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The importance of serpentinite mylonites for subduction and exhumation of oceanic crust

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Abstract

In the ultramafic Erro-Tobbio unit (Voltri-Massif; Western Alps) a set of overprinting structures in serpentinite mylonites is related to Alpine subduction to about 80 km depth and to subsequent exhumation. Antigorite mylonites are cut by en-echelon olivine veins, which in turn are dissected by multiple sets of shear bands containing olivine and titanian clinohumite. The transition from olivine-free to olivine-bearing structures indicates recrystallization during prograde metamorphism. All structures display the same top-to-the-NW kinematics providing evidence for a continuous non-coaxial deformation. The serpentinite mylonites surround km-scale bodies of pre-Alpine peridotite which show only minor Alpine overprint. This indicates that during subduction-related deformation, recrystallization and fluid flow were strongly localized within serpentinite mylonites.

Olivine-bearing, discontinuous shear planes with top-to-the-SE sense of movement crosscut the prograde structures. The inversion of shear sense suggests a change in position of the serpentinites relative to the downgoing slab, i.e. from the subducted slab to the upper plate during accretion. Thus, the shear sense inversion marks the change from burial to exhumation of the serpentinites. The low density of antigorite serpentinites (2.75 g/cm^3) causes strong buoyancy, thus providing a mechanism for the exhumation of deeply subducted rocks. It is suggested that serpentinites may act as carriers for the uprise of eclogite bodies, which have higher densities than the peridotitic upper mantle. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: subduction; serpentinite; structure; eclogite; exhumation; Alps

1. Introduction

The structure and petrology of eclogite-facies terrains permit reconstruction of the burial and exhumation histories of rocks that underwent subduction. Generally, high-pressure rocks only record the evidence of peak metamorphic features and of the retrograde breakdown and hydration reactions during their way back to the surface (Ernst, 1988). While the prograde metamorphic evolution may often be partially preserved by inclusions in peak metamorphic minerals, the structural record developed during subduction is generally erased because of continuous recrystallization of rocks during prograde metamorphism. In particular, the numerous metamorphic reactions, which occur in mafic rocks during the prograde transition from blueschist-to eclogite-facies, delete most of the prograde structures. However, in hydrated ultramafic rocks the main serpentine mineral antigorite is stable over a large P–T range up to high- and ultrahigh-pressure conditions (Ulmer and Trommsdorff, 1995; Ulmer and Trommsdorff, 1999)

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and no univariant reactions occur to cause complete change in the mineral paragenesis. Provided that exhumation occurs entirely within the thermal stability field of antigorite, serpentinites are the most suitable rocks for preserving prograde subduction-related structures.

Serpentinites originate from extensive hydration of mantle rocks on the ocean floor (O'Hanley, 1996). The results from seismic studies and ocean drilling revealed that large volumes of serpentinized mantle occur at passive continental margins (Boillot et al., 1992; Boillot et al., 1989) as well as at slow spreading ridges (Cannat et al., 1995). Field based studies demonstrated that serpentine is a major mineral of metamorphosed ultramafic rocks in Alpine ophiolites (Lagabrielle and Cannat, 1990; Lemoine et al., 1987; Piccardo et al., 1980; Trommsdorff and Evans, 1974). Therefore, the common occurrence of serpentinites in the oceanic lithosphere, as well as in high-pressure meta-ophiolites from orogenic belts, suggests that these rocks can play an important role in subduction and exhumation processes.

In this paper we describe a unique sequence of Alpine structures which developed in antigorite mylonites of the Erro Tobbio (ET) ultramafic unit (Voltri Massif, Western Alps; Fig. 1). The ET-unit underwent Alpine subduction during convergence between Adria and Europe. The Alpine subduction-related metamorphism of the ET-unit entirely occurred within the antigorite stability field (Scambelluri et al., 1991, 1995) and thus structures related to its burial and exhumation can be studied. Subduction-related structures in the ET unit have been recognized by Hoogerduijn Strating and Vissers (1991) and by Scambelluri et al. (1995), who emphasized the importance of antigorite mylonites for slab rheology and for water transport to mantle depth, respectively. However, at present no data is yet available concerning the structures related to the exhumation of these rocks from eclogite-facies conditions to shallow crustal levels. It is the purpose of this paper to show overprinting relationships of structures in antigorite mylonites and to unravel their kinematics, which document a whole orogenic cycle from subduction to exhumation to continental collision.

Antigorite contains 13 wt% of structurally bound water and therefore deeply subducted serpentinites are imporant H_2O-carriers to mantle depth (Scambelluri et al., 1995; Ulmer and Trommsdorff, 1995). The high amount of water results in low density of antigorite. We emphasize the importance of buoyant antigorite serpentinites in the problem of exhumation of eclogite facies terrains.

2. Geological setting

The Voltri massif is part of the Penninic ophiolites, which represent remnants of the Mesozoic Piemont-Ligurian ocean, and is located at the transition from the Alps to the Appennine (Fig. 1). Three different units can be distinguished within the massif, all consisting of variably metamorphosed ophiolitic material and related metasediments (Fig. 1). The Erro-Tobbio unit is the uppermost unit in this nappe stack and includes mainly peridotites and serpentinites with minor amount of associated meta-gabbros, eclogites an meta-rodingites. These rock types preserve an exceptionally well documented record of exhumation from mantle conditions through rifting and exposure at the Tethys ocean floor followed by Alpine subduction and exhumantion.

The exhumation history in the Erro Tobbio unit from pre-Alpine subcontinental mantle to emplacement on the Tethyan ocean is recorded in preserved peridotite bodies (Figs. 2 and 3) and has been studied in detail by Vissers et al. (1991) and Hoogerduijn Strating et al. (1993). Most peridotites display a foliation with an associated mineral stretching lineation marked by spinel and orthopyroxene. These tectonites are cut by mylonites, which can contain plagioclase indicating retrograde decompression. Tectonites and mylonites are locally crosscut by gabbroic or basaltic dikes (Fig. 3). This mafic magmatism is related to the opening of the Jurassic Tethys and provides evidence for the shallow exposure of the mantle rocks and for the pre-Alpine nature of these early mantle structures (Hoogerduijn Strating et al., 1993; Vissers et al., 1991). The mantle minerals are partially replaced by a low-grade assemblage consisting of serpentine (chrysotile and lizardite), magnetite, chlorite, ±tremolite, ±brucite and ±phyllosilicates indicating low grade hydration near the ocean floor (Scambelluri et al., 1997).

During Alpine convergence, the rocks of the Erro-Tobbio unit underwent prograde metamorphism. A maximum temperature of about 600°C for the Alpine

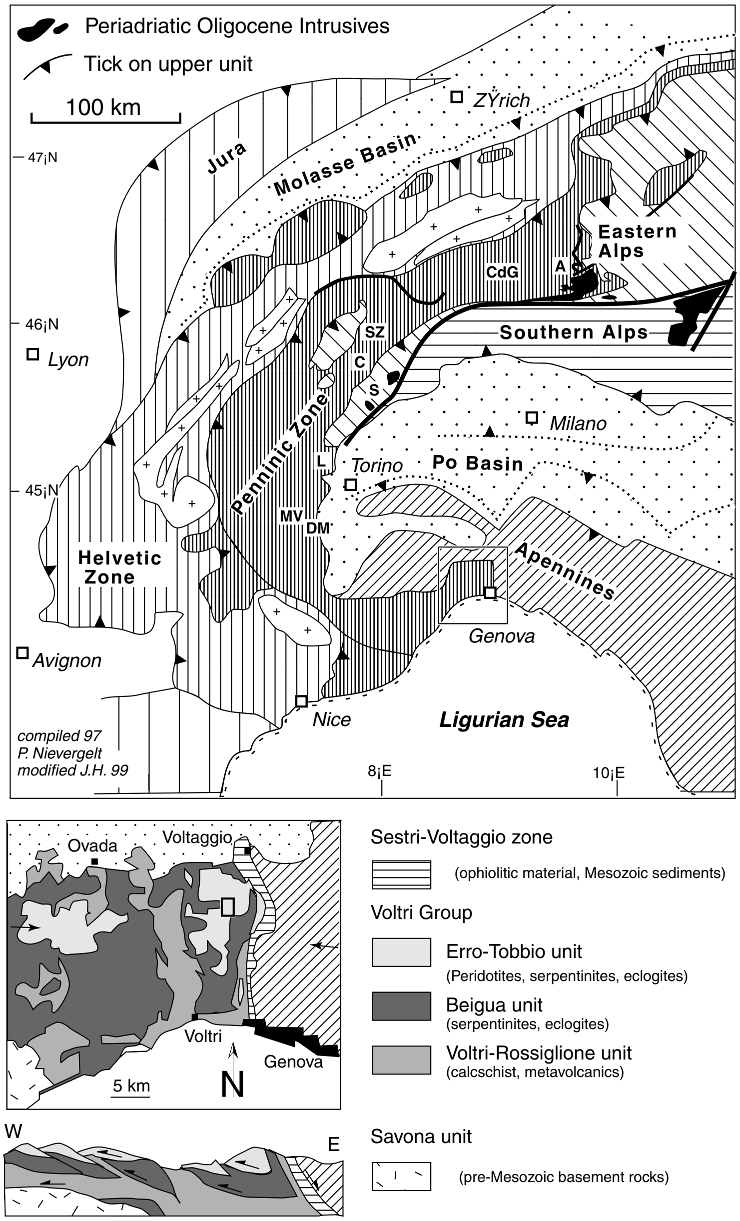

Fig. 1. Tectonic map of the Western and Central Alps. The Voltri massif is part of the Penninic zone and consists of three ophiolitic nappes derived from the Piemont-Ligurian ocean. The frame refers to the detailed map shown in Fig. 2. MV = Monviso ophiolite, DM = Dora-Maira massif, S = Sesia zone, L = Lanzo zone, C = Lago di Cignana, ZS = Zermatt-Saas ophiolite, CG = Cima di Gagnone (Cima Lunga unit), A = Avers.

metamorphism can be estimated by the stability of antigorite and titanan clinohumite. Peak pressure conditions were estimated in a mylonitic meta-gabbro with the paragenesis omphacite + chloritoid + garnet + zoisite ± talc to be 18–25 kbar (Messiga et al., 1995) indicating that the ET-unit was subducted to about 80 km depth. The rocks were finally affected by a greenschist facies metamorphic overprint, which is

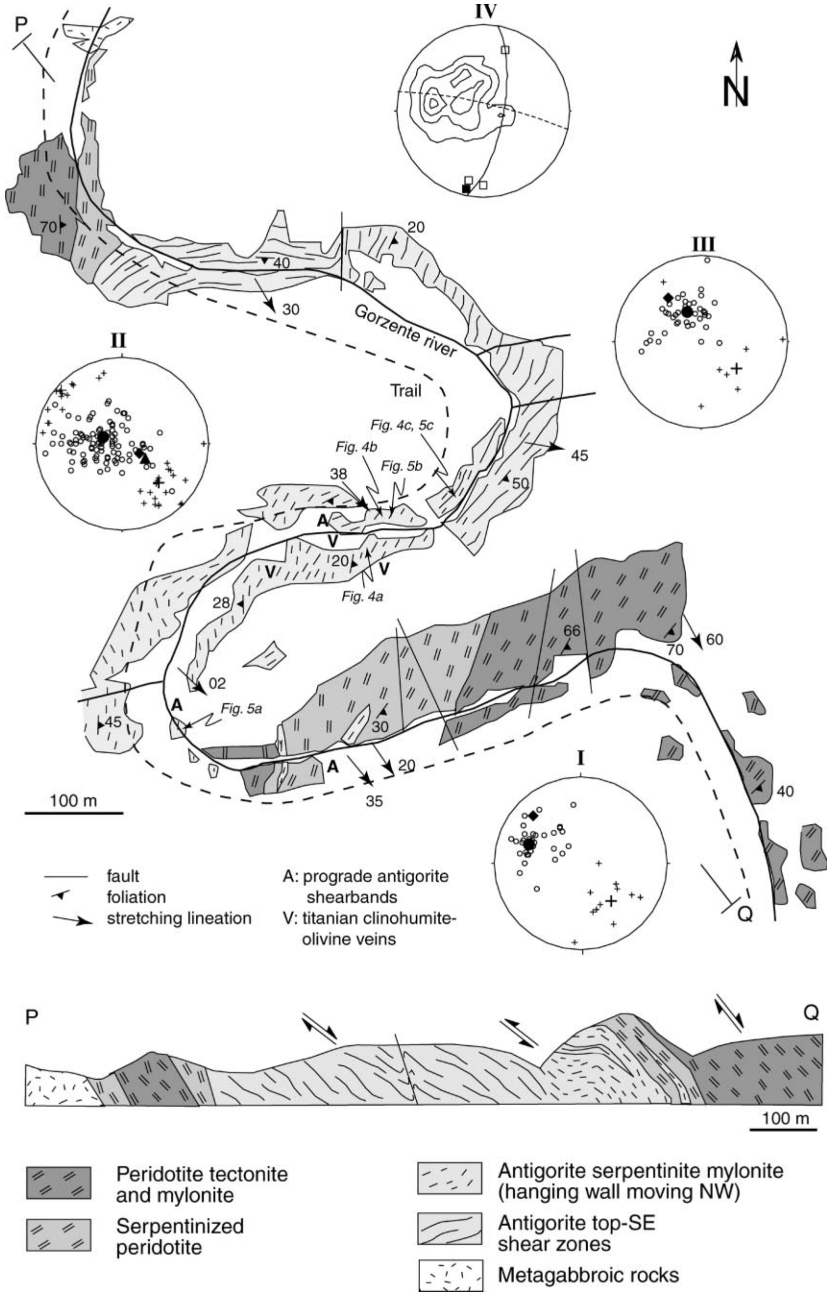

Fig. 2. Detailed structural map of the upper Gorzente river and cross section showing the relations between mantle structures (generally top-to-SE), prograde subduction related structures (top-to-NW) and early top-to-SE exhumation related structures (modified after Scambelluri et al., 1995). The location of outcrop photo (Fig. 4) and origin of samples for thin section photos (Fig. 5) are given. Structure data: crosses = lineations, circles = poles of foliations, bold cross = average of lineation, filled circles = average poles of foliations, filled diamond = average poles of shear bands and shear planes, filled triangle = average poles of olivine-titanian clinohumite veins. I: pre-Alpine structures: Shear bands dip generally steeper than foliation indicating a top-to-SSE sense of pre-Alpine shearing. II: Alpine prograde structures: The orientation of veins and shear bands indicate top-to-the-NW sense of movements. III: Alpine retrograde structures: The shear planes of the top-SE shear zones dip steeper than the foliation IV: Contour lines of foliation data (171 measurements, contoured at 1,3,5,7 times uniform; maximum density = 7.6). The variation of the foliation is due to the late stage folding. The pole (filled square) of the best fit great circle (dotted line) coincide with measured fold axis of the NW-vergent folding and lies on the average of the measured axial planes (solid line).

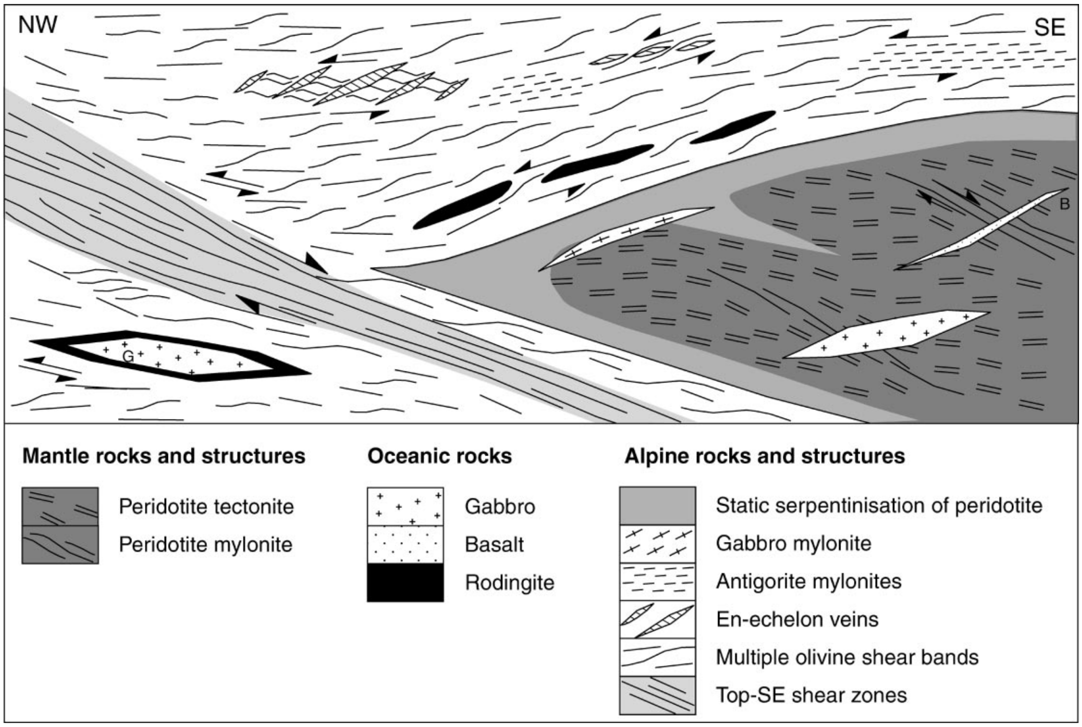

Fig. 3. Schematic summary sketch (not to scale) of the field relations showing the strong localization of deformation during the pre-Alpine as well as Alpine deformation.

related to collision of Adria with Europe (Hoogerduijn Strating, 1994). Late exhumation of the Erro-Tobbio unit in the Oligocene is documented in sedimentary breccias containing all major rock types of the Voltri massif (Hoogerduijn Strating, 1994).

3. Alpine structures and metamorphism in ultramafic rocks

Two main structural domains can be distinguished within the ultramafic rocks of the Erro-Tobbio unit (Fig. 3): (1) Peridotite bodies display pre-Alpine mantle structures and mineralogy and show partially hydrothermal alteration and static Alpine recrystallization. (2) Serpentinite mylonites and shear zones surround the peridotite bodies and record a polyphase Alpine dynamic recrystallization.

In the pre-Alpine peridotite bodies, mantle and low-grade oceanic assemblages are partially statically overgrown by an Alpine assemblage consisting of antigorite, olivine, titanian clinohumite, diopside, chlorite and magnetite. Gabbroic and basaltic dikes are frequently mylonitized (Fig. 3). Alpine structures in these peridotite bodies are restricted to a few olivine and titanian clinohumite veins (Hoogerduijn Strating and Vissers, 1991), which formed coeval with mylonitization of the mafic dikes under eclogite facies conditions.

In contrast, the surrounding serpentinite mylonites and shear zones record superposition of polyphase ductile structures (Figs. 2 and 3). Partially rodingitised mafic dikes and eclogitic metagabbros appear boudinaged in these domains indicating that deformation postdated the mafic magmatism and the subsequent calcium-metasomatism near the ocean floor. This indicates that the serpentine mylonites are related to Alpine deformation. On the basis of overprinting relationships in the serpentine mylonites (Figs. 4 and 5) we have established the following sequence of Alpine structures:

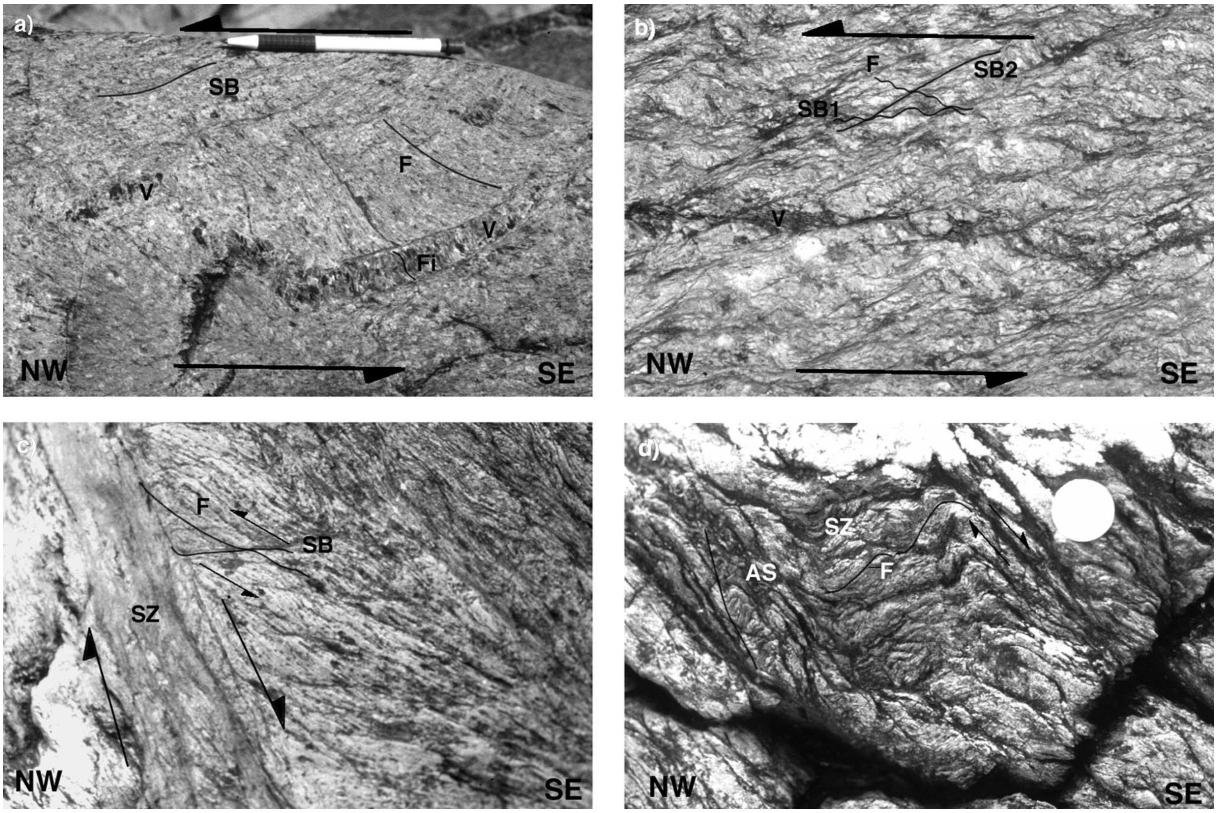

Fig. 4. Outcrop photos of Alpine structures: (a) En-echelon olivine veins (V) with fibers (Fi) and olivine bearing shear bands (SB) crosscut the antigorite mylonite foliation (F) indicating a top-to-NW sense of movement (length of photo = 30 cm). (b) A first set of olivine shear bands (SB1) is cut by a second set (SB2). These multiple shear bands indicate continuous deformation during subduction. An olivine vein (V) is boudinaged by the olivine bearing shear bands (length of photo = 15 cm). (c) A cm-wide top-SE shear zone (SZ) crosscuts the prograde structures. The orientation of the top-SE shear zone as well as the rotation of the foliation (F) into the shear zone indicate a top-to-the-SE sense of movement. The earlier formed olivine shear bands (SB), indicating a top-to-the-NW movement, are preserved in areas not affected by the S–C fabric (length of photo = 10 cm). (d) The late stage NW-vergent folding (axial surface = AS) overprints the S–C (SC) fabrics with still visible top-to-the-SE sense of shear and all previously formed structures (length of photo = 25 cm).

3.1. Subduction-related deformation

3.1.1. Antigorite mylonites

Antigorite mylonites display a slaty cleavage formed by antigorite and a stretching lineation marked by elongated magnetite. Associated shear bands are olivine-free and indicate a top-to-the-NW sense of movement (Fig. 5a). Foliation and lineation in the serpentinites are parallel to the ones in the nearby mantle tectonite (Fig. 2). The shear sense in the Alpine antigorite mylonites (top-to-the-NW) is opposite to the sense of movement in the tectonite (Fig. 2). This suggests a change in kinematics from the pre-Alpine to the Alpine structural evolution (see also Scambelluri et al., 1995). The antigorite shear bands are only preserved in restricted domains (Fig. 2).

3.1.2. En-echelon olivine veins

En-echelon veins occur in the antigorite mylonites at an angle of 20–40° (Fig. 4a) to the main foliation. The intersections of the veins with the foliation are perpendicular to the magnetite stretching lineation. The orientation of the venins (“V” in Fig. 4a), as well as locally developed mineral fibres in the veins (Fig. 4a), point to a top-to-the-NW sense of shearing. The vein paragenesis consists of olivine + titanian clinohumite + diopside + chlorite + magnetite. The presence of olivine indicates a prograde character of

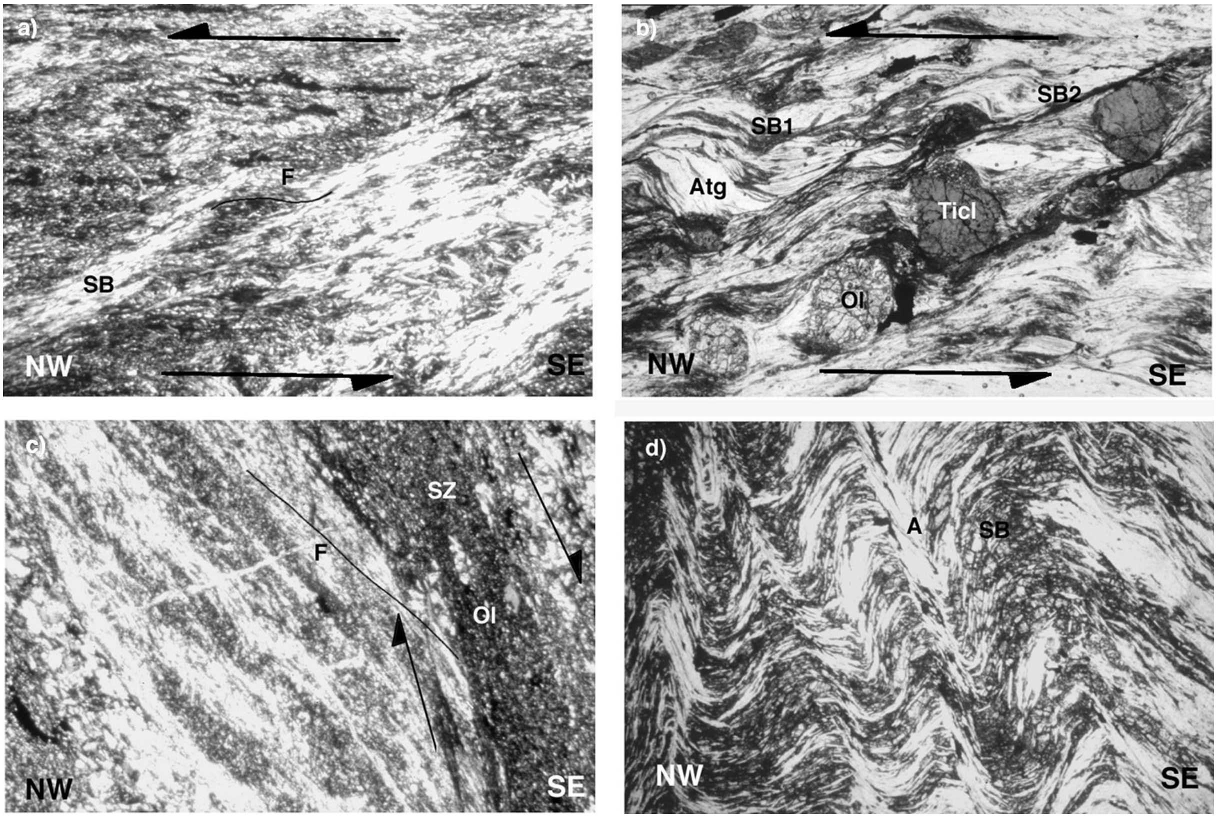

Fig. 5. Thin section photos of micro structures. (a) Antigorite shear bands (SB) in serpentine mylonites (F = foliation) indicate a top-to-the-NW sense of movement (length of photo = 5 mm). (b) Olivine (Ol) and titanian clinohumite (Ticl) originating from a vein are disrupted by olivine-bearing shear bands (SB2). Antigorite (Atg) is still stable and forms the main foliation. Deformed olivine-bearing shear bands (SB1) point to a continuous deformation in a general top-to-the-NW regime (length of photo = 5 mm). (c) Fine-grained olivine (Ol) is stable in the Top-SE shear zones (SZ) crosscutting the prograde foliation (*F*; length of photo = 2 cm). (d) Olivine bearing shear bands (SB) are overprinted by NW-vergent folds. In the axial plane of the folds, new antigorite (A) grew and olivine is not stable (length of photo = 3 mm).

the deformation with respect to olivine-free antigorite mylonites. Olivine forms through the reaction:

$$\text{Antigorite} + \text{Brucite} \leftrightarrow \text{Olivine} + \text{Water} \quad (1)$$

Which results in fluid release at temperatures of about 400–450°C (Fig. 6). Depending on the P–T trajectory of the subduction zone, this reaction can occur at pressures between 1.0–2.0 GPa, i.e. at conditions close to the blueschist-eclogite facies transition of mafic rocks. This indicates that the en-echelon veins formed during burial of hydrous ultramafic rocks (Fig. 6).

3.1.3. Multiple olivine shear bands

The antigorite mylonites and the en-echelon veins are overprinted by shear bands (Fig. 4b) in which the paragenesis antigorite + olivine + titanian clinohumite + magnetite + chlorite ± diopiside is stable. The orientation of the shear bands indicates still a top-to-the-NW sense of shear suggesting that the structures formed during a continuous process. In zones with intense shearing the veins are completely dismembered and rotated by the shear bands (Figs. 4b and 5b). In such highly deformed zones the angle between shear bands and foliation decreases. Consequently, a second set of olivine shear bands with a greater angle to the foliation developed (Fig. 4b). These multiple olivine shear bands provide evidence for a continuous deformation (Platt and Vissers, 1980) in an overall top-to-the-NW sense of shear. Intense deformation related to a top-to-the-NW sense of

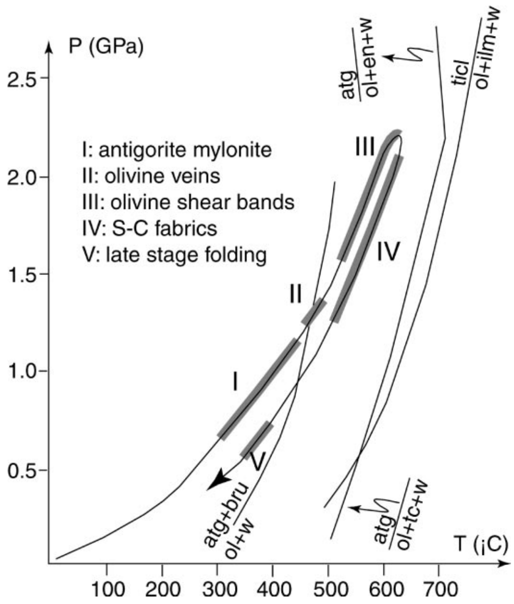

Fig. 6. Pressure–temperature-deformation diagram for the Erro-Tobbio unit. Reactions taken from (a) Johannes (1968); (b) Ulmer and Trommsdorff (1995) and (c) Weiss (1997).

movement has been observed in the whole Voltri massif and occurs also in deformed eclogites (Hoogerduijn Strating, 1994). Therefore, the multiple olivine shear bands most probably formed close to peak metamorphic conditions of about 600°C and 2.0–2.5 GPa (Fig. 6). The prograde evolution from ocean floor metamorphism to eclogite facies conditions demonstrates that structures in the serpentinites were formed during subduction. This is further supported by structural observations in mafic rocks. Gabbro dikes within weakly serpentinized peridotite bodies often show a mylonitic eclogitic foliation consisting of omphacite, garnet and zoisite. This indicates that under the prograde metamorphic conditions the peridotite bodies are more competent than the gabbros. On the other hand, gabbros and rodingites form boudins in antigorite mylonites indicating that serpentinites are mechanically weak compared to mafic rocks. The heterogeneous distribution of serpentinite mylonites and peridotite bodies in the Erro Tobbio unit (Fig. 3) indicates that fluid flow during subduction was localized and probably reflects the pre-subduction distribution of water inherited from hydrothermal alteration of ultramafic rocks on the ocean floor.

3.2. Exhumation-related deformation

3.2.1. Top-SE shear zones

Discontinuous cm-wide, meter-long shear zones crosscut all previous fabrics (Fig. 4c) and are dominant in the northern part of the mapped area (Fig. 2). The spacing between the shear zones is about 10 cm. The shear zones dip generally steeper to the SE than the main cleavage (Fig. 2). The rotation of the previous antigorite foliation into the shear zones indicates a top-to-the-SE sense of movement (Figs. 4c and 5c). In the domains unaffected by this shearing, the earlier formed olivine shear bands, indicating a top-to-the-NW sense of movement, are still preserved (Fig. 4d). The mineral assemblage is the same as in the multiple olivine shear bands and the grain size is generally in the order of a few microns (Fig. 5c). The top-SE shear zones have an opposite sense of shear with respect to the subduction-related deformation and formed after the peak pressure top-to-the-NW olivine shear bands, but are affected by later greenschist facies NW vergent open folding. This indicates that the top-SE shear zones developed during the exhumation of the eclogite-facies rocks (Fig. 6).

3.2.2. Late stage NW-vergent folding

The latest ductile structure of regional importance is an open crenulation with an axial plane dipping towards SE (Fig. 2). The general SE-dip of the foliation in the mapped area is caused by this NW-vergent folding (Fig. 2). Along axial planar cleavage planes, recrystallization of antigorite + diopside + chlorite + magnetite in ultramafic rocks and albite + amphibole + epidote + chlorite in mafic rocks indicates greenschist facies conditions for this deformation (Fig. 6).

3.2.3. Brittle structures

The ductile structures mentioned above are crosscut by faults often indicating thrusting top-to-the-NW (Fig. 2). However, also normal faults with top-to-the-SE sense of movement were observed which could be related to final exhumation of the ET-unit (Hoogerduijn Strating, 1994). Serpentine gouges occur along strike slip faults (Hoogerduijn Strating and Vissers, 1994).

4. Discussion

The detailed structural and petrographic investigation of serpentinite mylonites in the Erro Tobbio unit reveals that antigorite is a stable phase during the entire cycle of Alpine subduction and exhumation. This permits insight into deformation regimes in subduction zones and provides new constraints for subduction as well as for exhumation of high-pressure rocks.

4.1. Deformation during subduction

Most of the subduction-related deformation is strongly localized and accommodated in the incompetent serpentinite mylonites whereas the competent peridotite bodies display little or no Alpine ductile deformation. Even within the serpentinite mylonites strain localization is observed. The prograde structures survived in some domains because the later top-SE shear zones occur in localized domains. Thus, the structural record demonstrates that strain localization is an important factor controlling the rheology of ultramafic rocks during a whole orogenic cycle. Hoogerduijn Strating and Vissers (1991) concluded that in the example of the Voltri Massif shear stresses are controlled by the rheology of serpentinite mylonites rather than by the one of a basalt dominated slab. Strain localization in subducted serpentinite mylonites has consequences for accurate modelling of subduction zones because modelling parameters such as shear stress strongly depend on the rheology of and the strain distribution within the subducted slab.

The antigorite mylonites, the olivine veins and the olivine shear bands all developed in a simple shear-dominated deformation regime with top-to-the-NW kinematics. These structures formed under increasing metamorphic grade and reflect continuous non-coaxial deformation during ongoing subduction (Fig. 7). The top-to-the-NW sense of movement during subduction suggests a dip of the slab below the Adriatic lithosphere. The occurrence of low-grade metamorphic, obducted ophiolites on the Adriatic margin in the adjacent Apennine units indicates that the subduction started in an intra-oceanic setting (Hoogerduijn Strating, 1994). However, this hypothesis is difficult to prove because the contact to the overlying Sestri-Voltaggio zone (Fig. 1) is a post-collisional normal fault (Hoogerduijn Strating, 1994), which removed the original hanging wall of the subduction zone.

Antigorite mylonites are the dominant subduction structures down to $\sim$50 km depth (Fig. 7). Olivine veins indicate fracturing of the serpentinite during fluid release which occurred at the olivine-in dehydration reaction (1) (Hoogerduijn Strating and Vissers, 1991; Scambelluri et al., 1991). Kirby et al. (1996) described that shallow earthquakes in subduction zones often occur on top of the slab and suggested that these earthquakes are triggered by dehydration reactions. Thus, the observed hydro-fracturing may occur periodically on a very short time scale and may be responsible for small earthquakes on top of the slab (Fig. 7). From 50 to 80 km depth multiple sets of olivine shear bands formed (Fig. 7) providing evidence for continuous deformation and strain localization. Experimental investigations of serpentine dehydration showed that strain was localized along very fine-grained zones of olivine possibly indicating diffusion-controlled recrysallization mechanisms (Rutter and Brodie, 1987). Natural examples of such olivine-rich shear zones are probably very weak due to continuous solution and precipitation of olivine in the presence of a fluid phase. This implies that fluids produced by reaction (1) were (partially) trapped in the serpentinite mylonites and enhanced continuous solution and precipitation of olivine. δ^{18}O values of antigorite vary considerably in adjacent shear zones indicating that isotopic equilibrium was not achieved in the shear zones (Vallis et al., 1997). This points to a limited fluid flow at low fluid/rock ratio. The observation that hydrous serpentinite mylonites surround anhydrous peridotite bodies further indicates that fluid flow was limited and concentrated in the mylonites during subduction. Therefore, the serpentinite mylonites are not only zones with highly localized deformation but also zones of focussed fluid flow.

4.2. Significance of shear sense inversion

The top-SE shear zones occur between peak eclogitic deformation and greenschist facies conditions and are most probably related to retrograde metamorphism (Fig. 6). They display an opposite sense of movement with respect to the prograde subduction-related structures. We suggest that the shear sense inversion indicates a change in the position of the rocks relative to the

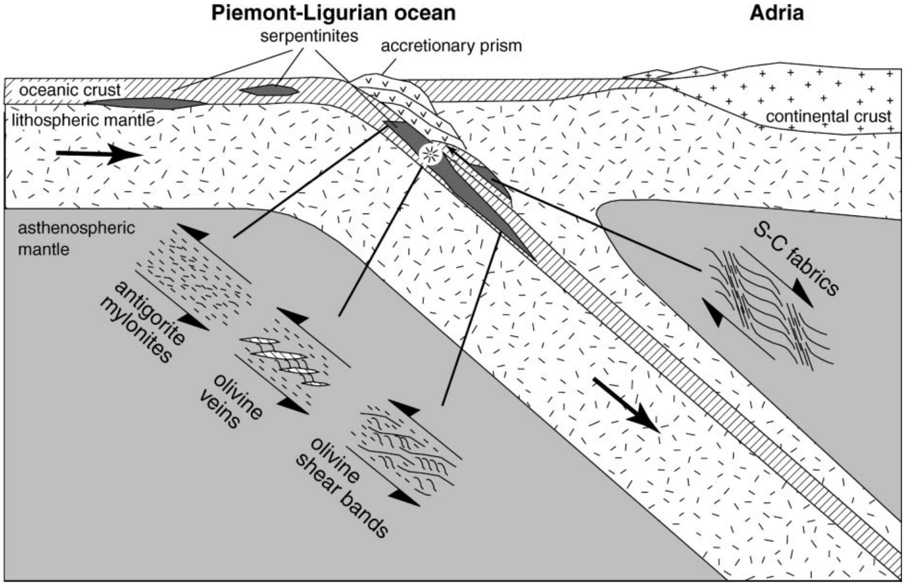

Fig. 7. Schematic sketch of deformation during subduction and exhumation based on the observed structures in the serpentinite mylonites of the Erro-Tobbio unit. Any subducted rock has to be detached from the down going slab in order to get exhumed. The shear sense during exhumation must be opposite to the one of subduction. The shear sense of prograde structures suggests subduction below the Adriatic plate.

downgoing slab. During the prograde metamorphism the serpentinites are situated within the downgoing slab representing the footwall of subduction (Fig. 7). During an advanced stage of subduction, the rocks on top of the slab are sheared off and accreted to the hanging wall of the subducting slab. The relative movement of the block undergoing exhumation to the overlying mantle wedge is opposite to the one of subduction (Fig. 7). Thus, from structural and metamorphic points of view, the shear sense inversion indicates initiation of exhumation. Up to now no structural data on the exhumation from eclogite to greenschist facies metamorphism has been reported for the Erro-Tobbio unit (e.g. Hoogerduijn Strating, 1994). The top-SE shear zones described here most probably represent this missing link in the Alpine structural evolution of the Voltri massif.

The top-SE shear zones occur in restricted domains only (Figs. 2 and 3) indicating strain localization during exhumation. Strain localization has often been proposed to explain the lack of pervasive retrograde deformation developed during the uprise of high- and ultra-high pressure rocks to the surface (e.g. Lago di Cignana, van der Klauw et al. (1997); Tauern Window, Stöckhert et al. (1997); Crete, Thomson et al. (1999)). However, the structures, which actually accompany the initial stages of exhumation are generally not documented. The localised top-SE shear zones in the ET-unit may be one of the few that preserved early exhumation. These structures may help to constrain models on the exhumation of high-pressure rocks. The observed shear sense inversion from subduction to exhumation support “extrusion type” models, which have been proposed on the basis of geometric arguments mainly from the study of exhumed eclogite facies continental crust (Michard et al., 1993; Schmid et al., 1996; Liou et al., 1997). Another model consistent with our structural data explains exhumation by extension caused by roll-back of the subduction zone (Rawling and Lister, 1999).

4.3. Importance of serpentinites for the exhumation of eclogites

In a review paper about the exhumation of high-pressure rocks Platt (1993) pointed out that buoyancy is the only effective force to exhume rocks from deeply subducted levels to the base of the crust. This is in agreement with the physical modelling of Chemenda et al. (1995) where the main force acting

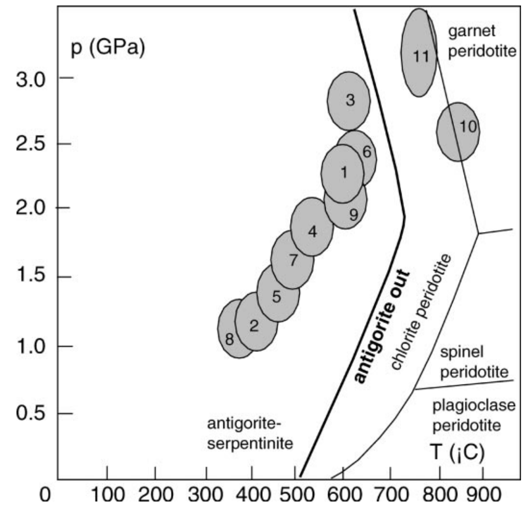

Fig. 8. All P–T estimations from exhumed Alpine eclogites derived from ophiolites (1–9) plot within the stability field of antigorite (for locations see Fig. 1). This observation strongly suggests that serpentinites are involved in the exhumation of eclogites. Eclogites within subducted continental crust or crustal mélange can record higher P–T conditions as for example the Cime di Gagnone eclogites in the central Alps (10). Units and source of p–T conditions: 1–7 Western Alps (1) Erro-Tobbio (Messiga et al., 1995); (2) Beigua unit (Messiga and Scambelluri, 1991); (3) Lago di Cignana UHP-unit, Saas-Zermatt, (Reinecke, 1991); (4) Saas-Zermatt, ophiolite (Fry and Barnicoat, 1987); (5) Monviso, (Lardeaux et al., 1987); (6) Monviso, (Messiga et al., 1999); (7) Lanzo (Kienast and Pognante, 1988); (8) Central Alps, Avers Bündnerschiefer (Ring, 1992); (9) Eastern Alps, Tauern window (Holland, 1979); (10) Cime di Gagnone, Cima Lunga unit (Heinrich, 1986); (11) Cima Lunga unit (Nimis et al., 1999). Antigorite-out boundary from Ulmer and Trommsdorff (1995).

against the pushing/pulling from the down-going slab is buoyancy. As soon as buoyant rocks get sheared off from the down-going slab they start exhumation unless buoyancy is balanced by friction. The oceanic crust mainly consist of mafic rocks which transform to eclogites during subduction thereby changing the density from about 3.0 to 3.5 g/cm^3. They are denser than average mantle rocks (3.3 g/cm^3) and thus exhumation of these rocks is not likely. England and Holland (1979) proposed from studies of Tauern window eclogites, that associated metacarbonates derived from oceanic sediments may be an effective carrier in exhuming dense eclogites. However, the volume of metacarbonates in high-pressure terrains is probably too small to be a significant factor in exhuming large eclogite bodies. We propose that ultramafic rocks can play a key role in the exhumation of dense eclogites. Hydrous ultramafic rocks still contain stable antigorite at eclogite facies conditions as demonstrated by this and other field based studies, and by laboratory experiments (Scambelluri et al., 1995; Widmer, 1996; Ulmer and Trommsdorff, 1995). Antigorite serpentinites have a density of about 2.75 g/cm^3 and are extremely buoyant with respect to peridotites and eclogites. This large density difference permits exhumation of dense eclogites that are attached or included as boudins in the serpentinites. The ET-unit consist approximately of ~65% variably serpentinized peridotites, ~30% serpentinites and 5% eclogites and eclogitic metagabbros with an estimated density of 3.2, 2.8 and 3.5 g/cm^3, respectively. This results in a bulk density for the ET-unit of about 3.1 g/cm^3, which is significantly lower than dry mantle rocks. The density contrast is considerably higher in the underlying Beigua unit (Fig. 1), which also underwent eclogite facies metamorphism (Messiga et al., 1995). The Beigua unit consist of ~90% serpentinite and ~10% eclogites and eclogitic metagabbros resulting in an average density of about 2.9 g/cm^3. These examples demonstrate that serpentinites are crucial in lowering the bulk density of exhumed high-pressure terrains below the mantle value.

The comparison of P–T conditions of Alpine eclogites with serpentine stability further supports the importance of serpentinites for eclogite exhumation (Fig. 8). All eclogites derived from remnants of oceanic crust in the Alps plot within the serpentine stability field. The highest metamorphic conditions are reported from Lago di Cignana in the Saas-Zermatt unit (Fig. 1) where coesite bearing metasediments indicate maximum conditions of 630°C and 2.8 GPa (Reinecke, 1991). Field relations and petrologic studies show that antigorite was stable in the Saas-Zermatt unit during subduction and exhumation (Widmer, 1996), in agreement with the experiments on antigorite stability by Ulmer and Trommsdorff (1995). In the western Alpine chain, the lack of eclogites derived from subducted oceanic crust recording metamorphic conditions beyond serpentine stability suggests that after serpentine breakdown there is no buoyant material left helping to exhume eclogites. Therefore we propose that serpentinites are the most important carrier material for the exhumation of eclogites derived from oceanic crust.

Serpentinites did not always survive Alpine subduction (Fig. 8). In the Adula nappe, which is situated more externally within the Penninic domain of the Alps (Fig. 1; Schmid et al., 1996), garnet peridotite lenses with associated eclogites occur (Evans and Trommsdorff, 1978). At Cima di Gagnone, these lenses contain boudins of meta-rodingite and are associated with high-pressure ophicarbonates demonstrating that the garnet-peridotites originated from serpentinites (Evans and Trommsdorff, 1978; Pfiffner and Trommsdorff, 1998; Trommsdorff et al., 2000). The metamorphic conditions at Cima di Gagnone are estimated to be in the range 800°C, 2.5 GPa (Evans and Trommsdorff, 1978; Heinrich, 1986) to 745 ± 35°C, 3.2 ± 0.3 GPa (Nimis et al., 1999) and are clearly beyond serpentine stability (Fig. 8). Transition from serpentinized high-pressure ultramafic rocks, such as those of the western Alpine ophiolite sequences, to garnet peridotites similar to those of Cima di Gagnone, is accompanied by dramatic water loss and by strong increase in the mean density of the ultramafic components in the subducting slab. However, the Adula nappe is a lithospheric melange originating from a continental margin setting which formed during continental collision (Trommsdorff et al., 2000). It is possible that to some extent crustal rocks were subducted to great depth providing a carrier for garnet-peridotites and eclogites. Subduction of continental crust has been observed at several places in the Alps such as the Sesia-Lanzo zone (Compagnoni et al., 1977; Pognante et al., 1989), Dora-Maira massif (Chopin et al., 1991; Michard et al., 1993) and the Adula nappe (Schmid et al., 1996; Meyre et al., 1999). The ascent of buoyant continental crust thus represents another effective process to exhume eclogites.

5. Conclusions

Antigorite mylonites in the Erro-Tobbio unit in the Voltri massif document structures formed during a whole tectonic cycle from subduction to exhumation of hydrated mantle rocks. Preserved prograde structures permit to reconstruct the deformation regime in subduction zones. Prograde deformation is characterized by continuous shearing, which is strongly localized in mylonites surrounding nearly undeformed mantle peridotites. The presence of anhydrous peridotite bodies within hydrous serpentinite mylonites indicates that fluids were localized and focussed in the highly deformed mylonites. These observations provide constraints for more sophisticated thermal and rheological models of subduction zones.

Shear sense inversion, documented in discontinuous top-SE shear zones, monitors the change of deformation from footwall to hangingwall in the subduction system related to the onset of exhumation of the serpentinites. Serpentinites have a low density at mantle depth. The density difference to the surrounding rocks favors buoyant exhumation, and serpentinites are the most likely carriers of associated dense eclogites. P–T conditions of Alpine eclogites derived from oceanic crust are always within the stability field of antigorite. This observation suggests that the presence of serpentinites is a prerequisite for the exhumation of oceanic crust subducting to eclogite facies. Insight into greater depth of subduction and exhumation is possible in continental collision zones where deeply subducted buoyant continental crust act as a carrier to exhume eclogites and garnet peridotites.

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