European continent into mantle lithosphere, previously exhumed to a shallow crustal level (about 10 km, < 300°). The high position of the mantle lithosphere already before it was involved in detachment faulting is shown by the generally brittle deformation along the normal faults in the Platta nappe. Therefore mantle uplift had to occur during an initial phase of rifting, probably during a preceding pure shear rifting event (here called first rifting event) (Manatschal et al. 1995). The final break-up along the Err-Platta margin occurred by tectonic exhumation of serpentinized mantle rocks in the footwall of low-angle detachment faults and subsequent extrusion of basalt of MORB-composition.

9. Conclusions

Detailed mapping of key areas, a structural analysis along the Err and Platta boundary between Val d'Err and Bivio and older information (Cornelius 1932, 1935, 1950, Stöcklin 1949, Dietrich 1969, 1970, Finger 1978), allowed us to reconstruct a continent-ocean transition in the Lower Austroalpine Err nappe and the Upper Penninic Platta nappe. This continent-ocean transition is characterized by a top-to-the-west low-angle detachment system active during rifting and responsible for the tectonic exhumation of mantle rocks at the sea floor leading to the break-up of the Piemont-Ligurian ocean in Late Jurassic time. The observations made in the Err and Platta nappes fit well with those reported from other fossil margins (e.g. Lemoine et al. 1987, Florineth & Froitzheim 1994) and modern, non-volcanic, sediment-starved margins, as for example the Galicia margin (Boillot et al. 1995a, 1995b).

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