

Ophiolite mélange zone records exhumation in a fossil subduction channel

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ABSTRACT

Recent models propose that the exhumation of high-pressure rocks occurs by means of return flow inside a low-viscosity channel of serpentinite situated between the plates. To test this hypothesis, we investigated a serpentinite mélange in the Western Alps, which contains exotic mafic and metasedimentary tectonic blocks, recording heterogeneous metamorphic evolutions and variable high-pressure ages. The peak metamorphic conditions range from eclogite- to garnet-blueschist-facies. The structural evidence and the pressure-temperature paths of the different blocks suggest coupling between blocks and matrix, at least in the blueschist facies. ^{39}Ar - ^{40}Ar dating indicates eclogite-facies peak at ca. 43 Ma and blueschist-facies peak at ca. 43 and 40 Ma in different blocks, respectively. These data point to diachronous metamorphic paths resulting from independent tectonic evolutions of the different slices. We therefore propose that this mélange formed during exhumation of subducted rocks equilibrated at different depths inside a subduction channel. This mechanism can be extended to other serpentinite mélanges in the Alps and other orogens (e.g., the Cyclades, the Coast Ranges of California) for which a growing heterogeneity in the timing of metamorphic equilibration and of pressure-temperature paths can be expected with further investigations.

Keywords: subduction channel; tectonic mélange; Western Alps; high-pressure, ^{39}Ar - ^{40}Ar geochronology

INTRODUCTION

The problem of exhumation of high- (HP) and ultrahigh-pressure (UHP) rocks has been tackled by field and petrologic studies (e.g., Platt, 1993; Duchêne et al., 1997a; Hermann et al., 2000) as well as by numerical and analog modeling (e.g., Cloos, 1982; Chemenda et al., 1996; Gerya et al., 2002). Past studies emphasize that i) exhumation occurs at (high) rates on the order of plate velocities and usually while subduction is still active, and ii) serpentinites possibly act as buoyant carriers of HP rocks (e.g., Guillot et al., 2001; Hermann et al., 2000). In particular, recent numerical models (Gerya et al., 2002; Stöckhert and Gerya, 2005) propose that water loss from the subducting plate produces a low-viscosity serpentinite channel in the overlying mantle wedge, where a forced return flow of subducted materials is established. A predictable consequence is the presence of HP and UHP rocks with complex structural relationships, different pressure-temperature (PT) paths and ages within subduction channels.

This prediction is not yet confirmed by geological data from exhumed subduction complexes. So far, the exhumation of HP rocks in different tectonic settings (e.g., the Franciscan Complex, Cloos, 1982; Anczkiewicz et al., 2004 and cited references; the Cyclades, Engi et al., 2005; Marschall et al., 2006; the Alps,

Gerya et al., 2002; Engi et al., 2005) has been attributed to return flow in low density channels mostly based on petrologic and geochemical evidence. However, a detailed field survey, together with petrology and geochronology of a serpentinite mélange including blocks of HP rocks recording variable PT conditions is still lacking. Here we present the study of a tectonic mélange in the Western Alps where we identify a link between deformation of the blocks and of the matrix and demonstrate that the lenses exhibit different PT paths and diachronous metamorphic evolutions, consistent with the chaotic incorporation in a subduction channel. The same mechanism may be responsible for development of other meta-ophiolitic mélanges in orogenic belts worldwide.

GEOLOGICAL AND STRUCTURAL SETTING

The studied mélange outcrops in the Ligurian-Piemontese HP ophiolites (Voltri Massif *Auct.*, Figure 1). The ophiolites consist of serpentinites with metagabbros and metabasites, metasediments and peridotites and are exposed along the whole Western Alpine belt. Units with peak eclogite (450–500 °C and 13–20 Kbars; Liou et al., 1998) or blueschist (400 °C and 12 Kbars; Desmons et al., 1999) alpine metamorphism are associated along complex structures reworked by greenschist facies tectonics during Adria-Europe collision (Capponi and Crispini, 2002).

The mélange (Figure 1A) is hosted by tectonized serpentinites and consists of a schistose chlorite-actinolite matrix enclosing meter-scale blocks of metagabbros, metabasites, metasediments and serpentinites. Composition of the matrix likely results from exchanges of Ca, Fe and Al from the blocks and Mg from the serpentinite. The mélange underwent a polyphase deformation with at least three folding events (D1/D2 - rarely distinguishable because of convergence in style and strong transposition - and D3); the blocks and the matrix were tectonically associated at least from D2. The D1/D2 mylonitic axial plane foliation is WNW-ESE-striking, ENE-dipping, and is partly reoriented by later D3 folds. The D1/D2 tight folds are strongly non-cylindrical, with hinge lines forming a girdle on the axial plane. The D1/D2 schistosity in the matrix is characterized by a greenschist facies chlorite + actinolite + apatite + sphene + ores $\pm$ epidote $\pm$ rutile assemblage. Relics of Na-amphibole point to the occurrence of an older blueschist facies foliation. These structures likely reflect a phase of subhorizontal shortening. D3 folds are sub-cylindrical tight to open folds; their axial plane-foliation has a NNW-SSE strike, steeply dipping to the W (Figure 1B) and locally transposes the previous structures, representing the most evident foliation in the field.

PETROGRAPHY AND PT EVOLUTION OF THE MÉLANGE BLOCKS

Striking features of the mélange blocks are: (i) the exotic nature with respect to the country rocks and locally to the whole Voltri Massif; (ii) the different peak PT conditions, ranging from eclogite to blueschist-facies, in some case after prograde lawsonite-blueschist facies equilibration.

Eclogite-facies rocks are either metabasites with typical garnet + omphacite + rutile assemblage or mafic quartzschists with alternating layers of glaucophane + garnet + phengite + quartz + apatite and aegirine-augite + garnet + phengite ($\text{Si}^{4+} = 3.65\text{--}3.78$ p.f.u.) + quartz $\pm$ glaucophane (sample C46). Peak blueschist-facies metabasites and metasediments show a Na-amphibole + almandine-rich garnet + phengite ($\text{Si}^{4+} = 3.37\text{--}3.58$ p.f.u.) assemblage (samples VR81, CP2); garnet is then overgrown by epidote. Locally (sample C9), aggregates of phengite + chlorite + biotite $\pm$ paragonite $\pm$ clinozoisite are interpreted as pseudomorphs after prograde lawsonite (e.g., Ballèvre et al., 2003); Na-amphibole grows in

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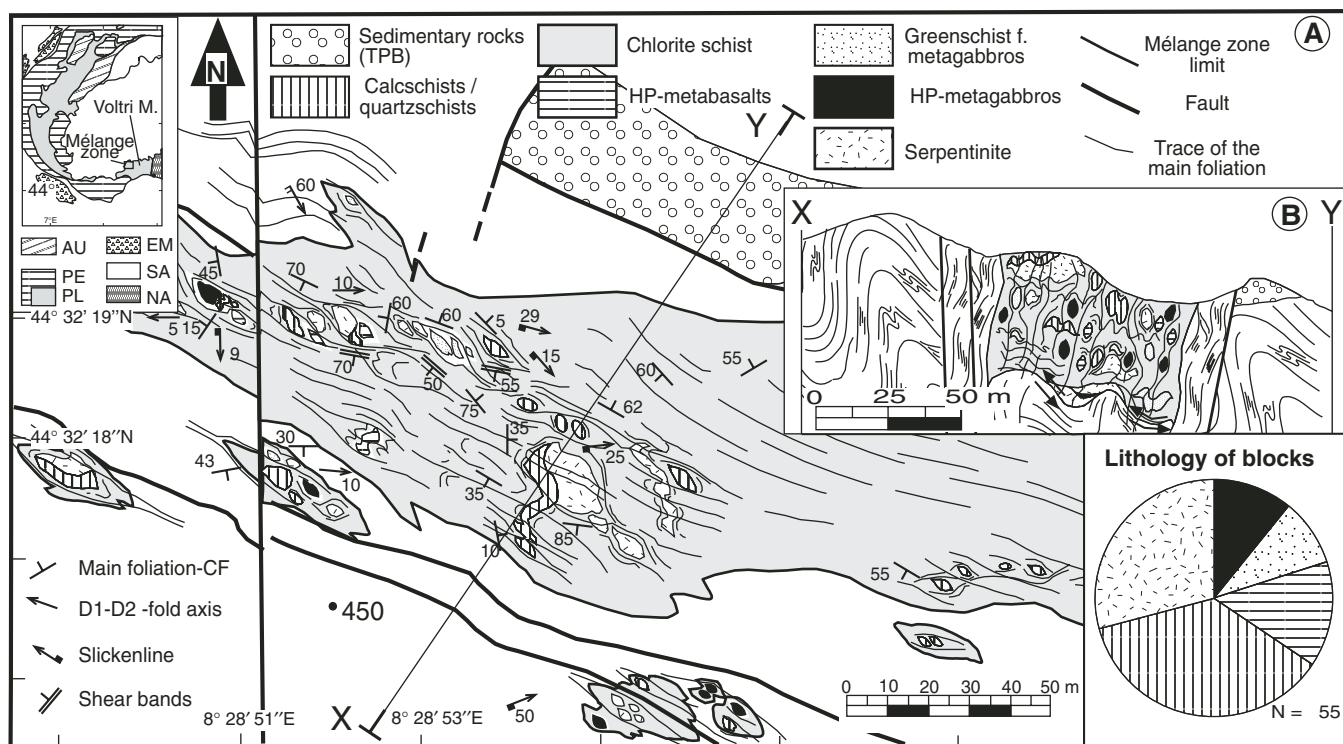


Figure 1. A: Geologic structural map of the mélangé; inset is a tectonic sketch map of Western Alps; AU—Austroalpine Units; PE—Penninic Units; PL—Piemont-Ligurian Units; EM— External massifs; SA—Southern Alps; NA—Northern Apennines. B: Section across mélangé.

the strain shadows around the pseudomorphs. Other mélangé blocks are metagabbros with synkinematic assemblages of either omphacite + lawsonite or omphacite + epidote and greenschist-facies metagabbros with no HP relics.

We chose four representative samples (C46, VR81, CP2 and C9) for detailed petrology and geochronology. To check that the different metamorphic assemblages are achieved at different PT and are not an effect of varying bulk-rock compositions, we calculated the relative pseudosections, which display the stable assemblages for a specific bulk composition in a PT grid (Figure 2). We adopted the software THERMOCALC and the system CNFMASH, following the approach of Carson et al. (1999). Peak eclogite-facies sample C46 (Figure 2A) equilibrated in the small trivariant field garnet + omphacite + Na-amphibole + paragonite. During exhumation it crossed the blueschist-facies field and the chlorite- and clinozoisite-bearing fields, since no Ca-amphiboles have been detected.

Sample VR81 equilibrated at blueschist-facies peak conditions, inside the large quadrivariant garnet + Na-amphibole + paragonite field (Figure 2B). Contouring this field for $x(\text{gl}) = \text{Fe}/(\text{Fe}+\text{Mg})$ and considering the Na amphibole coexisting with garnet (the texturally oldest amphibole), we constrain the maximum PT conditions ever achieved by the sample.

Sample C9 records peak conditions in the garnet + Na-amphibole + paragonite field (Fig.

2C). Prograde lawsonite (now pseudomorphed) was probably stable with garnet, mica, Na-amphibole and chlorite because of the presence of Na-amphibole near the rims of the pseudomorphs and of garnet porphyroclasts; chlorite was probably consumed during prograde reactions. Considering $x(\text{gl})$ and $n(\text{gl}) = \text{Na}/(\text{Na}+\text{Ca})$ of the Na-amphibole we refined the PT conditions of this assemblage (starred area in Fig. 2C). Transition to the peak assemblage was probably nearly isobaric, because no relic kyanite has been detected in this sample. Absence of Ca-amphibole points to a retrograde path characterized by cooling during uplift.

Therefore all the retrograde PT paths apparently converge in the blueschist facies field, ~14–15 Kbars and 500–530 °C (Figure 2); this agrees with the structural data and points to a coupling between blocks and matrix in the blueschist facies field.

GEOCHRONOLOGY

^{39}Ar - ^{40}Ar step-heating analyses (Table DR1 in the GSA Data Repository¹) were performed with a Micromass 5400 static mass spectrometer at

¹GSA Data Repository item 2007122, Table DR1 (Argon step-heating analyses and coordinates of the geochronology samples) and Figure DR1 ($^{36}\text{Ar}/^{40}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$ isochron plots), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Activation Laboratories Ltd. (Ontario). VR81 has been analyzed with a MAP[®] 215–50B mass spectrometer at the University of Bern. Since phengites which escape retrograde recrystallization usually retain their formation ages (Di Vincenzo et al., 2004 and cited references), we selected the samples C46 (eclogitic quartzschist, Fig. 3A), CP2 and VR81 (blueschist metabasites, Figs. 3B, 3C) as they are characterized by single-generation, compositionally homogeneous phengites. This enabled us to attribute the ^{39}Ar - ^{40}Ar ages of micas to a specific metamorphic equilibration (see Villa, 1998; Vance et al., 2003; Federico et al., 2005; Di Vincenzo et al., 2004; 2006 for discussion on the interpretation of ^{39}Ar - ^{40}Ar data).

All samples yielded saddle-shaped age spectra with well-behaved “plateaus” at intermediate temperatures. Ca/K ratios are low (0.016–0.04 for C46, 0.03–0.13 for CP2 and 0.008–0.056 for VR81) for plateau points. The low and high temperature points show elevated Ca/K values, supporting the presence of other, mainly alteration phases. Only points with low Ca/K ratios have been plotted in an isochron plot (Fig. DR1). They define regression lines with atmospheric intercepts. We consider the resulting ages as geologically meaningful and indicative of the peak metamorphic stage. The ages are 43.2 ± 0.5 Ma for sample C46 (eclogite equilibration), 43.4 ± 0.5 Ma for sample CP2 (blueschist equilibration) and 39.95 ± 0.37 Ma for sample VR81 (blueschist equilibration).

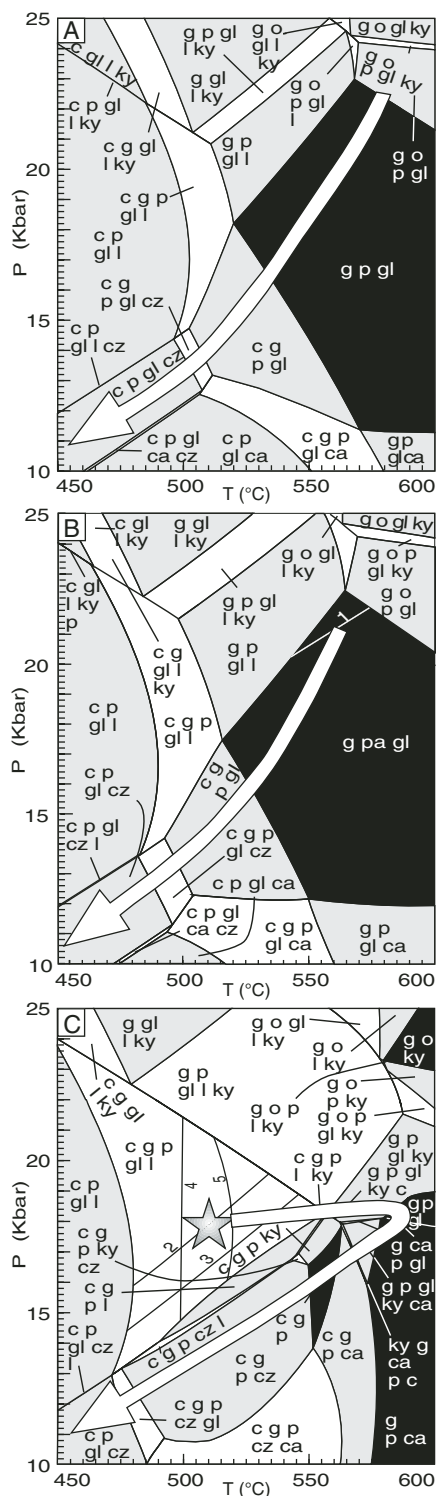


Figure 2. PT pseudosections in the CNFMASH system (+q +H₂O). C—chlorite; P—paragonite; GL—glaucophane; L—lawsonite; KY—kyanite; O—omphacite; G—garnet; CZ—clinozoisite; CA—Ca-amphibole. A: sample C46 (Al₂O₃: CaO: MgO: FeO: Na₂O = 24.71: 7.00: 19.47: 35.37: 13.45). B: sample VR81 (Al₂O₃: CaO: MgO: FeO: Na₂O = 29.66: 9.37: 13.38: 36.08: 11.51); 1: x(gl) = Fe/(Fe+Mg) = 0.570. C: sample C9 (Al₂O₃: CaO: MgO: FeO: Na₂O = 39.15: 16.52: 7.78: 29.86: 6.69); 2: n(gl) = Na/(Na+Ca) = 0.900; 3: n(gl) = 0.880; 4: x(gl) = 0.600; 5: x(gl) = 0.550.

MODEL OF EXHUMATION

Pseudosections prove that the different assemblages are not due to varying bulk-rock compositions and that the mélangé blocks actually equilibrated at variable peak and prograde metamorphic conditions (Figure 2). The structural analysis suggests that the blocks and the matrix were associated during the greenschist D2 deformation phase: the presence of Na-amphibole relics along the D2 schistosity is strong evidence that their coupling was at least accomplished in the blueschist facies.

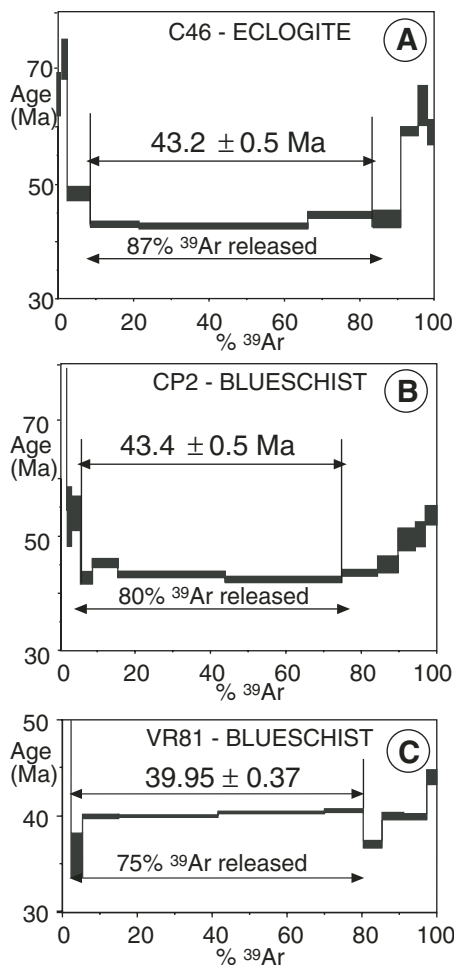
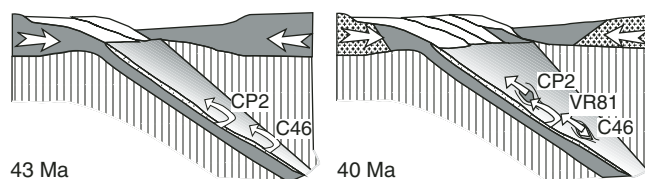


Figure 3. ³⁹Ar-⁴⁰Ar spectra; arrows highlight steps with homogeneous chemical signature used to calculate weighted ages ($\pm 1\sigma$ error); corresponding percentage of degassing is indicated.

Figure 4. Sketch reconstruction of the tectonic evolution of the mélangé (not to scale): At 43 Ma, samples CP2 and C46 were torn away from the slab and incorporated in the subduction channel; 3 m.y. later, another blueschist block (VR81) was extracted from the slab while the older fragments were being exhumed.



³⁹Ar-⁴⁰Ar dating shows that the different lenses underwent eclogite-facies metamorphism at ca. 43 Ma and peak blueschist-facies metamorphism at ca. 43 and ca. 40 Ma, respectively. These results prove that each block records a single peak stage during a subduction loop and that blocks underwent diachronous evolutions. Moreover, all retrograde PT paths are characterized by cooling on decompression (Figure 2), suggesting a physical upward motion parallel to the subducting plate.

Our geochemical and petrological data indicate that this mélangé formed in a subduction channel, consistent with the model of Gerya et al. (2002) who envisaged contrasting PT paths within the same subduction province. A possible scenario is proposed in Figure 4: at 43 Ma eclogite and blueschist blocks (e.g., samples C46 and CP2) were dismembered from the subducting plate at different depths. At 40 Ma other slices were tectonically sampled from depths corresponding to blueschist-facies conditions (e.g., sample VR81), while the exhumation flow of the older slices was already established in a serpentinite layer above the subducting plate.

The juxtaposition of different lithological blocks with different metamorphic grade is typical of serpentinite mélanges elsewhere in the world (Dobretsov, 1991; Engi et al., 2005; Anczkiewicz et al., 2004). In the Alps, tectonic blocks with variable HP metamorphic conditions have been described from a serpentinite mélangé in the Monviso Massif (Blake et al., 1995; Schwartz et al., 2000; Guillot et al., 2004). This mélangé has not been studied in detail from a geochronological point of view, but HP-ages in the Monviso Massif scatter from 60 to 45 Ma (Duchêne et al., 1997b; Cliff et al., 1998; Rubatto and Hermann, 2003). Engi et al. (2001) describe an orogen-scale mélangé zone in the Central Alps with HP-ages ranging from 63 to 36 Ma (Brouwer et al., 2005).

We therefore propose that the mechanism of exhumation in a subduction channel is potentially valid for many other mélanges in the Alps and in other orogenic belts; we believe that refining the petrologic and geochronologic studies on these structures will increase evidence of heterogeneity and diachronous PT evolution inside the different slices.

CONCLUSIONS

The numerical model of Gerya et al. (2002) predicts the development in subduction zones of a serpentinite channel with forced return flow of low-viscosity material at the interface between lower and upper plates. The study of a serpentinite mélange in the Ligurian Alps enables us to positively test this model in a natural occurrence. The exotic tectonic blocks enclosed in a serpentinite matrix followed different PT paths, some with prograde lawsonite-blueschist assemblages and then peak eclogite- or garnet-blueschist-facies and converging in the lower-pressure part of the blueschist facies. Pseudosections show that this variety is independent of bulk compositions and reflects differences in the PT evolution of the various blocks.

³⁹Ar-⁴⁰Ar dating on peak (eclogite or blueschist) phengites confirms that the blocks followed independent trajectories and are not part of a coherent slice.

The occurrence of meter- to nappe-scale mélanges in the Alps, often with different HP ages, points to the presence of independent tectonic slices with diachronous metamorphic evolution, chaotically gathered in a soft matrix during exhumation: these results likely imply exhumation in a subduction channel.

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