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An ancient ocean-continent transition in the Alps: the Totalp, Err-Platta, and Malenco units in the eastern Central Alps (Graubünden and northern Italy)

Excursion of the Swiss Geological Society, September 20 to 24, 2002.

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ABSTRACT

The South-Pennine ophiolites of the eastern Central Alps (Graubünden and northern Italy) are characterized by a predominance of serpentinized peridotites of subcontinental mantle origin, minor gabbroic intrusions, and the lack of a sheeted dike complex. Tholeiitic pillow lavas and flows and Middle Jurassic to Early Cretaceous oceanic sediments stratigraphically overlie the mantle rocks. The peridotites record deformation under decreasing temperature during extension leading to final exposure at the sea floor and their inclusion in tectono-sedimentary breccias (ophicalcites). Exhumation occurred along a system of detachment faults, which locally carry stranded klippen of continental crust and pre-rift sediments. The resulting stratigraphic and structural architecture is best compared with that of an ocean-continent transition along present-day magma-poor rifted margins such as the west-Iberian margin off Portugal.

Gabbros intruded the partially serpentinized mantle rocks at shallow depth at 161 Ma. Both gabbros and basalts are characterized by εNd values typical for an asthenospheric MOR-type source of the melts. They appear to document the onset of sea-floor spreading across an exhumed subcontinental mantle.

Day 1 of the excursion (Totalp area) focuses on the interplay of the tectono-metamorphic and sedimentary processes related to mantle exhumation; Day 2 (Platta nappe) on the architecture of the ocean-continent transition and deformation processes related to detachment faulting; Day 3 (Platta nappe) on the interrelations of mantle exhumation and magmatic activity; and Day 4 (Malenco unit) focuses on the petrology and processes related to a pre-rift crust-mantle boundary.

ZUSAMMENFASSUNG

Die süd-penninischen Ophiolithe der östlichen Zentralalpen (Gaubünden und Nord-Italien) sind gekennzeichnet durch die Vorherrschaft von serpentinisierten Peridotiten, die der subkontinentalen Mantellithosphäre entstammen, räumlich begrenzte Gabbro-Intrusionen und das Fehlen eines Gangkomplexes. Tholeiitische Kissenbasalte, massive Laven und Hyaloklastite sowie ozeanische Sedimente, die vom Mitteljura bis in die Unterkreide reichen, überlagern die Mantelgesteine stratigraphisch. Die Deformation der Peridotite während der jurassischen Extension erfolgte unter abnehmenden Temperaturen, wobei die serpentinisierten Peridotite schliesslich am Meeresboden exponiert wurden, wo sie als Komponenten in komplexen tektono-sedimentären Breccien (Ophicalcite) auftreten. Die Exhumierung der Mantelgesteine erfolgte längs einem System von flach einfallenden Abschiebungen (detachments), welche lokal überlagert werden von Klippen von kontinentaler Kruste und von prae-Rift-Sedimenten. Der stratigraphische und strukturelle Aufbau dieses jurassischen Ozeanrandes lässt sich am besten mit einem Ozean-Kontinent-Übergang vergleichen, wie er längs Magma-armer heutiger Kontinentalränder wie z.B. längs des iberischen Randes westlich von Portugal auftritt.

Die Gabbros intrudierten vor 161 Ma in bereits partiell serpentinisierte Peridotite. Gabbros und Basalte sind charakterisiert durch εNd-Werte wie sie typisch sind für eine asthenosphärische MOR-Herkunft der Magmen. Diese Magmen dokumentieren offenbar den Beginn des "sea-floor spreading" in einer Zone von exhumierter subkontinentaler Mantellithosphäre.

Der erste Tag der Exkursion (Totalp-Gebiet) zeigt die Interaktionen von tektono-metamorphen und sedimentären Prozessen bei der Mantelexhumation. Der zweite Tag (Platta-Decke) illustriert den Bau des Ozean-Kontinent-Überganges und die Deformation, die mit der Entwicklung der Abschiebungssysteme einhergeht. Der dritte Tag (Platta-Decke) zeigt die Beziehungen zwischen Mantelexhumation und magmatischer Tätigkeit; und der vierte Tag (Malenco-Einheit) dokumentiert die Petrologie einer prae-Rift Krusten-Mantel-Grenze und die mit ihrer Entwicklung verknüpften Prozesse.

Introduction

In retrospect, Graubünden appears to be a classical area for the history of research on ophiolites. In this area, Gustav Steinmann (1905) noted the close association of serpentinites, "diabase", and radiolarites, an association which later was to be called the Steinmann Trinity (Bailey & McCallien 1950, 1953; for a short history of the concept see Bernoulli et al. in

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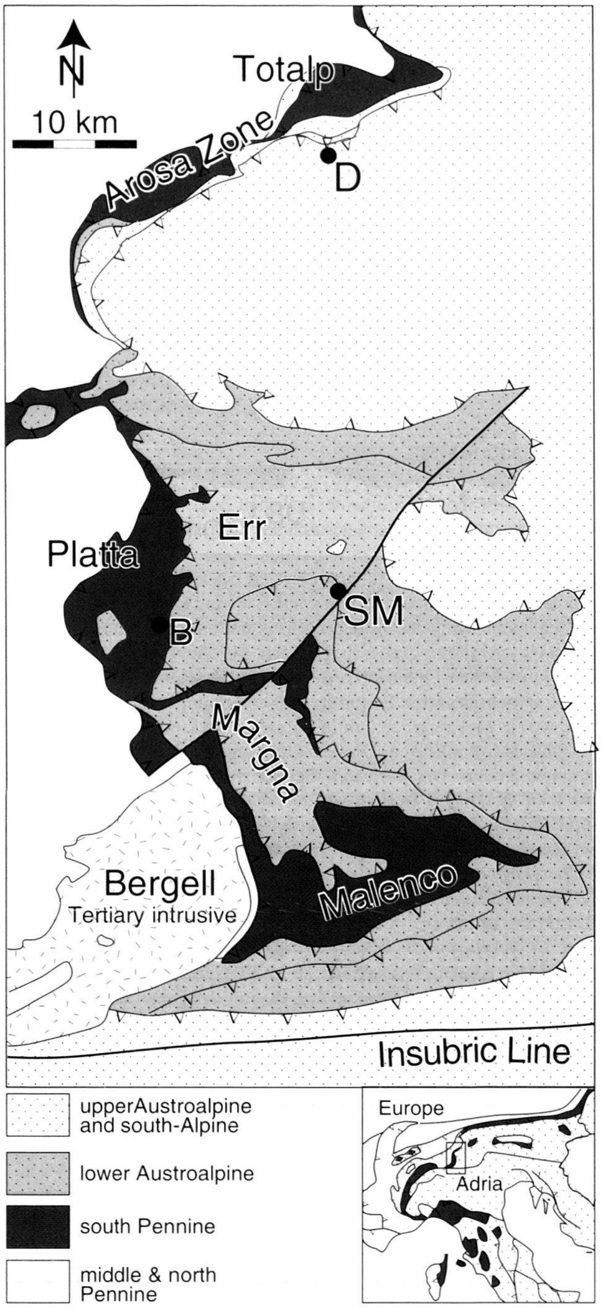

Fig. 1. Tectonic sketch map of the South-Pennine-Austroalpine boundary zone in Graubünden. D: Davos, B: Bivio, SM: San Murezzan. Modified after Froitzheim et al. (1994).

press). Steinmann was not the first to note the co-occurrence of these rocks, but he was possibly the first to recognize the particular geodynamic significance of this association which he considered to be typical for the deep axial part of the "geosyncline".

Before the advent of plate tectonics, the Alpine ophiolites were interpreted as intrusions emplaced during Early Cretaceous phases of Alpine "folding" of the geosynclinal sediments (Steinmann 1905, 1927; Argand 1916; Staub 1922), and it was only with the new paradigm of plate tectonics that ophiolites in mountain belts were equated with relics of oceanic lithosphere. In the following, the Err nappe with its continental basement and the ophiolitic Platta nappe (Fig. 1) were interpreted as the relics of a former continental margin (Trümpy 1975), because these units showed an almost identical middle Jurassic to early Cretaceous sedimentary evolution (Dietrich 1970). During the last years, this notion developed into the concept of an Ocean-Continent Transition (OCT), which separated a rifted margin preserved in the Austroalpine nappes of Graubünden from an oceanic domain in the west which has been largely subducted during Alpine convergence (Froitzheim & Manatschal 1996, Manatschal & Nievergelt 1997).

The ophiolites preserved along the South Pennine-Austroalpine boudary are characterized by the predominance of serpentinites which preserve the geochemical and petrographical characteristics of subcontinental mantle rocks (Trommsdorff et al. 1993; Müntener & Hermann 1996), small volumes of gabbros and basalts, the lack of a sheeted dike complex, and the occurrence of continent-derived crustal blocks (Froitzheim & Manatschal 1996, Manatschal & Nievergelt 1997; Fig. 2). Most of these observations are incompatible with exhumation of the mantle rocks in a spreading system and are more likely the result of mantle exhumation by lithospheric-scale detachment faulting in an ocean-continent transition zone. Indeed, the palinspastic section from the continental Err nappe to the ophiolitic Platta nappe (Fig. 2) presents conspicuous analogies to undeformed magma-poor margins like the Iberian margin west of Portugal, in terms of extensional detachment faulting, crustal thinning ($\beta > 2$), sediment distribution, overall margin architecture, and tectonic evolution (Manatschal & Bernoulli 1998, 1999; Whitmarsh et al. 2001).

In a cross-section, the ocean-continent transition s.str. defines the area between the break-up of the continental crust and the break-up of the continental mantle lithosphere. It is characterized by the occurrence of subcontinental mantle rocks exhumed along a system of detachment structures; the occurrence of extensional allochthons, gabbros, and dolerites of MOR-character genetically unrelated to the mantle rocks they intrude; and pillow-lavas and oceanic sediments overlying the exhumed mantle and the magmatic rocks intruding it (Fig. 2). The underpinnings of the margin are exposed in the Malenco nappe, where the exhumation of the pre-Mesozoic crust-mantle boundary can be reconstructed in detail (Müntener & Hermann 1996; Hermann et al. 1997).

In the following we shall give a short geological introduction and a description of the outcrops visited by or planned for the excursion following the workshop "Birth and Early Evolution of Alpine Oceanic Basins" held during the Annual Meeting of the Swiss Academy of Natural Sciences in Davos.

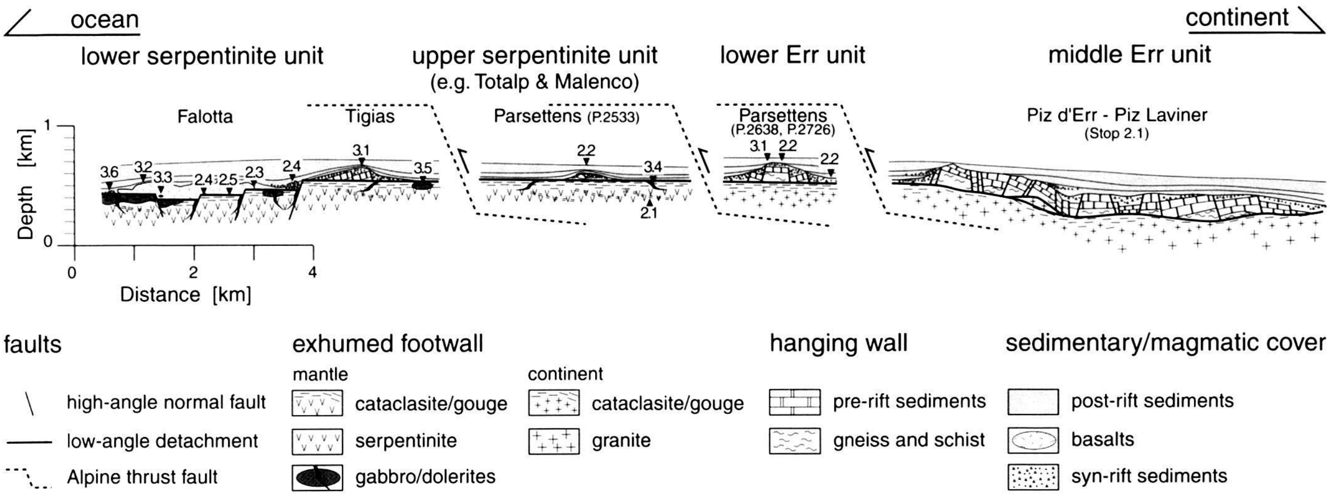

Fig. 2. Palinspastic reconstruction of the Err-Platta ocean-continent transition. Numbers in the figure refer to stops described in the text.

The ocean-continent transition of the South-Pennine - Austroalpine boundary in Graubünden

General situation

Along magma-poor continental margins, the transition from continental to oceanic crust occurs across a zone consisting of serpentinized peridotites directly overlain by deep-water sediments. The South Pennine-Austroalpine boundary zone in the eastern Alps preserves all the structural and petrological elements of such an ancient ocean-continent transition (Manatschal & Nievergelt 1997). In this part of the Alpine nappe edifice, the lower Austroalpine Err nappe represents the distal, sediment-starved continental margin of the Adria continental fragment. It consists of thinned continental crust, overlain by tilted blocks, slivers of shallow continental crust, and pre-rift sediments, which were emplaced during the middle Jurassic along an oceanward-dipping system of detachment faults (e.g. extensional allochthons, Froitzheim & Manatschal 1996; Manatschal & Nievergelt 1997; Fig. 2). The Err nappe was thrust to the west and onto the South-Pennine Platta nappe in Late Cretaceous time.

The Totalp, Platta, and Malenco units represent a strip of transitional crust, formerly bordering the oceanic crust of the Liguria-Piemonte segment of the Tethyan ocean. In the Platta nappe, the ophiolites are preserved in two major thrust sheets, the upper serpentinite unit preserving more continentward parts of the OCT and the lower serpentinite unit preserving more oceanward parts of the OCT. The mantle rocks in the Totalp slice and Val Malenco show many similarities with those of the upper serpentinite unit. Whereas in the Totalp, in the upper serpentinite unit, and in the Malenco unit the Mesozoic magmatic rocks are scarce or virtually absent, they are more common in the lower serpentinite unit where the original geometrical and age relationships between mantle rocks, gabbroic intrusions, pillow lavas, and oceanic sediments can be well observed. In both units of the Platta nappe, exhumed mantle rocks, extensional allochthons, and pillow basalts are stratigraphically overlain by Middle to Late Jurassic radiolarites and/or Early Cretaceous pelagic limestones of Maiolica facies (e.g. Calpionella Limestone) (Fig. 2). Because during Alpine orogeny temperatures never exceeded approximately 250°C in the north (Ferreiro-Mählmann 2001), and 450° in the south (Trommsdorff 1983), the pre-Alpine history of mantle deformation, gabbro intrusion, and hydration during continental break-up is well documented.

A fossil crust-mantle boundary: pre-rift conditions and rift-related exhumation

The pre-rift situation at the crust-mantle boundary is well exposed in Val Malenco (Fig. 1). Detailed field, petrographic, petrologic, and isotopic investigations of the high-grade metamorphic rocks revealed that lower crustal granulites form part of a fossil crust-mantle boundary (Müntener & Hermann 1996; Hermann et al. 1997; Hansmann et al. 2001). A tholeiitic gabbro intrusion displays intrusive contacts to both lower crustal granulite above and mantle rocks below. The intrusive complex ranges from Mg- to Fe-rich gabbronorites and Fe-Ti and quartzdiorite dikes (Müntener & Hermann 1996; Hermann et al. 2001). Differentiation of the gabbro complex was mainly driven by fractional crystallization of pyroxenes and plagioclase, resulting in a tholeiitic differentiation trend (Hermann et al. 2001). The lower crustal metapelites experienced extensive partial melting which produced migmatites and residues rich in garnet and kyanite. Two different types of leucosomes can be observed: (1) small granitic bodies in the immediate vicinity of the gabbroic rocks; and (2) farther away, leucogranitic dikes

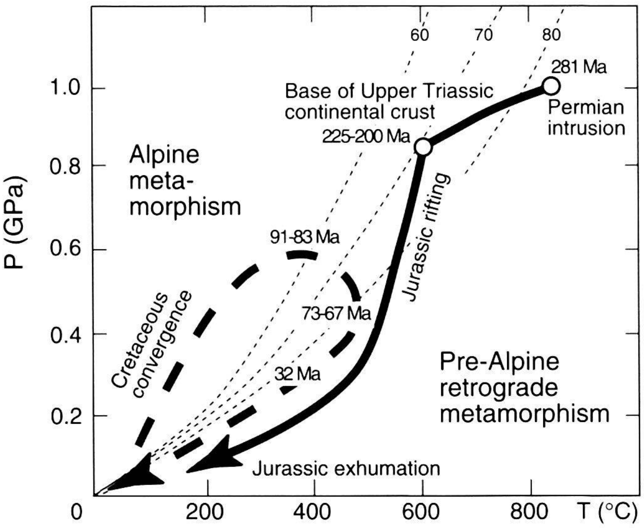

Fig. 3. Pressure-temperature-time diagram for the Malenco crust-mantle complex, after Müntener et al. (2000), Villa et al. (2000) and Hansmann et al. (2001). Black arrow indicates the Permian to Jurassic retrograde metamorphic evolution, while the dashed arrow indicates the burial and exhumation related to the Alpine cycle. Geotherms corresponding to different surface heat flows (in mW/m^2) are taken from Chapman (1986).

which cut across highly differentiated gabbro dikes (Müntener & Hermann 1996; Ulrich & Borsien 1996).

The peak metamorphic paragenesis in the metapelites consists of garnet, kyanite, biotite, quartz, ilmenite/rutile, and feldspars. Phase relations and mineral chemistry suggest peak metamorphic pressures of about 1.0 GPa and a temperature of 800-850°C (Müntener et al. 2000) (Fig. 3). A maximum temperature estimate of 870° was deduced by using Zr-saturation temperatures in a granitic body close to the gabbro intrusion (Hansmann et al. 2001). Phase relations in mantle and gabbroic rocks are consistent with the results from the lower crustal rocks.

U-Pb determinations on single zircons from differentiated gabbros and from granite bodies in the metapelites yield ages of 281±19 Ma and 278±2.6 Ma respectively (Hansmann et al. 2001). These ages strongly suggest that emplacement of the gabbroic rocks and partial melting in the lower crust are coeval and of Permian age. Recent zircon and monazite dating of the granulites refined this picture and provided additional constraints on the timing of granulite facies metamorphism (Hermann & Rubatto in press). Zircons from the lower crustal metapelitic granulites display inherited cores with apparent ages ranging from 520 to 3050 Ma and three metamorphic overgrowths with ages of 280±5, 269±3, and 258±4 Ma. Monazites record the same three metamorphic ages at 280±5, 270±5, and 258±4 Ma (Hermann & Rubatto in press). These data indicate that granulite facies metamorphism induced by underplating of mafic rocks lasted for about 20 my.

Two stages of retrograde metamorphism followed (Fig. 3). Mineral parageneses in garnet-kyanite gneiss, metagabbro, and metaperidotite record a first stage of near-isobaric cooling under anhydrous conditions. The near-isobaric cooling probably reflects slow relaxation of a high geothermal gradient after the gabbro intrusion. The rocks at the crust-mantle boundary cooled over a period of about 30 to 50 my and reached about 1 to 0.8 GPa and ~ 600°C in Late Triassic time. The Malenco crust-mantle boundary thus provides strong constraints on the pre-rift conditions in the deep crust and upper mantle. Exhumation of the crust-mantle complex began with the onset of continental rifting during the latest Triassic-early Jurassic. Hydrous phases partially replaced the granulite facies mineral assemblages in all rock types and indicate a fluid influx at about 0.9 GPa and 650°C (Müntener et al. 2000) (Fig. 3). Continued hydrous recrystallization is accompanied by near-isothermal decompression. Dating of amphiboles formed during this hydration yield late Triassic to early Jurassic ages (Villa et al. 2000), indicating that decompression was related to Jurassic rifting.

Structures related to mantle exhumation

Structures of the distal Adriatic margin are well exposed in the Err nappe. The most prominent structure is a system of low-angle detachment faults. The faults form break-aways in the continental crust, cut oceanwards into mantle and are overlain by extensional allochthons (Fig. 2). Relics of this detachment system are also found in the Platta nappe, where they separate extensional allochthons consisting of continental crust and Permian to Late Triassic sediments from the exhumed mantle rocks (Manatschal & Nievergelt 1997). Syn-rift sediments of Middle Jurassic age (Saluver Group) onlap onto the exhumed fault planes and include characteristic clasts derived from the detachment faults (Froitzheim & Eberli 1990). These observations testify the exhumation of detachment faults at the sea floor during Jurassic time.

Pre-rift lower crustal rocks have not been identified in the Err nappe but occur farther south in the Malenco area. These lower crustal rocks are separated from the upper crust by a crustal-scale, continentward-dipping fault, the Margna fault. P-T-t data show, that this fault thinned the crust to about 10 km during Early Jurassic time (Müntener & Hermann 2001). Thus, although no direct cross-cutting relationships between continentward and oceanward dipping detachment structures exist, there is strong evidence that within the distal margins, crustal-scale faults dipping continentwards thinned first the crust to about 10 km before oceanward dipping detachment faults cut into the mantle and led to its exhumation to the sea floor.

Mantle rocks in the ocean-continent transition

Mantle rocks in the OCT are invariably serpentinized peridotites derived from spinel lherzolites and harzburgites into which gabbros and basaltic dikes intruded. Trace elements in the mantle clinopyroxene reveal that mantle rocks close to the continent may represent spinel peridotite mixed with (garnet-) pyroxenite layers while the ultramafic rocks at some distance from the continent are pyroxenite-poor peridotites that equilibrated in the plagioclase stability field (Müntener et al. 2002). Bulk rock analyses of the peridotites located farther oceanwards show fertile to extremely depleted compositions and most clinopyroxenes equilibrated with plagioclase. Textural relationships indicate that some plagioclase peridotites in the Platta nappe were formed by melt infiltration and melt-rock reaction. Whether melt infiltration was related to the onset of sea-floor spreading or represents an older and independent event in the lithospheric mantle is, however, not yet clear. Two-pyroxene and single-orthopyroxene thermobarometric data from the Platta nappe reveal an increase in the equilibration temperature from 850°C±50 at 0.8-1.2 GPa in mantle rocks close to the continent to >1000°C further oceanwards (Desmurs et al. 2001); however, the age at which the equilibration temperature has been acquired is unknown.

Deformation in the mantle rocks was polyphase and occurred under retrograde metamorphic conditions. Granulite-facies (=anhydrous) deformation is characterized in the mantle units next to the continent (Totalp, upper serpentinite unit of the Platta nappe, and Malenco) by a penetrative spinel foliation and subparallel pyroxenites. Towards the ocean, i.e. in the lower serpentinite unit of the Platta nappe, the high-temperature, granulite-facies deformation changes, the rocks look less deformed and pyroxenites are rare (Desmurs et al. 2001). All other types of deformation appear to be similar throughout the OCT. Localized shear zones formed by peridotite mylonite to ultramylonites are commonly inclined relative to the top of the exhumed mantle and show a top-to-the-continent sense of shear. Tectonites reflecting deformation and hydration processes occurring under lower amphibolite facies and still lower metamorphic conditions are commonly preserved along detachment structures capping the mantle and include serpentinite mylonites, cataclasites, and gouges. These "colder" shear zones invariably show a top-to-the-ocean sense of shear. Cross-cutting relationships between top-to-the-ocean and top-to-the-continent shear zones are spectacularly exposed in an outcrop at Sur al Cant south of Bivio in the Platta nappe. In this outcrop the high-temperature top-to-the-continent mylonites are cut by colder and localized top-to-the-ocean serpentinite gouges (Bernoulli et al. in press, their Fig. 12). The gouge zone cuts also a rodingitized basaltic dike, indicating that magmatic activity had already initiated when the younger, top-to-the-ocean shear zone was active.

Locally, serpentinite mylonites are overprinted by tectonic brecciation, which was accompanied and/or followed by the replacement of serpentine minerals by calcite, and the formation of tectono-sedimentary breccias near or at the sea floor (Bernoulli & Weissert 1985; ophicalcites I of Lemoine et al. 1987). The fabric and the components of these breccias document an in situ origin. Typically, non-fragmented peridotite/serpentinite grades rapidly across a narrow zone of host rock, cut by different generations of veins and dikes, into complex breccias cemented by white sparry calcite and/or red microsparitic internal sediment. These breccias are overlain by matrix-supported breccias (ophicalcites II of Lemoine et al. 1987) that locally contain fragments of continental basement rocks and Triassic dolomites presumably derived from extensional allochthons. These tectono-sedimentary breccias form a more or less continuous layer along the surface of the serpentinites suggesting that these were exhumed and brittly deformed along extensional detachment faults.

Magmatic rocks in the ocean-continent transition

Magmatic rocks in the OCT generally become more voluminous oceanwards (Fig. 2). In the Platta nappe, gabbros which intruded the partially serpentinized mantle rocks occupy less than 5% of the total observed serpentinite volume. Desmurs et al. (2002) showed that smaller intrusions less than 100 m across differ from larger, sill-like bodies by their magmatic evolution. They are more homogeneous, consist of Mg-gabbro and show a decrease in grain size from the core towards the rim. The sill-shaped larger bodies show a great diversity in composition from primitive olivine-gabbros to highly differentiated Fe-Ti-P gabbros and diorite. Internal magmatic layering is not observed and primary contacts with the host rocks are commonly strongly overprinted. The main constituent in the larger bodies is Mg-gabbro forming up to 90% of the body. The relationships between Mg-gabbros and Fe-gabbros are irregular but both are cut by Fe-Ti-P-gabbros and still younger diorite dikes. U-Pb zircon ages from three different gabbros and one albitite yielded precise ages of 161 ± 1 Ma, indicating that all intrusive rocks were emplaced within a very short time range (Schaltegger et al. 2002). Ar/Ar age determination on phlogopite in a pyroxenite of the Totalp serpentinite yielded a cooling age of 160±8 Ma (Peters & Stettler 1987) indicating that mantle exhumation and cooling occurred simultaneously with the emplacement of the first magmatic rocks within the OCT.

Massive basalts, pillow lavas, pillow breccias, and hyaloclastites (Dietrich 1969) occur in patches of variable thickness and size in the Platta nappe and their abundance increases also oceanward. Generally, near the edge of the continental crust, pillow lavas form isolated bodies less than 100 m in diameter and are few tens of metres thick. Oceanwards, they appear to be aligned and their emplacement may be controlled by late, syn-magmatic high-angle faults. The basalts stratigraphically overlie serpentinites, ophicalcites, gabbros, and associated breccias, indicating that their emplacement post-dates exhumation of the mantle rocks to the sea floor. However, basaltic dikes are truncated by late fault zones formed by serpentine gouges, clearly indicating ongoing extension during magmatic activity.

Based on mineral and bulk rock chemistry as well as simple modelling, Desmurs et al. (2002) demonstrated that the gabbro bodies record different magmatic processes ranging from pre-

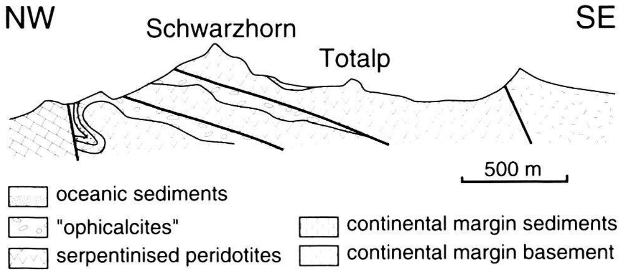

Fig. 4. Schematic cross-section across the Totalp imbricate.

dominantly fractional crystallization to solidification without fractionation. Mg numbers and Ni contents of equilibrium olivine calculated from primitive basalts and gabbros indicate that few mafic rocks are primary melts but most represent fractionated compositions ranging from T- to N-MORB. Most mafic rocks may be explained by low to moderate degrees of melting of an N-MORB type mantle, as indicated by initial Hf isotope data of zircons and Nd data of whole-rock samples (Schaltegger et al. 2002). The source of some basalts, however, is enriched in incompatible elements. This compositional variation seems to correlate with the spatial distribution of the mafic rocks within the ocean-continent transition in that mafic rocks with T-MORB signatures occur close to the continental margin, whereas N-MORB signatures are more frequently found oceanwards (Desmurs et al. 2002).

Oceanic sediments

The sediments overlying exhumed mantle rocks, ophicalcites, extensional allochthons, and basalts are: (1) red and dark gray shales and breccias; (2) cm-bedded ribbon cherts (Radiolarite Formation, Middle to Late Jurassic; Bill et al. 2001); (3) gray, thin-bedded limestones with greenish, shaly interbeds (Calpionella or Aptychus Limestone, late Tithonian? - Berriasian); (4) black shales with dm-bedded fine-grained limestones (Palombini Formation, approx. Valanginian to Barremian) (Dietrich 1970; Weissert & Bernoulli 1985). The red and gray shales occur only locally; they are associated with debris-flow deposits, unfossiliferous and may be interpreted as sediments derived from reworked fault rocks associated with mantle exhumation which were overprinted by hydrothermal activity. The radiolarites and the Calpionella Limestone contain breccias and graded sandstones including clasts of both serpentinite and continental basement rocks indicating local submarine relief at the time of deposition. The facies evolution of the pelagic sequence is determined by subsidence and paleoceanographic changes, in particular by a pronounced drop of the calcite compensation depth at the Jurassic-Cretaceous boundary accompanying the replacement of radiolarian-dominated planktic assemblages by coccolith- and nannoconid-dominated ones.

Day 1: Totalp area (Davos): Mantle exhumation, ophicalcites, and oceanic sediments

Excursion route

From Davos to Klosters and by cable-car to Gotschnagrat; from there by foot to the Parsennhütte, Parsennfurgga, Obersasställi, Totalpsee, and back to Parsennhütte. The Totalp unit consists of at least three individual tectonic slices, separated by ophicalcites and oceanic sediments (Fig. 4). The outcrops show peridotite mylonites and several types of pyroxenites, partially serpentinized mantle rocks deformed under decreasing temperatures during Mesozoic rifting and exhumation, and their relationships with the overlying oceanic sediments. Return by foot from Parsennhütte to Davos Wolfgang or to Gotschnagrat. Coordinates of the localities are from the topographic map of Switzerland (Landeskarte der Schweiz, 1:25'000, 1197, Davos). Geological map: Cadisch & Leupold (1929).

Stop 1.1: Along track from Parsennhütte to Parsennfurgga

Coord. 781'320/191'450
Along the track from Parsennhütte to Parsennfurgga ophicalcitic breccias (ophicalcite I) are overlain by polymictic breccias including blocks of cataclastic continental basement rocks and gabbros with a high-temperature foliation. The origin and age of the gabbro fragments is uncertain (Permian gabbro from lower continental crust (e.g. Malenco) versus Jurassic gabbro associated with onset of sea-floor spreading (e.g. Platta). The breccias are overlain by red shales and Calpionella Limestone (Lower Cretaceous). The succession is tightly folded around an east-west trending, sub-horizontal fold axis.

Stop 1.2: Obersasställi, Pt. 2442

Coord. 780'640/191'050 to 780'680/191'200.
In the north (near Pt. 2422), the hill of Pt. 2442 exposes a partially overturned sequence of thin-bedded ribbon cherts (Radiolarite Formation, Middle to Upper Jurassic) and pelagic limestones (Calpionella Limestone, Lower Cretaceous) resting stratigraphically on ophicalcites (Fig. 4). In these, replacement of serpentine minerals by calcite is documented by relics of pyroxene floating in a red microsparitic limestone matrix. This fabric is cut by younger fractures filled by a white calcite cement with a drusy fabric, and younger, red, microsparitic internal sediment. Internal sediments in the in-situ fractured rocks are partially dolomitized. The carbon isotope values (δ–C = 2.2%o PDB) of these dolomites are compatible with dolomite formation by marine waters. The basal part of the Radiolarite Formation includes graded layers composed of debris of ophicalcite testifying the pre-Alpine origin of these rocks.

Stop 1.3: Northwest of Pt. 2582

Coord. 780'425/190'200
Partially serpentinized, foliated lherzolites and centimetre-scale websterite dikes. At this locality, the Totalp peridotites

are less serpentinized and most mantle minerals are preserved. The lherzolites show a high-temperature foliation dipping steeply to the southeast. The peridotites are fertile spinel lherzolites consisting of olivine, clinopyroxene, orthopyroxene, spinel, and occasionally titanian pargasite. The clinoyproxenes of the Totalp lherzolites are rich in Na_2O (up to 2.1 wt%) and Al_2O_3 (up to 7.6 wt%) (Peters 1963) and are typical for subcontinental peridotites. Trace elements measured by Laser Ablation ICP-MS show nearly flat chondrite normalized REE patterns with La_N ~2-4 and Ce_N/Yb_N >0.25. (O. Müntener, unpublished data). Pyroxenite dikes at a cm scale are always parallel to the high-temperature foliation and are boudinaged. They contain variable proportions of ortho- and clinopyroxene, Cr-rich spinel and minor amounts of titanian pargasite and rare phlogopite.

Stop 1.4: Southwest of Pt. 2582

Coord. 780'425/189'915
At this stop, the original outcrop has been destroyed for easier skiing. Nevertheless, garnet pyroxenite blocks are occasionally found within blocks of serpentinized lherzolite. The original orientation with respect to the spinel peridotite foliation (discordant or concordant) is unclear (Peters 1963). The garnet pyroxenites consist mainly of pyropic garnet, hercynite, clino- and orthopyroxene, and titanian pargasite. Orthopyroxene-garnet barometry (at temperatures between 850 and 950°C) indicates equilibration pressures of 1.5 to 1.8 GPa, indicating that lherzolites and pyroxenites equilibrated in the spinel peridotite field.

Stop 1.5: Along track from Totalpsee to Parsennhütte

Coord. 781'650/190'800
Strongly localized peridotite mylonites occur in massive weakly deformed serpentinized peridotites. Serpentine veins of a few centimetres with relatively sharp contacts to the surrounding foliated spinel lherzolites cutting the latter in characteristic tablets are the most striking features in the outcrop. Porphyroclasts of spinel, clinopyroxene or deformed and rotated orthopyroxene, sometimes several centimetres long, are surrounded by a mylonitic fabric of olivine, orthoypроxene, clinopyroxene, spinel, and occasionally titanian pargasite. The age of this mylonitic foliation is unknown, but probably not related to the exhumation of the Totalp peridotite, as equilibration temperatures are indistinguishable from the surrounding peridotites and pyroxenites (Peters & Stettler 1987).

Stop 1.6: Valley southeast of Parsennfurgga

Coord. 781'300/191'240
Outcrops and blocks in the float show sedimentary and diagenetic fabrics in ophicalcites type I. Non-fragmented or tectonically brecciated serpentinites grade rapidly through a narrow zone of host rocks, cut by different generations of dikes, into complex breccias dominated by a carbonate matrix. Two different types of calcite can be distinguished in these ophicalcites: the first is a limestone, usually red, which under the microscope shows an equigranular fabric of anhedral calcite crystals with hematitic pigments between them. This limestone carries variable amounts of serpentinite clasts and pyroxene mineral grains. Sedimentary lamination and geopetal infill show that this type is a mechanically deposited sediment that later recrystallized. The second calcite type consists of clear sparry calcite crystals lining the walls of cracks and crevasses in the serpentinite breccias. It also fills the remaining voids in geopetally filled sheltered cavities and is interpreted as a cement. Both forms of calcite occur in various combinations. In some cases, deposition of internal sediment was preceded by precipitation of an early cement, and vice versa; however, the red limestones are restricted to the upper part of the ophicalcites. The breccias are of polyphase origin, as shown by the different phases of fragmentation and generations of cementation and sediment infill. Lithification of the breccias and cementation of pockets and fractures must have occurred during an early stage of diagenesis as cemented breccias occur as composite clasts in younger breccias.

Stop 1.7: East-southeast of Parsennhütte

Coord. 782'300/191'340
A north-vergent syncline with an east plunging axis exposes oceanic sediments stratigraphically overlying the exhumed mantle rocks. Type-I ophicalcites are overlain by type-II ophicalcites, matrix-supported breccias with clasts of serpentinite and ophicalcite I embedded in a reddish limestone matrix. Scarse pebbles of oolitic dolomites, probably of Triassic age, indicate lateral sediment transport, probably by debris flows. The ophicalcites are overlain by dark-coloured and red, non-calcareous shales. Geochemical signatures suggest that these shales are derived from the reworking of fault gouges and had acquired a strong hydrothermal overprint. Up-section, they are followed by red, thin-bedded ribbon cherts (Radiolarite Formation) and pelagic limestones (Calpionella Limestone). In the Calpionella Limestone some dm-thick breccias with clast of continental basement rocks are intercalated.

Day 2: Val d'Err-Alp Flix: Architecture of the ocean-continent transition and mantle exhumation processes

Excursion route

From Tinizong by car through the north-Pennine Arblatsch Flysch to Val d'Err. A driving authorisation is requested for Val d'Err and can be asked at the local authority in Tinizong. From Val d'Err by foot over Parsettens, Piz Colm, and Falotta to Flix. The excursion leads through an open Alpine terrain but includes a few steeper slopes. Walking distance is about 10 km (about three and a half hours of walking). Coordinates of

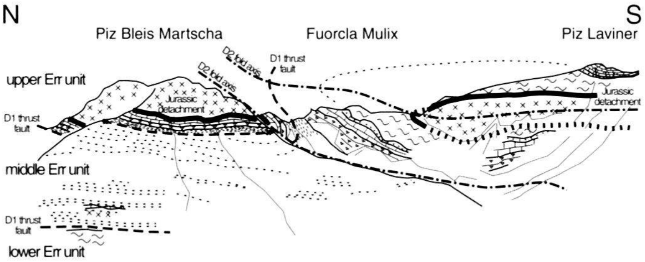

Fig. 5. Panorama of the eastern side of Val d'Err. Modified after Manatschal (1995).

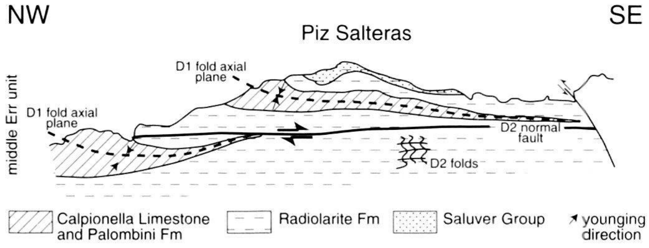

Fig. 6. Relationships between isoclinal Alpine D1-folds, Alpine D2-folds, and an Alpine D2-normal fault in the southwest face of Piz Salteras. From Manatschal & Nievergelt (1997).

the localities are from the topographic map of Switzerland (Landeskarte der Schweiz, 1:25'000, 1236 Savognin and 1256 Bivio); Geological map: Cornelius (1932).

Stop 2.1 Parsettens, Pt. 2473

Coord. 772'800/159'700

Panoramic view of the Piz Salteras-Piz Laviner mountain ridge: In the northern slope of Piz Laviner at the southern end of Val d'Err, a rift-related detachment, the Err detachment, is well observable (Figs. 2 and 5). This detachment fault can be traced westwards towards Piz d'Err. To the north, it is folded around a subhorizontal, east-west directed Alpine fold axis (Alpine D2 structure). The hinge of the north-vergent fold and its inverted limb are well observable at Fuorcla Mulix. To the north, the peaks of Piz Bleis Martscha and Piz Val Lunga are formed by basement rocks, which cover, separated by a Jurassic detachment, an overturned Permo-Mesozoic sedimentary sequence. This isoclinally folded sequence (Alpine D1 structure) forms the upper Err unit, which has been thrust over the middle Err unit and, not well observable, the lower Err unit and the upper serpentinite unit of the Platta nappe (Fig. 5). In the western slope of Piz Salteras, syn-rift sediments composed of breccias, turbidites, and hemipelagic limestones, and post-rift sediments including radiolarian cherts, Calpionella Limestone, and Palombini shales, are isoclinally folded (Fig. 6). These large-scale isoclinal folds formed during the emplacement of the west to northwest vergent thrust sheets (upper, middle, and lower Err units) and form Alpine D1 structures. D1 folds and thrust contacts are cut by a prominent fault structure which can be followed across the western slope of Piz Salteras and further to the southeast where it cuts the Platta nappe in the area of Malpass above Flix. This fault, interpreted as a Late Cretaceous extensional D2 fault (e.g. Handy et al. 1993), cuts across the already existing Cretaceous thrust stack. Thus, at least in the area of Alp Flix - Val d'Err, the units derived from the oceanic and continental domains have been juxtaposed already very early during convergence and have been affected only weakly by post-Cretaceous deformation and metamorphism (Ferreiro-Mählmann 1995).

Along a north-south-directed section in the Val d'Err, small-scale variations in the distribution of post-rift sediments can be observed in the middle Err unit. To the south, at Fuorcla Mulix, the Middle Jurassic syn-rift breccias are stratigraphically overlain by Palombini shales of Early Cretaceous age. In contrast, to the north, at Piz Salteras, radiolarian cherts and Calpionella Limestone are found between the syn-rift breccias and the Palombini shales. These observations indicate that within the distal continental margin local hiatus exist and that it took tens of millions of years to level the submarine topography related to rifting and break-up. This is confirmed by the frequent occurrence of breccias composed of continental and oceanic clasts within the radiolarites and pelagic limestones of the ocean-continent transition (see Stop 2.4 for post-rift breccias and Stop 3.1 for a hiatus between pre-rift and post-rift sediments; Fig. 2).

Mantle rocks of the upper serpentinite unit (Platta nappe): The serpentinized peridotites exposed at Stop 2.1 preserve textures and deformation structures which are characteristic for the mantle rocks of the upper serpentinite unit. At places, localized mylonitic shear zones occur within the peridotite. These high-temperature mylonites affected a pre-existing spinel foliation. The microstructures associated with the shear zones are still visible within small pyroxenite dikes (olivine websterite) present within the lherzolite host. They consist of rotated or kinked porphyroclastic ortho- and clinopyroxenes showing undulous extinction and neoblastic mineral growth in the plane of the new foliation or recrystallization in a mosaic fabric. The asymmetric clasts associated with this event of high-temperature shearing show commonly a top-to-the-east, i.e. a top-to-the-continent sense of shear. The neoblastic assemblage consists of secondary Al- diopside, orthopyroxene, olivine, and spinel, which are altered to chlorite, serpentine minerals, and magnetite. This association is interpreted to have formed under spinel-peridotite facies conditions with a later low-grade overprint. As no age data are available for this deformation event, it cannot be related with certainty to rifting. Only the late, hydrous deformation of the mantle rocks is undoubtedly related to exhumation during Jurassic rifting (see Stop 2.3). The mantle rocks observed in the upper serpentinite unit at Parsettens are similar to those observed at Totalp and in Malenco.

Stop 2.2: Parsettens, Pt. 2533

Coord. 772'000/159'600

At Stop 2.2, remnants of the former ocean-continent transition are preserved within an imbricated and folded stack formed by the lower Err unit and the upper serpentinite unit. Despite of the Alpine tectonic overprint, some primary rift-related contacts are preserved. A map and a simplified section across the northwest ridge of Piz Castalegns are shown in Fig. 7 and some contacts are described below (Fig. 2).

At Pt. 2533 serpentinized peridotite is capped by ophicalcite which is in tectonic contact with a massive breccia composed of gneiss, schist, and granite clasts ranging in size from several tens of metres to some few centimetres. Deformation along the contact predates the replacement processes leading to the formation of the ophicalcite and is therefore interpreted to be pre-Alpine. Within the polymict, clast-supported breccia in the hanging wall, fractures are filled with a matrix of limestone and red clay in which smaller rounded crystalline-basement clasts are floating. Thus, these breccias may result from tectonic processes associated with mantle exhumation and may have formed and been emplaced along detachment faults during final exhumation to the sea floor.

At Pt. 2638, a small imbricate composed of continental rocks is separated by Alpine thrusts from two serpentinite imbricates. The continent-derived unit is composed of crystalline basement overlain along a tectonic contact by a strongly reduced sequence of Permian volcanics, sandy dolomites (Early Triassic), massive dolomites (Middle and/or Late Triassic) and breccias with crystalline basement and carbonate clasts accompanied by sandy shale (Saluver Group, Middle Jurassic). The tectonized contact between the basement and its Permo-Mesozoic cover is truncated by the Alpine thrust; it consists of a brittle fault zone represented by green cataclasites and black gouge. These fault rocks show conspicuous similarities to fault rocks associated with the Jurassic detachment faults in the Err nappe (Manatschal 1999). Based on this analogy and on the fact that the contact is truncated by an Alpine D1 thrust, we interpret this tectonic contact as part of a pre-Alpine rift-related detachment.

At Pt. 2726, within a smaller thrust sheet belonging to the lower Err unit, a porphyric granite is capped by the same association of green cataclasites and black gouges, as observed at Pt. 2638. Here, the strongly tectonized crystalline basement is covered by crystalline breccias similar in composition to those observed at Pt. 2533, which, however, grade over less than two metres up-section into a brown breccia with crystalline basement and carbonate clasts which in turn is overlain by coarse-grained sandstones. Laterally, the breccia wedges out and the sandstones directly overlie the tectonized basement. Thus, at Pt. 2726 an exhumed and tectonized basement is preserved, which is covered by Mesozoic sediments, clearly indicating a pre-Alpine age of deformation related to the exhumation of the basement. All the observations made along the Castalegns northwest ridge are compatible with observations made in the

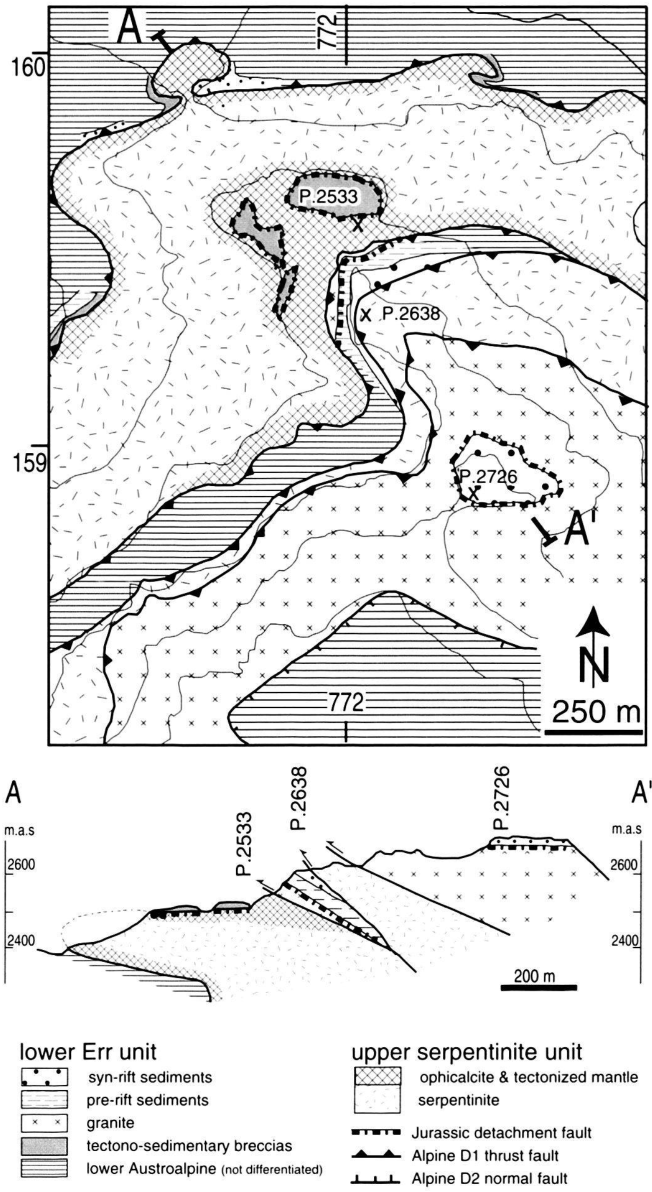

Fig. 7. Map of the Parsettens area and section across the northeastern Castalegns ridge. From Manatschal & Nievergelt (1997).

Tasna ocean-continent transition (Florineth & Froitzheim 1994) as well as with reports from drilling at the Iberia margin (Manatschal et al. 2001). Thus, at Stop 2.2 we see direct evidence for a detachment structure, which cuts from the crust into the mantle and which led to the exhumation of continental mantle and crustal rocks to the sea floor.

A very similar situation, however, strongly overprinted by Alpine deformation, is found at Cuolm da Bovs northwest of Castalegns (771.400/159.700; 2400 m.a.s.). At this place, a sliver of continent-derived rocks is surrounded by serpentinite. This sliver contains crystalline breccias, formed by gneiss and gran-

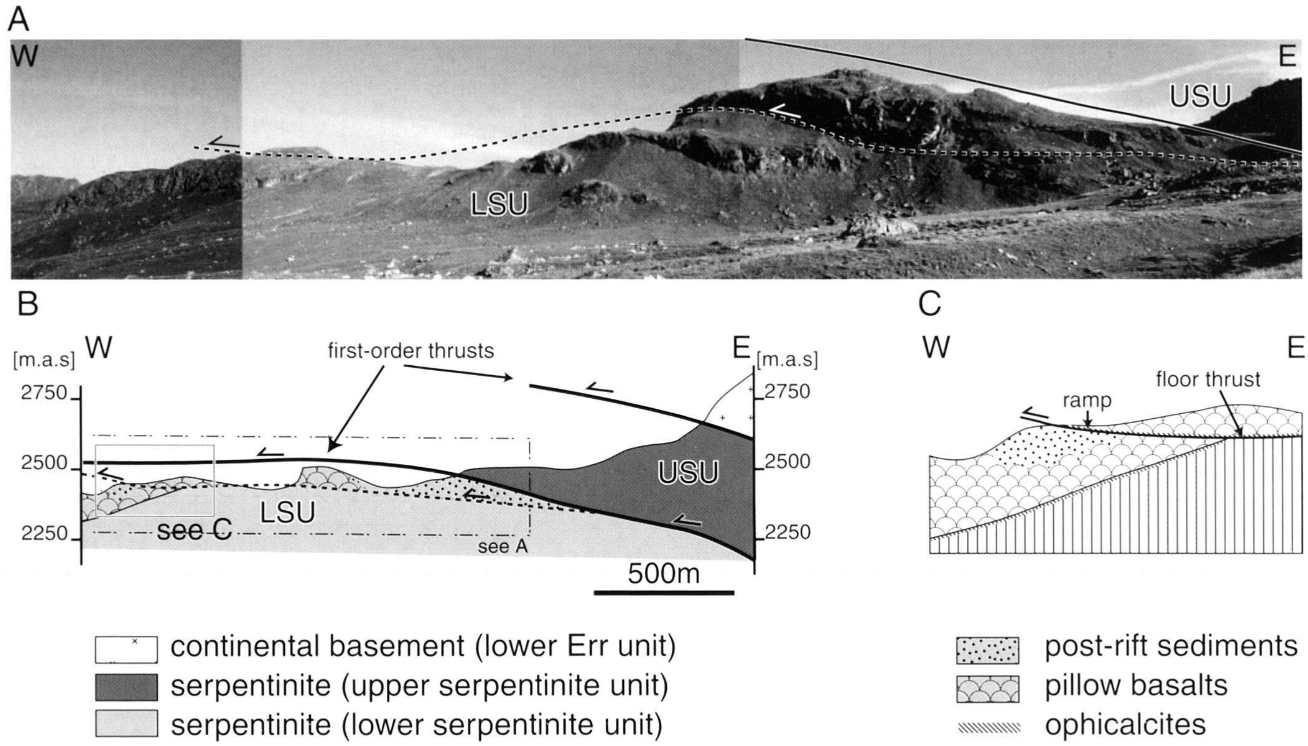

Fig. 8. View of Falotta, north of Bivio, showing the two serpentinite units of the Platta nappe and the associated cover imbricates. USU: upper serpentinite unit; LSU: lower serpentinite unit; B: present-day situation; C. detail of section B, adapted from Desmurs et al. (2001).

ite, overlain by a crystalline/dolomite-bearing sedimentary breccia of the Saluver Group, cherts of the Radiolarite Formation alternating with shales, and shale-rich limestones of the Palombini Formation. 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 described at Stop 2.2. The common occurrence of continent-derived breccias associated with serpentinized mantle rocks in the Platta nappe is interpreted to be related to detachment faulting and therefore to continental break-up.

From Piz Colm (Pt. 2415), there is a beautiful panoramic view across the Alps.

Stop 2.3: Falotta, west of Pt. 2502

Coord. 770'300/157'350

At Stop 2.3, a top-mantle section in the lower serpentinite unit is preserved which bears some information on the deformation and alteration processes related to mantle exhumation to the sea floor (Fig. 2). The section shows a transition from a massive serpentinized peridotite to brittly deformed mantle rocks. An increase in strain towards the top of the section is associated with a transition from serpentine cataclasites to fault gouges, which coincides with a change from angular to well-rounded serpentinite clasts and from a clast- to a matrix-supported texture. In the gouge, calcite replacement and calcite veins become more abundant towards the top of the section and show the structures commonly observed in ophicalcites such as jigsaw-puzzle arrangement of clasts and polyphase veining. Because deformation within the section predates replacement by calcite, it is interpreted to be pre-Alpine and to be related to mantle exhumation. The ophicalcite forming the top of the mantle section is overlain by a monomictic breccia, which consists only of mantle rocks. However, variably deformed types of serpentinized peridotite clasts can be observed, some of which represent peridotite and serpentinite mylonites. The section is overlain along a reactivated Alpine contact by pillow breccias forming the top of Pt. 2502.

Stop 2.4: Falotta, Pt. 2455

Coord. 769'900/157'350

At Stop 2.4, pillow basalts overlie tectonized ophicalcites. The contact shows some evidence of Alpine tectonic overprint. We believe, however, based on the overall situation, that the basalts were emplaced on already exhumed and deformed mantle rocks similar to what is seen at Stop 2.3 (Fig. 2).

Walking to Stop 2.5, we will see strongly deformed manganiferous radiolarian cherts and Calpionella Limestone containing mass-flow deposits yielding clasts of serpentinite. Elsewhere in the Platta nappe, also clasts of granites and basalts can be found together with mantle-derived material in the clastic intercalations in the radiolarian cherts and Calpionella Limestone (see also Stop 2.1; Fig. 2).

Stop 2.5: Falotta, southeast of Pt. 2423

Coord. 769'550/157'200

In the ophicalcites at Stop 2.5, a foliation defined by Fe-oxides can be traced across calcitized domains of the serpentinite. This shows that replacement processes in which calcite replaces serpentine minerals are one of the mechanisms to form ophicalcites.

On the walk to Flix, there is a good view of the Falotta ridge. Along this ridge, the internal structure of the Platta nappe is nicely visible (Fig. 8). By and large, the internal structure of the Platta nappe is formed by two serpentinite units interleaved by associated cover imbricates which are derived from the top of the lower serpentinite unit. During the emplacement of the upper onto the lower serpentinite unit, the contact between the cover sequence (basalts or sediments) and the mantle has been reactivated by a second order fault initiating along the basement-cover contact, and pillow basalts were locally thrust over strongly folded post-rift sediments (radiolarian cherts and Calpionella Limestone, between Stops 2.4 and 2.5).

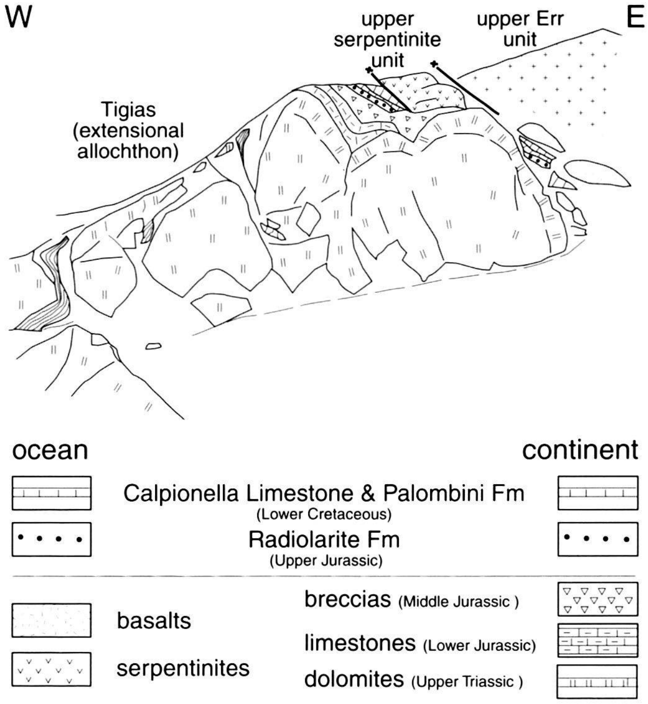

Fig. 9. Schematic view of the Tigias unit east of Flix. The Tigias unit is interpreted as a small, continent-derived extensional allochthon which was emplaced during late rifting on the exhumed mantle rocks of the lower serpentinite unit. The Mesozoic contacts have been reactivated during Alpine orogeny. Modified after Nievergelt, unpublished.

Day 3: Tigias - Savriez - Val da Natons – Marmorera: Magmatism and sedimentation in the ocean-continent transition

Excursion route

From Sur to Flix by car. From there by foot along the Ava da las Tigias up to Giond'Alva and further to Malpass, Pare Neira, and through Val da Natons to Marmorera. The excursion will lead through an open Alpine terrain but will include some steeper slopes. The overall walking distance is about 7 km and walking starts at 1975 m.a.s., the highest point is at 2500 m.a.s at Giond'Alva, and the end of the excursion is at 1700 m.a.s. at the village of Marmorera. Coordinates of the localities are from the topographic map of Switzerland (Landeskarte der Schweiz, 1:25 000, 1256 Bivio); Geological map: Cornelius (1932)

Stop 3.1: Giond'Alva

Coord. 771'900/154'250

On the walk up to Giond'Alva, along Ava da la Tigias, we cross one of the best-preserved extensional allochthons consisting of Lower Austroalpine rocks in the northern Platta nappe (Figs. 2 and 9). This sliver is sandwiched between the upper and the lower serpentinite units and is interpreted as a small extensional allochthon stranded on the exhumed mantle. A complete stratigraphic section from Triassic dolomite to the Lower Cretaceous Palombini Formation is observed, forming an isoclinal Alpine fold. In the Middle to Upper Jurassic radiolarian cherts (Radiolarite Formation) overlying the allochthon, sedimentary breccias with clasts of gneiss, pillow basalts, and spinel mineral grains are observed. This mixed detritus of oceanic and continental provenance documents the neighbourhood of the lower Austroalpine continental margin sequences and the oceanic Platta domain, and is an additional argument for the pre-Alpine emplacement of the allochthon on the exhumed mantle. South of Ava da las Tigias, this sliver wedges out and only a few blocks of crystalline basement rocks and dolomite can be followed along the top of the lower serpentinite unit.

At Giond'Alva, a pre-rift sequence consisting of Permian volcanics and Triassic dolomites is overlain by a reduced sequence of sedimentary breccias which are intercalated with shales (Fig. 10). Although the age of the breccias is unknown, the occurrence of clasts of red chert, similar to radiolarian chert, in the breccias and the lithological similarities between the intercalated shales and those of the Palombini Formation, suggest an early Cretaceous age and consequently a post-rift

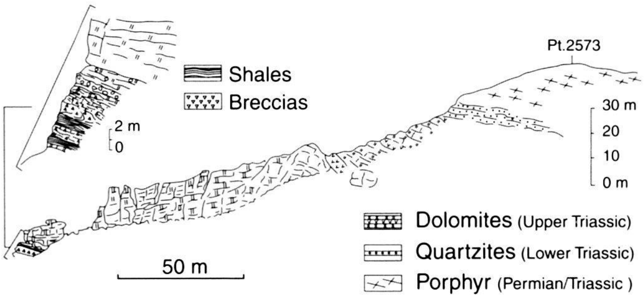

Fig. 10. Schematic section across Giond'Alva. Modified after Nievergelt, unpublished.

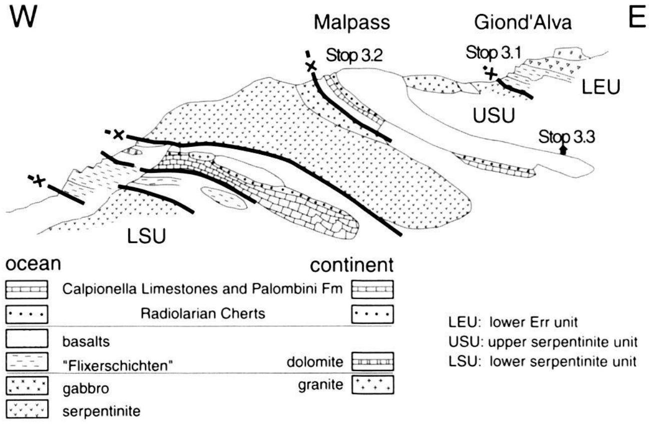

Fig. 11. View of the Malpass – Giond'Alva mountain ridge. Modified after Nievergelt, unpublished.

origin of these breccias. This implies a major hiatus between the breccias and the dolomites (see also Stop 2.1; Fig. 2).

Stop 3.2: Malpass

Coord. 771'800/154'150 to 771'400/154'100
At Stop 3.2, a stratigraphic contact between pillow breccias and radiolarian cherts of the Radiolarite Formation is exposed (Fig. 2). The radiolarian cherts are only a few metres thick and are overlain by Calpionella Limestone. The radiolarian cherts are the first sediments overlying continental as well as oceanic rocks in the Platta-Err ocean-continent transition (e.g. Stop 2.1) and are therefore interpreted as the first post-rift sediments. Although the radiolarian cherts in Grisons have not yet been dated so far, a late middle to late Jurassic age is suggested by analogy with other areas of the Liguria-Piemonte ocean (Bill et al. 2001).

Stop 3.3: Val Savriez

Coord. 771'700/153'850
Pillow breccias contain clasts of albitite and foliated gabbro indicating that these rocks had been deformed and/or were near the sea floor when the pillow breccias were deposited (Fig. 2). An albitite clast from this locality has been dated using U/Pb on zircons at 161±1 Ma (Schaltegger et al. 2002).

Stop 3.4: Pare Neira

Coord. 770'500/153'000 to 771'500/153'100
Dolerite dikes cutting across the serpentinized peridotites are exposed at the eastern termination of Pare Neira; they belong to the rare magmatic rocks found in the upper serpentinite unit (Fig. 2). From the western end of Pare Neira, we can observe the subspherical shape of the gabbro intrusions along the northern slope of Val da Natons and the large Natons gabbro body in the southern slope of the valley.

Walking along the Pare Neira ridge, we cross the hinge of an isoclinal fold in which the primary contact between pillow basalts and radiolarian cherts is well preserved.

From Pare Neira, we have a good view onto to the Malpass-Giond'Alva mountain ridge (see Stops 3.1, 3.2, and 3.3, Fig. 11). Between the lower and the strongly reduced upper serpentinite units, several smaller imbricates occur, consisting of cover sequences, i.e., basalts or continent-derived blocks both of which are associated with the same type of post-rift sediments. Additionally, a sliver of mantle rocks is integrated in the second-order thrust stack, which is rather the exception than the role in the Platta nappe. In many of the imbricates, only the inverted limb is preserved what may be related to the reactivation of pre-Alpine structures within the ocean-continent transition.

Stop 3.5: Kanonensattel, Pt. 2255

Coord. 770'300/152'800
At Stop 3.5 a decametric Mg-gabbro body is well exposed due to the glacial erosion of the weaker sediments and serpentinites surrounding it. The small Mg-gabbro body shows a decrease in grain size from the core to the rim. The gabbro body has been interpreted, based on the geochemical data (Desmurs et al. 2002), to have formed by in situ crystallization of a MORB-magma. It was deformed under retrograde metamorphic conditions ranging from amphibolite to greenschist facies.

Stop 3.6: Val da Natons

Coord. 770'700/152'200
The exhumation history of a gabbro from its shallow intrusion into partially serpentinized peridotite to the first exposure on the sea floor is summarized in Fig. 12. A cataclastic gabbro is cut by small dikes of albitite, it includes enclaves of serpentinite and fractures filled by ophicalcite. The gabbro is stratigraphically overlain by a sedimentary megabreccia including first metre-sized blocks of serpentinite, then of gabbro set in a matrix of serpentinite arenite. A few gabbro blocks, several

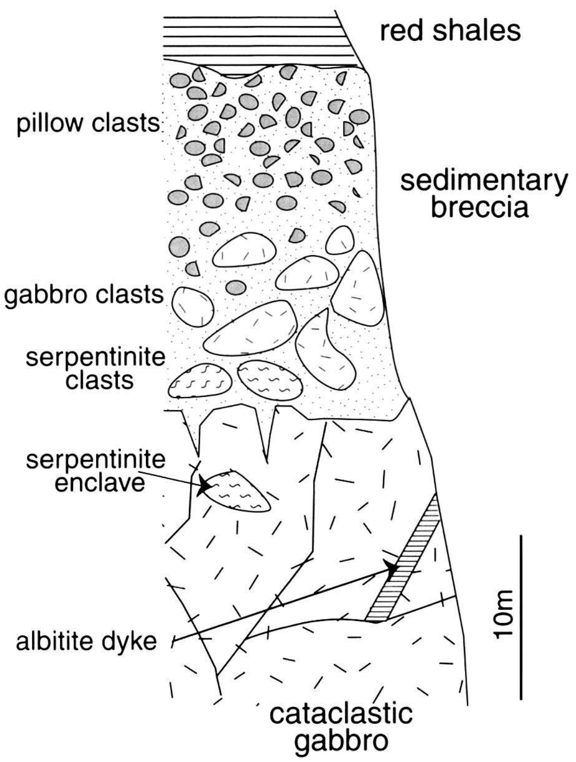

Fig. 12. Idealized stratigraphic succession from the exhumed gabbro to the overlying sediments. Val da Natons (Coordinates of Swiss Topographic Map: 770'690 to '850/152'200 to '300). From Desmurs et al. (2001).

metres across, show localized bands of flaser gabbro fragmented and overprinted by cataclastic deformation. An overlying breccia contains clasts of these flaser gabbro together with serpentinite and abundant pillow fragments embedded in a matrix of serpentinite arenite. This breccia is again overlain by pillow breccias covered in turn by red shales. The absence of a pre-Alpine foliation and the random arrangement of the unsorted polymictic blocks suggest that the gabbro breccias have a sedimentary origin. Together, these observations show that the gabbros were exhumed on the sea floor along discrete shear zones active under decreasing temperature, an interpretation which is compatible with the occurrence of gabbro clasts in the pillow breccias observed at Stop 3.3.

Day 4: Chiareggio – Alpe Pirola – Lago Pirola – Chiareggio: Petrology and exhumation history of a pre-rift crust mantle boundary

Excursion route

From Chiareggio (1610 m) in Val Malenco by foot along a trail to Alpe Pirola and Lago Pirola. All outcrops are in the Malenco nappe and show lower crustal metasedimentary and igneous rocks and the heterogeneity of former subcontinental mantle. Along the trail, there are beautiful views of the internal structure of the lower Austroalpine Margna nappe. Return by foot to Chiareggio either via Val Ventina (steep descent on old moraine material from the Ventina Glacier) to Rifugio Porro/Gerli (and possibility to visit the ophicarbonates in front of the Ventina Glacier, see stop 4.5) and to Chiareggio or descent along the same trail from Lago Pirola to Chiareggio. The description of the stops largely follows that of Müntener et al. (1999). Coordinates of the localities are from the topographic map of Switzerland (Landeskarte der Schweiz, 1:50'000, 278, Disgrazia).

Stop 4.1: Alpe Pirola

Coord. 780'650/131'000

Along the foot path from Chiareggio to Alpe Pirola. Large blocks of granulite-facies marbles and calcsilicate rocks can be found at Alpe Pirola. Coarse-grained quartz-free calcite marbles consist of olivine, diopside, phlogopite, ±spinel, ±humite. Strongly retrogressed lithologies contain dolomite+antigorite. In silica-saturated marbles variable proportions of diopside, grossular, calcite, quartz, wollastonite, ±phengite, ±kalifeldspar, ±plagioclase, ± clinozoisite may be found. Rocks overprinted by retrograde amphibolite-facies metamorphism are dominated by tremolite and clinozoisite-bearing assemblages. The paragenesis wollastonite + grossular + quartz + calcite indicates minimum temperatures of ~ 750°C at 1 GPa, consistent with thermodynamic calculations on olivine marbles (Hermann 1997). The variety of assemblages is consistent with the assumption that bulk rock chemistry of the protolith dominates the granulite-facies paragenesis in individual samples and that the fluid chemistry was internally controlled. In contrast, the pre-Alpine retrograde assemblages are consistent with an externally controlled low XCO_2 fluid.

Walk along trail over the contact between lower crustal granulites and metagabbros to the stone huts below the wall of Lago Pirola.

Stop 4.2: Lago Pirola

Coord. 780'750/130'650

The outcrops are formed by a schistose chlorite-actinolite-clinozoisite-albite rock, which is a metagabbro originating from the Permian Braccia gabbro. The primary flaser-type texture is partially preserved, with chlorite + amphibole growing on former pyroxenes and clinozoisite and albite on former plagioclase. The main foliation is deformed by the first and second phase of backfolding with steeply north-northeast-dipping axial planes and by the transverse folding with steeply west-dipping axial planes. Superposition of these structures results in a variety of spectacular fold interference patterns visible along the main footpath.

A few tens of metres to the east of the stone huts, the pre-Alpine flaser structure in the gabbro is preserved in a lens

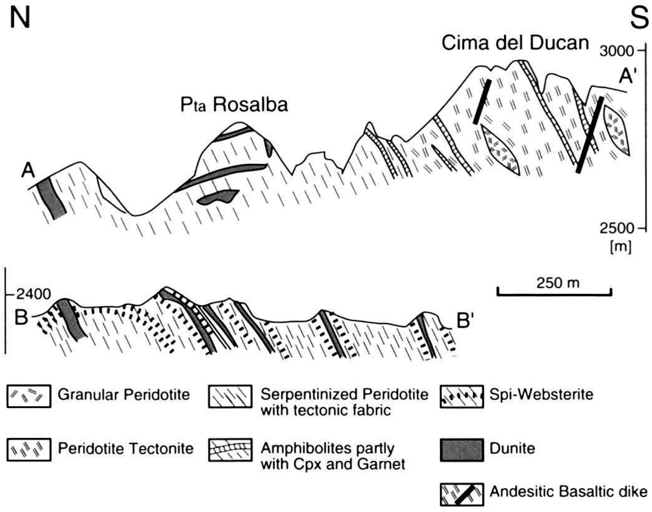

Fig. 13. Panoramic view of the Malenco mantle rocks from Lago Pirola (adapted from Müntener & Hermann 1996). A-A': Weakly deformed lenses of granular peridotite are embedded in a tectonite foliation. Spinel websterites and amphibolitized garnet clinopyroxenites are parallelized in this foliation. Towards the left of the profile the peridotite tectonites are strongly serpentinized. B-B': Field relationships between the layered peridotites and dunites south of Lago Pirola. The peridotite shows a weak open fold indicated by spinel websterites. On the southwestern side of the antiform the dunites are subparallel to the banding defined by spinel websterites. On the northeastern side, however, the dunites are clearly discordant to spinel websterites.

weakly affected by Alpine deformation. Amphibole and clinozoisite are not oriented indicating static growth during Alpine metamorphism. Several layers of former pyroxenites are still visible. The orientation of the flaser texture is in agreement with kyanite lineations in the pelitic granulites and with spinel lineations in the peridotites indicating a common high-temperature deformation of all rock types. Leucogranites that formed by partial melting of metapelitic xenoliths within the gabbros are discordant to the gabbro flaser texture indicating that the gabbro intrusion and partial melting of the pelites are closely linked. U-Pb dating of zircons of a nearby leucogranite resulted in Permian ages (Hansmann et al. 2001) indicating that partial melting of xenoliths and intrusion of the gabbro are coeval.

Walk along highly deformed metagabbros on a trail to the foot of M^{te} Senevedo.

Stop 4.3: Foot of M^{te} Senevedo

Coord. 781'450/130'650

Following along the footpath to the east, the deformed contact between the Braccia gabbro and lower crustal granulites can be seen. A Fe-Ti gabbro dike cuts across the granulites. This dike is made of greenschist-facies minerals but its composition is similar to those of the primary Fe-Ti gabbroic dikes of Alpe Braccia. Dikes of gabbros in peridotites and pelitic granulites are evidence for a ±intact crust-mantle section in Val Malenco. The surrounding rocks are made of coarse-grained garnet gneisses and a few intercalations of granulite-facies marbles mainly preserving their pre-Alpine structure. In the garnet gneisses all transitions from incipient melting (migmatite) to coalescing and pooling of leucogranites can be found. Despite an intense static Alpine metamorphic overprint many pre-Alpine relics are preserved, among them are garnet (partially or completely chloritized), kyanite (retrogressed to paragonite ± phengite ± chloritoid), and knobs of blue quartz, the color being caused by micrometre-sized TiO_2 inclusions. Metamorphic conditions for the metapelitic primary assemblage garnet + kyanite + plagioclase + quartz + ilmenite ± biotite point to pressures of ~1.0 GPa and temperatures around 800°C (Hermann et al. 1997; Müntener et al. 2000). The high amount of former garnet and kyanite suggests that most of the rocks have a restitic character. Garnet often exceeds 30 vol% resulting in an original density of the pelitic granulite of at least 3.3 g/cm^3, similar to mantle rocks (Hermann et al. 1997).

Stop 4.4: SE of Lago Pirola

Coord. 781'470/130'300

These glacier-polished outcrops form an area of about one km^2 and consist in large parts of serpentinized, layered ultramafic rocks with cpx-rich websterite and cpx-poor lherzolite to harzburgite, occasionally cut by dunite. The main mass of the ultramafic rocks is a massive, magnetite-bearing chlorite-olivine diopside serpentinite. However, around M^{te} Braccia further to the southeast, several lenses of fresh spinel peridotite and chlorite-amphibole peridotite can be found. The dominant pre-Alpine structure is a mineral stretching lineation trending southeast-northwest and a weak foliation. In the southwestern part of the outcrop this lineation is parallel to the websterite layers which steeply dip towards southwest. Depending on the grade of pre-Alpine deformation these websterites form boudins of centimetres to tens of metres in size. In a few blocks, however, they branch and form interconnected dikes, indicating an igneous origin for the websterites. Towards the northeast, the layers turn to a horizontal position before dipping towards the northeast providing evidence for a large-scale antiform (Fig. 13). The mineral lineation, however, remains constant and the weak foliation probably represents the axial surface foliation of this folding. Mantle dunites are partially discordant to the layered peridotite. On a large scale, close to M^{te} Braccia, dunites form anastomosing zones enclosing peridotite and spinel websterite. These observations indicate that the dunites are younger than the folded layered peridotite. Younger deformation (exhumation related?) is preserved by dunite boudins which locally display mylonitic textures.

The most important rock types observed in this outcrop are: (1) Serpentinized peridotite: The main mass of the ultramafic rocks is a massive, magnetite-bearing chlorite-olivine diopside serpentinite. The serpentinite is cut by different types of veins, consisting of (a) olivine, chlorite, magnetite, titanian clinohumite, and diopside; and (b) chlorite veins with relics of phlogopite. The latter possibly represent altered phlogopite-

Ti-amphibole veins (Müntener 1997). (2) Spinel websterite: Spinel websterites consist of cm-sized bright green clinopyroxene, Cr-Al spinel and orthopyroxene (replaced by amphibole ± chlorite). In many places a clustering of pyroxene + spinel can be found. This cluster texture probably indicates breakdown products of former garnet, or represents extensive exsolution of Al-phases from an Al-rich pyroxene precursor. Websterites completely overprinted by Alpine metamorphic assemblages are characterized by abundant white diopside (pseudomorphic after primary clinopyroxene) in a chlorite ± serpentine ± titanian clinohumite matrix. (3) Amphibolite (ex garnet clinopyroxenite): The garnet clinopyroxenite in this outcrop is completely retrogressed to amphibolite consisting of pargasite, ± chlorite, ± titanite, ± diopside. Fresh samples from the M^{te} Braccia area consist of Al-rich clinopyroxene, garnet, Ti-rich pargasite, and rare corundum, the latter containing micrometre-sized Cr-Al spinel inclusions. (4) Dunite: These rocks are easy to recognize in the field because of a distinct red-brown weathering color and a fine grain size on weathered surfaces. Despite an intense Alpine metamorphic overprint, olivine and Cr-Al spinel are partially preserved although many of the dunites are serpentinized to more than 50%. Field relations with the surrounding peridotites suggest that the dunites are replacive; they formed by dissolution of pyroxene and precipitation of olivine ± Cr-rich spinel.

Stop 4.5: Val Ventina, Pt. 2255

Coord. 770'300/152'800

Ophicarbonate outcrops in Val Ventina. Just below the end of the Ventina glacier beautifully exposed ophicarbonate rocks can be seen. The ophicarbonate rocks consist of blocks of schistose serpentinite, with a diameter ranging from millimetres to a few metres, embedded in a matrix of carbonate, i.e. calcite and/or dolomite. In part, the ophicarbonate breccias show properties of debris flows. In situ fragmentation of antigorite serpentinite are probably similar to jigsaw breccias observed in less metamorphosed ophicarbonates in the Platta nappe, and locally tectonically overturned geopetal fabrics can be seen. Oxygen and hydrogen isotopes of minerals from the ophicarbonates do not display a systematic trend with increasing temperature suggesting the absence of isotopic equilibrium during contact metamorphism (Pozzorini & Früh-Green 1996; Abart & Pozzorini 2000). The relatively constant carbon isotope compositions of the Ventina ophicarbonate matrix are comparable to marine carbonate signatures (Pozzorini & Früh-Green 1996).

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