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From magmatism through metamorphism to sea floor emplacement of subcontinental Adria lithosphere during pre-Alpine rifting (Malenco, Italy)

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Abstract

Major ultramafic masses of the Penninic domain of the Alps and of Liguria are subcontinental *Adria* lithosphere that was emplaced as the floor of the Tethyan ocean during Mesozoic spreading. Field relationships among three lithologic complexes of the Penninic/Austroalpine border region from Val Malenco demonstrate the evolution of such pre-Alpine crust-mantle rifting: 1. The *Malenco ultramafics,* pre-rift subcontinental mantle of the Adriatic plate and substratum of 2. the *Margna continental crust* and 3. the Jurassic to Cretaceous *Forno ophiolite suite.*

Lithologies 1 and 2 are crosscut by the post-Variscan, pre-Alpine, tholeiitic Fedoz gabbro that intruded at the crust-mantle boundary. Ductile flaserization of the gabbro and a *retrograde metamorphic evolution* beginning with granulite facies and ending with greenschist facies mark the pre-Alpine exhumation of Fedoz gabbro, Malenco ultramafics and lower Margna crust. Unit 3 formed after opening of the Tethyan ocean and overlies partly Malenco ultramafics which are also crosscut by its MORB dykes.

These and further observations permit recognition of the following sequence of events:

1. Thinning of the later NW-Adria plate in the Permomesozoic and concomitant intrusion of Fedoz gabbro.
2. Ductile flaserization and later dynamic recrystallization of the gabbro under granulitic to amphibolitic conditions in a low-angle asymmetric extensional shear zone following partly the crust-mantle boundary. Extensional uplift and retrograde metamorphism of Malenco mantle, lower Margna crust and Fedoz gabbro.
3. Emplacement of denudated, partly antigorite-serpentinized Malenco mantle on the floor of the opening Jurassic ocean. Formation of a passive continental margin.
4. Ophicarbonate deposition in fractures and on top of the ex-subcontinental, ultramafic ocean floor.
5. Formation of the Forno ophiolites on top of the ultramafic ocean floor. Oceanic mineralization. Sedimentation from the middle Jurassic to mid-Cretaceous.
6. Alpine deformation and metamorphism in all units.

Similar relationships hold for the Penninic-Austroalpine border region in Piemonte and in Liguria. The Platta ophiolites north of Malenco are visualized as a northern continuation of the Forno ophiolites.

Keywords: ultramafics, ophiolite, extensional metamorphism, mantle denudation, Adriatic plate, Penninic/Austroalpine border, Malenco serpentinite, Central Alps.

Introduction

Many ultramafic bodies along the arc of the Alps have been referred to as "ophiolitic" because of their association with gabbros, basalts, and oceanic cherts and because they were emplaced at shallow levels during opening of the Jurassic Ligurian-Piemont basin. Many ultramafic bodies of the Alps, however, show features that distinguish them from typical ophiolite sequences. Major occurrences of such ultramafics (Fig. 1) are Erro-Tobbio, Voltri group, Ligurian Alps (PICCARDO et al., 1980, 1990, 1992; VISSERS et al., 1991; HOOGERDUIJN STRATING, 1991); Lanzo (NICOLAS, 1969;

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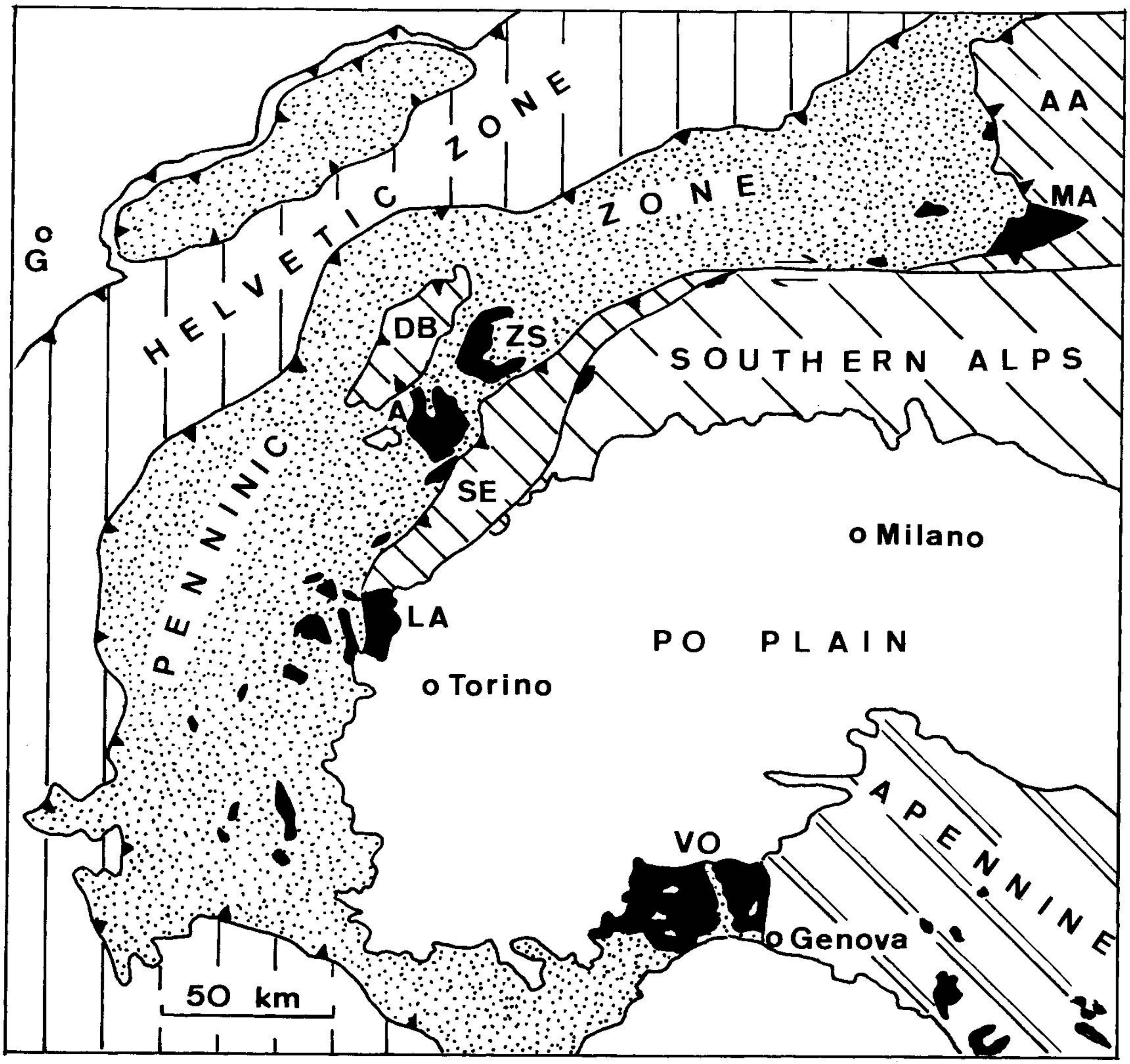

Fig. 1 Major occurrences of ultramafic rocks (black) in the Central, Western Alpine and Northern Apennine arc. MA = Malenco; ZS = Zermatt-Saas (Breithorn); A = Aosta (M. Avic); LA = Lanzo; VO = Voltri (Erro-Tobbio). AA = Austroalpine nappes east of Malenco, SE = Sesia zone; DB = Dent Blanche nappe; G = Geneva.

Ernst, 1978; Pognante et al., 1985; Bodinier et al., 1991; Boudier and Nicolas, 1985); M. Avic, Aosta Valley and Breithorn, Zermatt-Saas area (Dal Piaz, 1969) and Malenco (Trommsdorff and Evans, 1974). Among the peculiarities of these "ophiolites" are the absence of a true basaltic layer, at the same time the presence of a direct superimposition of the ultramafics by ophicarbonate rocks or oceanic sediments, and finally the presence of intrusive gabbroic bodies and crosscutting MORB type gabbroic to basaltic dykes in the ultramafics. To explain these features Lemoine et al. (1987, Fig. 5) drew for the Ligurian ultramafics a major, oblique, normal detachment fault (Wernicke, 1981, 1985) that cuts across the lithosphere and leads to the denudation of subcontinental upper mantle rocks, which then become exposed on an ocean floor. Lemoine et al. (1987, Fig. 5) postulated such a crust-mantle detachment fault dipping towards Europe and following the crust to mantle boundary below the European (Briançonnais) continent. For such a model it is essential to provide proof for the former association of the inferred lithospheric mantle with continental crust and for the retrograde path of metamorphism during detachment faulting of both the lower continental crust and its substratum, the lithospheric, subcontinental mantle. Whereas the tectonic process of mantle denudation through rifting is at present under study along passive continental margins (e.g. Galicia: BOILLOT et al., 1988; BOILLOT et al., 1990) and pre-oceanic rifts (Northern Red Sea: VOGGENREITER et al., 1988; BOHANNON et al., 1989; PICCARDO et al., 1988, 1993) the situation in the Alps is obscured by the tectonic and metamorphic signatures of the Cretaceous to Tertiary orogeny. It is the purpose of this paper to provide field evidence for A) the lithospheric subcontinental character of the Malenco ultramafics with respect to the Austroalpine Margna unit; B) the intrusion of mantle-derived magmas during the pre-Alpine extension; C) the uplift and denudation of the Malenco mantle during pre-Alpine rifting; D) its subsequent association with MORB type basaltic magmas. The pre-Alpine, syn-extensional, retrograde metamorphic history of lower granulitic Austroalpine crust, of the Fedoz gabbroic suite and of the subcontinental Malenco ultramafics will also be addressed in this context.

Regional setting

Three major lithologic complexes characterize the Penninic-Austroalpine boundary in Val Malenco, Italy (Fig. 2). They are from east to west: 1) the topping Margna unit, a system of west facing, recumbent anticlines of Austroalpine basement and Mesozoic cover; 2) the Malenco unit, an ultramafic body and pre-oceanic substratum of granulitic Margna basement (not of the Margna nappe, which is Alpine!) with later oceanic ophicarbonate zones that formed in the Jurassic; and 3) the ophiolitic Forno unit consisting of metamorphosed Jurassic oceanic sediments and mineral deposits as well as of basaltic pillow lavas, volcanoclastic rocks and associated mafic dykes

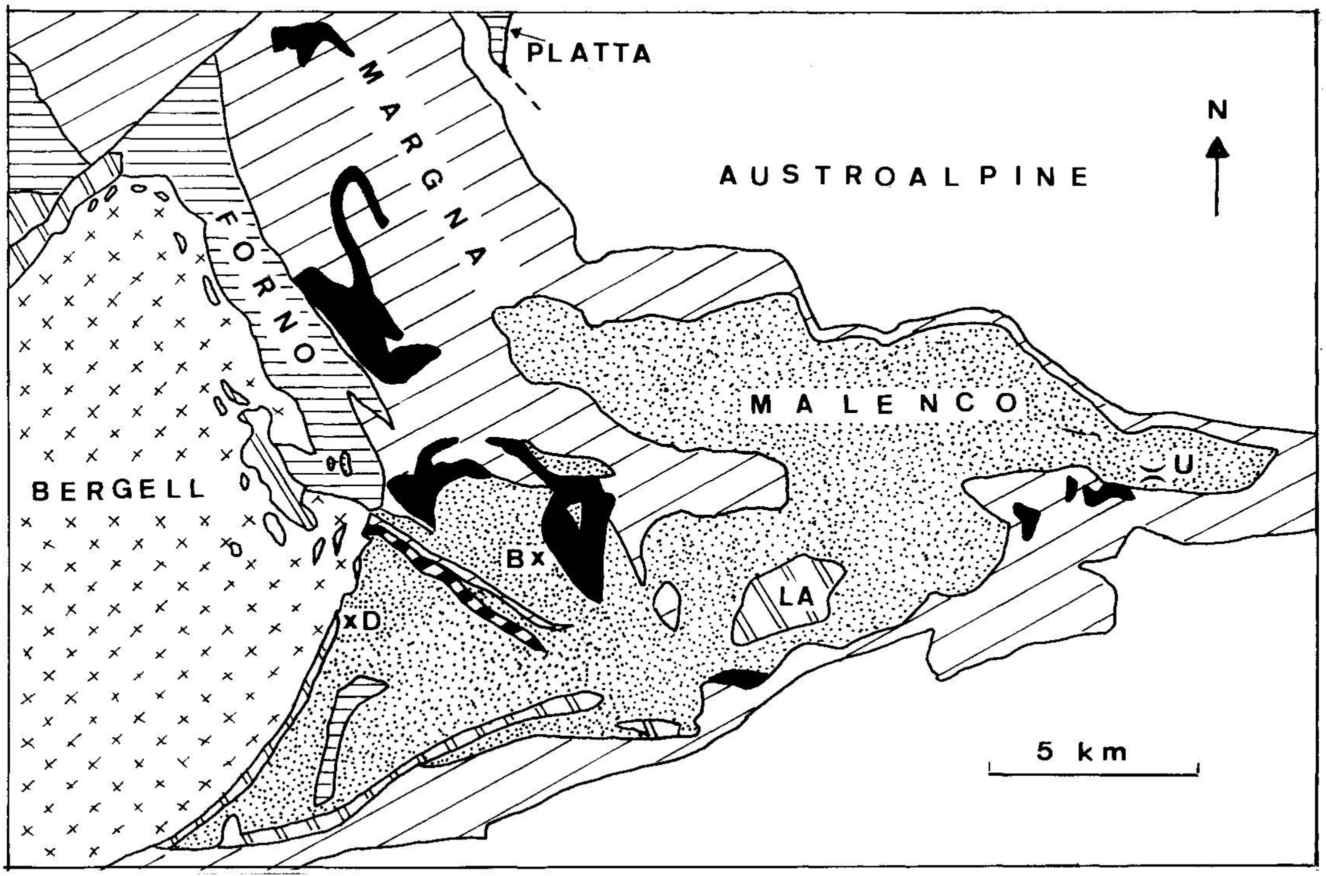

Fig. 2 Geological Map about the Malenco ultramafic body (stippled). Occurrences of Fedoz gabbro are in black. D = Monte Disgrazia; B = Monte Braccia; U = Pass d'Ur. The Margna nappe overlies the Malenco ultramafics, Lanzada-Scermendone zone and Suretta nappe (LA) underlie the Malenco ultramafics. The Forno unit overlies part of the Malenco ultramafics that became denudated in the Jurassic Tethyan ocean. The black and white striped pattern refers to a major ophicarbonate zone within the Malenco unit. The southwards ending Platta ophiolites are indicated on the figure.

that also crosscut marginally the Malenco unit. Malenco unit and Margna basement belong to the pre-Alpine lithosphere of the Adriatic plate. Both units are crosscut by a Gabbro (Fedoz gabbro) of post-Variscan metamorphism, pre-Alpine (GAUTSCHI, 1980) age which forms major bodies in the granulitic core of the Margna unit (Fedoz suite of STAUB, 1917). Along their contact zone the Malenco and Margna units are frequently imbricated with mylonites and tectonic breccias occurring in between the two lithologies. The ophiolitic Forno unit represents a part of the Piemont ocean that formed adjacent to the Austroalpine margin in the late Jurassic.

Field relationships, lithology and petrology

MARGNA UNIT

The *basement* of the lowermost Austroalpine (MONTRASIO and TROMMSDORFF, 1983; HERMANN and MÜNTENER, 1992) Margna unit comprises a metasedimentary suite of pelitic, carbonate and mafic rocks that underwent a high-grade Variscan amphibolite facies metamorphism (GUNTLI and LINIGER, 1989). This suite (Fedozserie of STAUB, 1917; CORNELIUS, 1923) is crosscut by granitoid rocks (Malojaserie of STAUB, 1923) and, later, by a gabbro complex (Fedoz gabbro) as discussed below. Granitoid rocks become dominant in higher sections of the Margna unit where they approach up to 50% of its total volume (SPILLMANN and BÜCHI, 1993). They include as roof pendants garnet-amphibolites which are interpreted as belonging to the pre-granitic metamorphic basement of the Margna unit. Geochemically, the granitoid intrusives show close affinities to the late-Variscan intrusive rocks of the nearby Bernina nappe (GUNTLI, 1987; BENNING, 1990). The Permo-Triassic *sedimentary cover* of the Margna unit starts with terrigenous clastic deposits followed by platform carbonates due to the transgression of the Tethyan ocean (HERMANN and MÜNTENER, 1991). In the Jurassic, fault-controlled sedimentary breccias recorded from the Margna unit (CORNELIUS, 1935; HERMANN, 1991) and from adjacent Austroalpine units (FROITZHEIM and EBERLI, 1990) indicate the disintegration of the Adriatic continent and the beginning formation of a passive continental margin.

FEDOZ GABBRO

Within the granulitic core of the Margna unit a gabbroic intrusion covering an area of about 10 km^2 is dominant. This so called "Fedoz gabbro" (STAUB, 1917) shows intrusive contacts crosscutting the Variscan foliation of the metasedimentary Fedoz suite and associated granitoid rocks of the Margna basement (GAUTSCHI, 1980). It will be demonstrated later that the Fedoz gabbro also forms dykes in the Malenco ultramafics (see also HERMANN et al., 1993). The Fedoz gabbro forms a locally stratiform complex intruded at ≥ 20 km depth (GAUTSCHI, 1980), with a wide variety in grain size (from dm to < mm). Chemically, it shows a tholeiitic differentiation trend ranging from relatively Mg-rich (11%) gabbros through olivine (fa 26)-gabbronorites to diorites (GAUTSCHI, 1980). Especially the coarse-grained varieties of the Fedoz gabbro almost invariably show a flaser-texture. Postmagmatic events in the Fedoz gabbro have been thoroughly studied by GAUTSCHI (1980). A flaser texture with ductile deformation of clinopyroxene (Cpx), plagioclase (an 50), orthopyroxene (Opx), ilmenite (GAUTSCHI, 1980; HERMANN et al., 1993) has been demonstrated to belong to a granulitic stage. Still granulitic, static recrystallization with CPx, OPx and green spinel, partly as coronas about olivine and plagioclase (800 °C / ≥ 6.5 kb) occurred after formation of the flaser texture. Later stages in the evolution of the gabbro involve the static formation of garnet and pargasitic amphibole (locally coronitic) corresponding to amphibolite facies conditions followed by greenschist facies conditions. During the latter event, the gabbroic dykes in the Malenco ultramafics have become rodingitized. Clearly distinct from this post-Variscan *pre-Alpine retrograde* evolution of the Fedoz gabbro are later, Alpine, upper greenschist facies, events in which barroisitic and actinolitic amphiboles dominate together with an albitic plagioclase, chlorite and zoisite. This upper greenschist event corresponds to the Alpine metamorphism as typical for the Mesozoic cover and basement of the whole Margna nappe (GUNTLI and LINIGER, 1989; SPILLMANN, 1989).

It is remarkable that the highest grade phenomena found in the Fedoz-series rocks are found in the vicinity of the gabbro contact. These phenomena comprise incipient melting of metapelitic rocks at the post-Variscan intrusive contact near Lago Pirola and the occurrence of wollastonite, olivine and humites (BANGERTER, 1978; SCHUMACHER, 1975) in metacarbonates of unknown age, some tens to hundred meters from the contact.

From the summary of observations a general sequence of events can be established for the Margna rocks. 1) High grade (amphibolite facies) metamorphism of the pre-granitic basement of the Margna, Variscan or older. 2) Intrusion of granitoid rocks (belonging to the late-Paleozoic suite) into high levels of the Margna basement. Intrusion and differentiation of the Fedoz gabbro (late Variscan to Mesozoic). 3) High temperature ductile deformation i.e. flaserization of the gabbro. 4) Granulite facies reequilibration of the gabbro (800 °C – 6.5 kb) most likely during slow cooling. 5) Amphibolite stage in the gabbro. 6) Alpine metamorphic cycle, upper greenschist facies.

Events 2 to 5 record processes of ductile deformation and of retrograde metamorphic evolution during post-Variscan, pre-Alpine times. These processes will later be ascribed to extensional attenuation accompanied by simple shear of the future Adriatic lithosphere.

UR-"BRECCIA"

Along the border between Malenco serpentinite and Margna basement east and north of Val Malenco a tectonic "breccia" can be observed in many localities. The matrix of this "breccia" is formed by felsic micaschists rich in sphene, chlorite, albite and quartz containing cm to meter sized knobs and components of metasomatized ultramafic (Malenco derived) and gneissic (Margna derived) rocks. According to the type locality at Pass d'Ur (Fig. 2) the rock has been called Ur-breccia. Petrographic and structural investigations of the breccia (Sidler and Benning, 1992) demonstrate a metasomatic event with mobility of Na, Ca and Si at the contact Margna-Malenco. They suggest a very early formation of the breccia, possibly before overthrusting of the Austroalpine nappes. The subsequent deformational and metamorphic history of the breccia is polyphasic. The primary sense of shear associated with brecciation is undetermined. The fact that Malenco derived components have been integrated in a felsic matrix of the breccia indicates a relatively brittle behaviour of the components. This indicates that the ultramafics had not yet (or only little) been serpentinized at the time of breccia formation. In agreement with this statement are observations of Burkhard and O'Neil (1988) who propose that one and the same marine water has caused concurrent serpentinization and metasomatic activity at the Malenco-Margna boundary.

THE MALENCO ULTRAMAFIC BODY

This is one of the largest ultramafic masses in the Alps. It covers an area of about 130 km^2 (Fig. 2). It is overlain by and intensely interfolded and imbricated with the Margna rocks which form most of its northern, eastern and southeastern border. Below the Malenco ultramafics, in the Lanzada tectonic window, follows the Penninic Suretta unit which continues in a complex sliced up zone around the southwest end of the ultramafic mass (Montrasio, 1984). Near Monte Braccia (Fig. 2) the Malenco ultramafics are crosscut by Flaser-gabbro, which is in continuation with, and shows the identical chemistry, deformational and metamorphic history as the Fedoz gabbro. These outcrops will be discussed in a separate paragraph. Along its western and northwestern border the Malenco ultramafics are intruded by basaltic rocks of the ophiolitic Forno complex which also will be discussed later. The Oligocene Bregaglia intrusive approaches very closely all the western border of the Malenco ultramafics where they are contact metamorphosed over a distance of 1.5 to 2 km (Trommsdorff and Evans, 1972).

Most of the Malenco ultramafics are formed by a schistose, antigorite-olivine-diopside-chlorite-magnetite rock. In some areas, however, to the W and N of Monte Braccia and SW of Monte Disgrazia (Fig. 2) primary structures and relic mineralogies are still preserved. The ultramafics in these areas contain abundant relics of the mantle minerals particularly clinopyroxene: they are predominantly spinel lherzolites showing frequently clinopyroxene enriched and clinopyroxene depleted banding. Where the Alpine deformation and serpentinization are less developed granular to low strain (tectonites) and high-strain (mylonites) banded mantle textures are preserved. Particularly within granular and low-strain rocks, various generations of pyroxene rich (i.e. clinopyroxenite to websterite) bands are locally present. They sometimes crosscut as dykes the main pre-Alpine foliation in the less deformed rock types but they are usually parallelized and strongly deformed in the foliated rocks.

In places, large bodies with layered structures and cumulate textures are recognizable (Honegger, 1977). The former are present by parallel spinel and clinopyroxene rich lherzolite and dunite layers alternating within dm with pure clinopyroxenite and less commonly websterite layers. The latter are evidenced by ovoidal olivine and spinel, sometimes with honeycombed textures. Dunitic pods with spinel cumulates are also widespread.

All the above pre-Alpine features indicate that the Malenco mantle was mainly represented by rather fertile lherzolites, early equilibrated under spinel facies conditions (i.e. at lithospheric mantle depths), similar to many other fertile lherzolites from the Alps – Apennine chain (PICCARDO et al., 1990). The Malenco mantle was subjected through time to strong deformation at mantle depths and moreover became intruded at different times and depths by melts derived from deeper mantle sources.

The entire Malenco serpentinite shows various degrees of deformation and serpentinization. The spectrum ranges from massive, layered lherzolites with less than 20% serpentine to schistose, completely serpentinized rocks. The predominant rock-type is a schistose titanian clinohumite bearing magnetite-chlorite-diopside-olivine-antigorite rock (TROMMSDORFF and EVANS, 1972) which because of its perfect schistosity is mined in large quarries and used as a building stone, for tiles, floors, staircases, pathways etc. Most of the metamorphic minerals within the serpentinite occur in several generations. Antigorite occurs deformed and undeformed and is aligned along several schistosities that formed during metamorphism. It can be demonstrated, however, that even early generations of serpentine minerals, replacing mantle olivine, are antigorite. Chrysotile on the other hand is quite rare (MELLINI et al., 1987) and is mainly restricted to various generations of veins. In many localities of Val Malenco cm to dm thick veins and nodules are observed containing patchily distributed, often several cm large, crystals of titanian clinohumite (ticl; DE QUERVAIN, 1938; TROMMSDORFF and EVANS, 1980). The veins occur in several generations within early extensional cracks (pre-Alpine?) that are deformed or augen-shaped containing diopside + olivine + titanian clinohumite + magnetite (± antigorite) and late, undeformed extensional veins and fissures containing essentially chlorite + titanian clinohumite. Similarly titanian clinohumite occurs also in the serpentinite as a rock-forming mineral, preferably in lherzolitic and pyroxenitic rocks. The source for the titanium lies in the breakdown of titanian tschermaks component of the magmatic clinopyroxene (TROMMSDORFF and EVANS, 1980; PICCARDO et al., 1988). The lower stability limit of ticl assemblages is close to the lower stability limit of forsterite (EVANS et al., 1976; TROMMSDORFF and EVANS, 1980) and lies at 3000 bars at temperatures above ~370 °C. As ticl breaks down to olivine + geikielite at 3 kb and ~520 °C (TROMMSDORFF and EVANS, 1980) its stability field may have a width of about 150 °C.

The conditions of ticl formation may be a useful indicator of the late stages of the pre-oceanic retrograde evolution as well as of the climax of Alpine metamorphism.

FEDOZ GABBRO DYKES

East of Monte Braccia (localities Val Füraas and Alpe Girosso) up to 50 cm thick dykes of Fedoz gabbro have been detected within the Malenco ultramafics. These dykes occur within some tens of meters from the contact of the ultramafics and are in continuation at Alpe Girosso with the main gabbro intrusion. Although some shearing has taken place a Ur-breccia is missing in the whole area of Monte Braccia. The dykes are discordant to the layered structure in cumulate pods (Fig. 3). The dykes frequently show a ductile flaser texture (pre-Alpine). In thin section the same pre-Alpine retrograde history as for the main gabbro body is observed. Ductile deformation of clinopyroxene and plagioclase is followed by recrystallization of diopside and plagioclase An_{50}. During further pre-Alpine retrogression pargasite and perhaps spinel (now chlorite) dominate. The first serpentinization in the surrounding ultramafics was accompanied by marginal rodingitization of the dykelets with overgrowth of grossular, diopside and chlorite over the preexisting mineralogy and over the flaser texture. Apart from elements that are mobile during rodingitization the bulk chemistry of the gabbro dykes is identical to that of the Fedoz gabbro. The same holds for their mineral chemistries (work in progress).

The fact that Fedoz gabbro still preserves primary intrusive contacts with both Margna basement and Malenco ultramafics demonstrates that both units were, during the time of gabbro intrusion, in close juxtaposition with the Malenco ultramafics forming the substratum of the Margna crust.

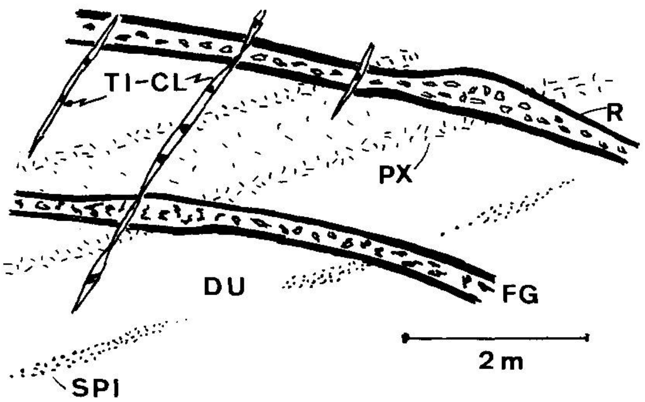

Fig. 3 Relations at outcrop Val Füraas, east of Monte Braccia (see Fig. 2). Spi = spinel layering cut by dunite (DU), Px = pyroxenite layers, FG = Fedoz gabbro dykes with rodingitized (R) rims. Ti–Cl refers to titanian clinohumite in extensional cracks. Drawn from the field.

OPHICARBONATE ROCKS

They occur in several localities along the margins and within the Malenco serpentinite. They form breccias with serpentinite components embedded in a matrix of carbonates, mostly calcite but also dolomite, or veined rocks with calcite fillings often occurring in several systems of extensional fissures. There is general agreement that these types of ophicarbonates are rapidly formed deposits above, or fissure fillings within, the fractured ultramafic ocean floor respectively (LEMOINE et al., 1983; BERNOULLI and WEISSERT, 1985). Stable isotope signatures of the carbonates from veins and breccias of the ophicarbonate suite in Val Malenco are clearly marine (POZZORINI, in prep.). This is also partly true for the stable isotopes of antigorite within the components of the ophicarbonate breccias. These components are massive or schistose with a generation of antigorite predating ophicarbonate formation and representing probably antigoritization during mantle uplift below a continental margin. From the most prominent ophicarbonate occurrence of Val Malenco, forming a several km long and tens to hundreds meter wide SE–NW trending vertical zone north of Monte Disgrazia (Fig. 2; TROMMSDORFF and EVANS, 1977), an association of Fe–Cu–Ni–Zn sulfide deposits has been described (DE CAPITANI et al., 1981). The entire of the phenomena described here in connection with ophicarbonates has very likely evolved as a consequence of mantle-denudation processes along the Austroalpine continental margin. Stable isotope compositions have been determined for Malenco ultramafics by BURKHARD and O'NEIL (1988). Relatively high δD values (–42 to –34‰) and low $\delta^{18}O$ values (4.4–7.4‰) for antigorites from Malenco ultramafics outside the Bergell contact aureole were interpreted as strong evidence for dominance of marine water during serpentinization. If formation of antigorite is assumed to have happened at about 400 °C, water/rock ratios of 0.2 result for the serpentinization in the eastern Malenco area. BURKHARD and O'NEIL (1988) also analyzed carbonate that occurs in small amounts within the Malenco serpentinite and aside from ophicarbonate rocks. This carbonate also has clear marine signatures of stable isotopes ($\delta^{13}C$ = –3.3 to –2.2‰ PDB; $\delta^{18}O$ = 10.3–14.9‰). Finally amphibole from the brecciated and metasomatized contact zone between Malenco ultramafics and Margna nappe, the Ur-breccia (δD = –3‰) gives similar ocean water signatures as established for antigorite from the adjacent ultramafics. These authors interpret this situation in that serpentinization and metasomatism took place concurrently in presence of the same fluid prior to orogeny and when Margna and Malenco units were in close juxtaposition.

THE MONTE DEL FORNO OPHIOLITE UNIT

This unit (FERRARIO and MONTRASIO, 1976) occurs between the eastern border of the Oligocene Bregaglia intrusive and the western border of the Malenco and Margna nappes (Fig. 1). Although throughout affected by Alpine regional metamorphism and by the contact metamorphism of the Bregaglia intrusive the Monte del Forno unit still shows most features of an ocean floor sequence (PERETTI, 1985). It consists of metabasaltic rocks and their metamorphosed sedimentary cover on top of a serpentinized mantle. Within the thick metabasaltic suite pillow lavas and pillow breccias are locally well preserved (MONTRASIO, 1973). The sea floor hydrothermally altered part of the mafic suite includes a several km long zone with sulfide Fe–Cu–Zn mineralizations (PERETTI and KÖPPEL, 1986). Major and trace-element geochemical data (GAUTSCHI, 1980) as well as the Pb-isotopic signature of unaltered mafic rocks (PERETTI and KÖPPEL, 1986) demonstrate their MORB character. An additional mafic suite with a somewhat more primitive Forno chemistry (GAUTSCHI, 1980) occurs south of Monte della Disgrazia (Fig. 2). Both mafic suites are in direct contact with the Malenco ultramafics. Their dykes crosscut the ultramafics near their borders and have become rodingitized subsequently. Thus, there are at least two rodingitization events, which concur with polyphasic serpentine growth in the ultramafics. The Forno dykes are clearly distinguishable from the Fedoz main gabbros and dykes by their finer grain size, the lack of flaserization and less clearly on basis of their major element and trace element chemistry (GAUTSCHI, 1980) which for many elements remains unchanged during rodingitization (EVANS et al., 1981). The sedimentary cover of the mafic rocks of the Forno unit (PERETTI, 1985) begins with a basal quartzite of up to 25 m thickness which may represent metamorphosed radiolarian cherts. The quartzite contains metamorphosed manganese ore deposits (PETERS et al., 1973; FERRARIO and MONTRASIO, 1976) and thin greenschist and calcsilicate intercalations. The quartzite is overlain by metapelites and finally by diopside-quartz schists. Although no stratigraphic age for the whole suite can be established, this metasedimentary sequence is perfectly analogous to Jurassic to Cretaceous ophiolites plus sedimentary cover in other parts of the Alps.

Post-Variscan, pre-Alpine history of the Malenco-Margna system

Our data from the field unequivocally demonstrate that Malenco ultramafic rocks formed the lithospheric subcontinental mantle below the Margna basement during pre-Alpine, post-Variscan times. Proof for this is the post-Variscan intrusion of tholeiitic Fedoz gabbro which, at Monte Braccia, still crosscuts both the Malenco ultramafics and the Margna rocks. Most of the Fedoz gabbro crystallized within the lower crust of the Margna unit as a partly layered complex. After this intrusion the Malenco mantle, the lower Margna crust and the Fedoz gabbro underwent various stages of retrograde metamorphism. Ductile deformation of clinopyroxene and plagioclase led to a flaser-texture of the gabbro prior to static recrystallization, both under *granulite facies* conditions. This recrystallization produced equigranular domains of diopsidic clinopyroxene and of plagioclase (An_{50}) after the preexisting flaser minerals. Very high grade conditions in the Margna basement with incipient melting of pelites within meters from the gabbro contacts and spinel peridotite facies conditions in the Malenco ultramafics also correspond to granulite facies. Fixpoints are along the pre-Alpine trajectory of retrograde metamorphism: a coronitic stadium (T ~ 800 °C, GAUTSCHI, 1980) in the metagabbro with coronas about olivine and about ilmenite; a stage in amphibolite facies with coronitic garnet and amphibole (pargasitic to tschermakitic) growth; a stage of antigorite (+ diopside and perhaps titanian clinohumite) growth (< 520 °C, EVANS et al., 1976) in the ultramafics with concomitant rodingitization of flaserized gabbro dykes, corresponding to greenschist facies (HERMANN et al., 1993).

It is possible that the origin of the breccia between the Margna and Malenco units (Ur-breccia) predates serpentinization of the Malenco mantle. As reasons may be taken that, at the time of breccia formation, the ultramafics (components) behaved relatively brittle and the Margna gneisses (matrix) relatively ductile, and that the same oceanic water serpentinized and metasomatized ultramafics and breccia respectively.

Partly serpentinized Malenco mantle then became exposed at the Tethyan ocean floor. So far, no proof can be given for a corresponding exposure of Fedoz gabbro. *Fractures* within the newly formed serpentinitic ocean floor were filled with calcite and ophicarbonate breccias were rapidly formed near the roof of the fractured mantle. Sulfide deposits within the ophicarbonate suite mark the increased oceanic hydrothermal activity during or shortly after ophicarbonate deposition. The serpentinites and ophicarbonate deposits then became transsected by fine-grained basaltic dykes and overlain by a suite of mafic volcanics and pillow lavas, part of the Forno complex. Chemical and isotopic characteristics of these mafics are those of MORB (GAUTSCHI, 1980; PERETTI and KÖPPEL, 1986). Abundant slices of mylonitized Margna basement with Fedoz gabbro and of metacarbonate rocks in between the Forno suite and the Malenco ultramafics occur at Alpe Zocca and south of Val Sissone (MONTRASIO and TROMMSDORFF, 1983). This would nicely fit into the scenario of mantle denudation but so far we were unable to prove, whether this imbricate structure is due to Alpine or pre-oceanic tectonics.

Roughly parallel to the exhumation of the Malenco unit went the breaking up of the more distal continental basement of the Margna unit with deposition of Jurassic breccias on the Triassic platform sediments. Upper Jurassic radiolarian cherts with manganese nodules and flyschoid Cretaceous sediments complete the cycle of Mesozoic sedimentation on top on the Margna (HERMANN, 1991).

Discussion and conclusions

PRE-OCEANIC STAGE

Post-Variscan, late Paleozoic mafic intrusions into the Lower Austroalpine and Southalpine crust have been attributed to partial melting of rising asthenosphere in connection with lithospheric extension beneath an extending crust (VOSHAGE et al., 1990; QUICK et al., 1992; for a review see DAL PIAZ, 1993). Correspondingly, the relatively well constrained history of the Malenco-Margna system may be used to construct tentative schemes (Fig. 4A, B) for the situation around the time of gabbro intrusion (i.e. late Paleozoic to Jurassic). If a depth of intrusion is accepted at somewhat above 20 km (from Gautschi's value of about 6.5 kb for the granulitic reequilibration) then this depth also marks the position of the crust to mantle boundary. In this case the intruded Adriatic crust was already thinned. If an asthenospheric mantle source is assumed for the primary melts of the Fedoz gabbro suite, as suggested from the bulk rock chemistry, it must be inferred that during early extensional stages the asthenospheric mantle under the future Adria plate underwent upwelling in combination with lithospheric thinning (PICCARDO et al., 1992, 1993) and progressive partial melting on decompression.

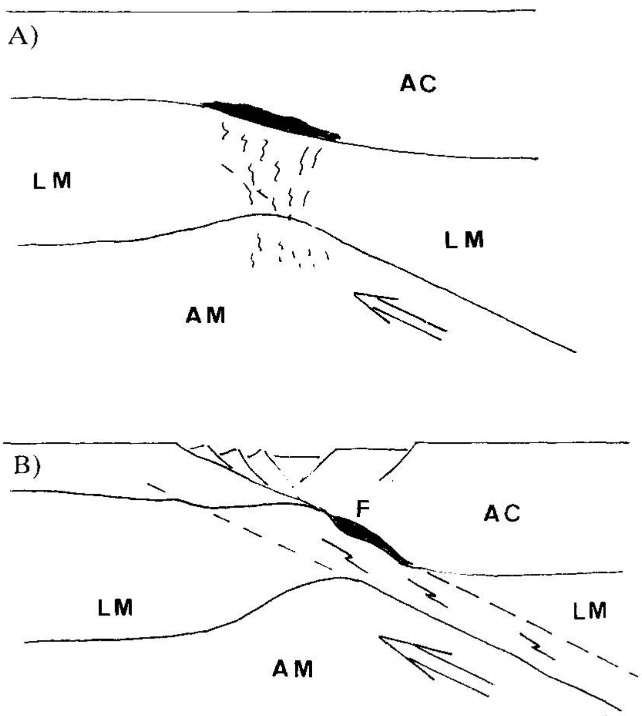

Fig. 4 Possible situation during intrusion and during flaserization of Fedoz gabbro. A) Intrusion of gabbro at the base of thinned Adria crust. B) Ductile flaserization of the gabbro in a low angle, extensional fault system. AC = Adria crust; AM = Asthenospheric mantle; F = Fedoz gabbro; LM = Lithospheric mantle.

Taking into account all the petrographic and geological-structural features, it can be concluded that early tholeiitic melts have intruded the extending lithosphere of the future Adria plate along the crust-mantle contact whereas there is evidence that the later MORB type melts (i.e. the Forno basalts) have been intruded subsequently when the Malenco lithospheric, subcontinental mantle was already exposed on the seafloor.

An active tectonic environment for the time after gabbro intrusion must be postulated from the granulitic, ductile flaserization of the gabbro. We preferred to link this flaserization with ductile shearing caused by extensional faulting of the Adriatic crust (Fig. 4B). The schemes in figures 4 and 5 take account of the fact that the known Fedoz gabbro was not exposed to the earth surface during the pre-Alpine rifting.

JURASSIC SCENARIO

The field data presented in this paper permit to construct a scenario of the Austroalpine continental margin during the Jurassic (Fig. 5): Partly serpentinized mantle (SE) forms the Tethyan ocean floor. These mantle rocks are part of the former Austroalpine subcontinental mantle that became denudated through normal faulting and ductile detachment. Ophicarbonate breccias (OC) in fractures and on top of the mantle and Jurassic breccias (JB) at the margin and on top of the Austroalpine continent mark the broken up surface of the thinned Adriatic plate. The basin east of Margna indicates the south-end of the northwards opening Platta ocean, which joins the Forno basin north of the ending Margna peninsula (see also Liniger, 1992). West dipping normal folds occur along the continental margin of the Forno-Platta basin. East dipping, high angle nor-

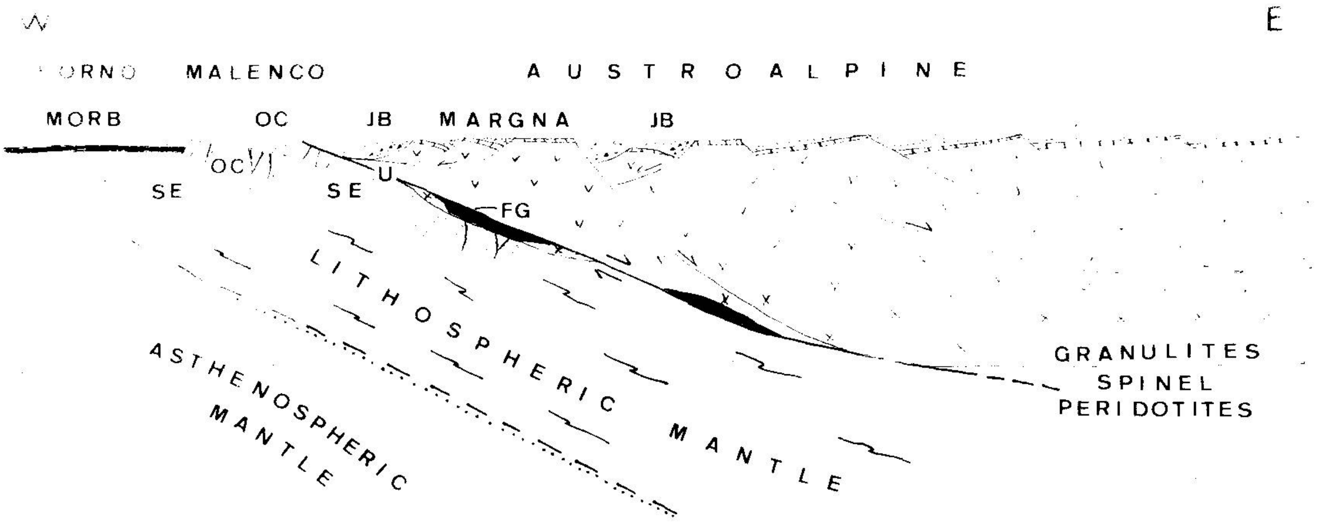

Fig. 5 Jurassic scenario for the Malenco region. 'E' and 'W' correspond to the inferred, approximate directions east and west. FG = Fedoz gabbro, SE = serpentinized ex-subcontinental lithosphere, OC = ophicarbonate rocks in fracture zones and on top of the ultramafics. The fractured Margna and Austroalpine rocks carry Jurassic breccias (JB). East of Margna the southwards ending basin of the Platta ocean is indicated crosses mark granulitic lower Austroalpine crust.

mal faults occur within the Austroalpine. Low angle detachment faults control the Austroalpine margin (FROITZHEIM and EBERLI, 1990) and use partly the crust-mantle interface (Ur-breccia, U) to unroof the lithospheric, subcontinental mantle. Fedoz gabbro and surrounding Margna rocks are on their decompressional, retrograde metamorphic path caused by the faulting away of the Austroalpine continent.

The situation as outlined in this discussion bears similarities with other regions in the Alps. As early as 1917 STAUB has compared the Margna and Dt. Blanche nappes (Fig. 1) on basis of their lithologies and tectonic positions. In particular, the Permian gabbro of Mt. Collon in the Dent Blanche nappe has been compared with the Fedoz gabbro by STAUB (1917) and GAUTSCHI (1980). The gabbro masses of Mt. Collon and Matterhorn have been studied by DAL PIAZ et al. (1977) and DAL PIAZ and ERNST (1978), who pointed out the sub-alkaline character with olivin-tholeiite affinity of the primary melts, their mantle origin (initial Sr ratios < 0.704) and the late Paleozoic age (248 m.y.) of emplacement. DAL PIAZ et al. (1977) interpreted the Dt. Blanche gabbros as products of proto-Alpine extensional processes which led to the thinning of the Hercynian continental crust and to the subsequent opening of the Mesozoic (Tethyan) ocean basin. Antigorite serpentinites with fractures of ophicarbonate and overlaying ophicarbonate rocks containing components of platform sediments (DRIESNER, 1991, 1993) occur in middle Val d'Aosta near Châtillon (ELTER, 1987). The serpentinites bear striking similarities to those from Val Malenco and they most likely represent denudated and rifted subcontinental mantle.

Large peridotite-serpentinite units in the Western and Ligurian Alps (i.e. Lanzo and Erro-Tobbio) and Northern Apennine (i.e. External Ligurides) show overall similar characteristics and are close to Austroalpine crust. They have been interpreted as lithospheric mantle emplaced at the sea-floor of the Liguria-Piemont basin during early stages of continental breakup (Lanzo: POGNANTE et al., 1985; and N-Lanzo: BODINIER et al., 1991; Erro-Tobbio: PICCARDO et al., 1990, 1992; VISSERS et al., 1991; External Ligurides: PICCARDO, 1977, PICCARDO et al., 1990, 1992; RAMPONE, 1992). The P-T evolution of the Ligurian lherzolites during rifting has been related in particular to progressive unroofing of lithospheric, subcontinental mantle forming the footwall of a mantle scale, low angle, extensional detachment zone (VISSERS et al., 1991; PICCARDO et al., 1992). Taking into account the vast evidence for pre-oceanic, extensional tectonics in the marginal regions of the Adria plate (DAL PIAZ and ERNST, 1984; HODGES and FOUNTAIN, 1984; HANDY, 1987; BRODIE and RUTTER, 1987, 1989; BENCIOLINI, 1989; LARDEAUX and SPALLA, 1991; DAL PIAZ, 1993 (and references therein); QUICK et al., 1993; FROITZHEIM and EBERLI, 1990; BERNOULLI et al., 1990; LEMOINE and TRÜMPY, 1987), and the indications of sea-floor emplacement of lithospheric subcontinental mantle in the Ligurian basin as discussed above; and in view of the field evidence for lithospheric, subcontinental mantle denudation presented here for the Malenco region, we propose that denudation of *Adriatic* lithospheric, subcontinental mantle and its exposure in the Tethyan ocean basin was a major process during pre-Alpine rifting.

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Erratum

From magmatism through metamorphism to sea floor emplacement of subcontinental Adria lithosphere during pre-Alpine rifting (Malenco, Italy)

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Fig. 5, p. 199
to be replaced by correct version:

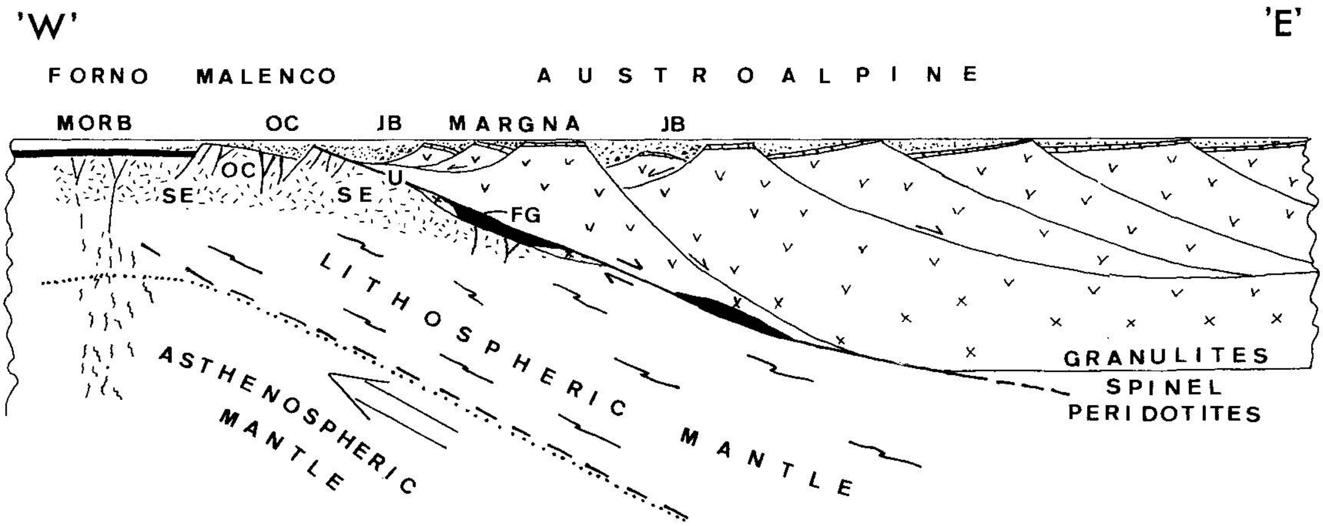

Fig. 5 Jurassic scenario for the Malenco region. 'E' and 'W' correspond to the inferred, approximate directions east and west. FG = Fedoz gabbro, SE = serpentinized ex-subcontinental lithosphere, OC = ophicarbonate rocks in fracture zones and on top of the ultramafics. The fractured Margna and Austroalpine rocks carry Jurassic breccias (JB). East of Margna the southwards ending basin of the Platta ocean is indicated crosses mark granulitic lower Austroalpine crust.