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Numerical model of the effect of serpentinites on the exhumation of eclogitic rocks: insights from the Monviso ophiolitic massif (Western Alps)

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Abstract

The intimate association of serpentinite mélange with eclogites worldwide suggests that serpentinites may have played an important role in the exhumation of eclogites. Serpentinites may have formed by fluid percolation in the mantle wedge or by underplating of oceanic serpentinites. We have tested numerically the role of serpentinites in the exhumation of eclogites using physical parameters obtained in the Monviso massif of the Western Alps. Our calculation shows that the buoyancy of serpentinized peridotites in dense anhydrous peridotites may contribute to the exhumation of eclogitic blocks. Small eclogitic blocks ($<$km^3) may be exhumed in completely hydrated mantle wedge, but it is not common considering the absence of totally serpentinized peridotites in mantle wedges. The exhumation of large eclogitic blocks ($>$50 km^3) requires a viscosity of the serpentinite wedge to be between 10^{20} and 10^{21} Pa and a density difference between the serpentinite wedge and the surrounding mantle on the order of 100–400 kg m^{-3}. This condition is satisfied by only partially hydrated peridotites containing 10–50% serpentinites. Such serpentinized peridotites are expected to form at a depth ranging from 20 to 60 km in subduction zones by dehydration of subducting plates. Our conclusion is supported by the common occurrences of partially hydrated peridotites in close association with high-pressure to ultra-high-pressure metamorphic rocks.

Keywords: Channel flow model; Eclogite; Serpentinite wedge; Exhumation; Subduction zone; Alps

1. Introduction

High-pressure, low-temperature metamorphic rocks of continental or oceanic origins are exposed in the internal part of many mountain belts. The rocks were buried deep either by subduction or by thickening of the crust (Platt, 1993). They commonly retain the peak metamorphic conditions, suggesting their rapid return to the Earth's surface (Duchêne et al., 1997a; Ernst, 1999). These high-pressure metamorphic rocks display different tectono-metamorphic evolutions, reflecting their tectonic settings, including internal parts of collisional belts, mélange zones in accretionary prisms or oblique subduction zones (Cloos, 1982; Spalla et al., 1996). Various models have been proposed for their exhumation, including isostatic reequilibration (Ahnert, 1970), thrusting (Argand, 1916; Michard et al., 1993; Spencer, 1993;

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Steck et al., 1998) and extensional collapse (Dewey et al., 1993; Jolivet et al., 1996).

Isostatic reequilibration followed by erosion was first proposed by Ahnert (1970), but it cannot explain the rapid rate (>5 mm year^{-1}; Duchêne et al., 1997a; de Sigoyer et al., 2000) of exhumation. In addition, it is not consistent with the onset of exhumation generally before crustal thickening (Polino et al., 1990; de Sigoyer et al., 2000).

Thrusting and subsequent erosion have been proposed to explain the exhumation of Alpine and Himalayan eclogites (Argand, 1916; Chopin, 1987; Spencer, 1993; Steck et al., 1998). Many eclogitic massifs are, however, surrounded by normal faults (e.g., Ballèvre et al., 1990; Chopin et al., 1991; Guillot et al., 1997).

Large pressure differences between the eclogites and their surrounding rocks prompted the proposal of extensional collapse as the mechanism for the exhumation of eclogites in Norway (Dewey et al., 1993) and in the Agean domain (Jolivet et al., 1996). The mechanism can only explain the last 20 km of exhumation (de Sigoyer et al., 1997; Rolland et al., 2000) and the pressure difference may not be related to extension-related displacement. Moreover, the retrograde metamorphism recorded in the eclogites is inconsistent with the temperatures expected from late orogenic extensional processes (Gardien et al., 1997).

Buoyancy-driven extrusion has been proposed for the exhumation of eclogites by Chemenda et al. (1995, 1996, 2000) and Ernst (1999). However, this model does not consider the density increase during the eclogitization. This mechanism may be applicable to the exhumation of high-temperature rocks such as granulites (Thompson et al., 1997; Burg et al., 1997) but not for cold, rigid rocks such as mafic eclogites, except if subducted rocks are of continental origin and eclogitization only partial.

The exhumation of metamorphic rocks in an active subduction zone requires a mechanically weak zone at the interface between the subduction plane and the rigid mantle wedge. Corner flow (Platt, 1993) and channel flow system (Cloos, 1982) of the mantle wedge have been proposed to explain the exhumation of blueschist and eclogitic rocks (Cloos, 1982; Cloos and Shreve, 1988; Platt, 1986; 1993; Allemand and Lardeaux, 1997). At shallow depths, <40–50 km, hydrated sediments with a viscosity $<10^{17}$ Pa (Cloos and Shreve, 1988) can easily lubricate the interface between the two plates to facilitate exhumation of blocks of blueschists (<15 kbar<400 °C) rocks greater than hundreds of meters in size, as documented in the Franciscan complex (Cloos and Shreve, 1988; Platt, 1986). At greater depths, >50 km, accretionary wedges pinch out, and sediment abundances decrease significantly. Subducted serpentinites coming from the subcontinental lithospheric mantle exposed on the ocean floor (Scambelluri et al., 1995) or in the hydrated mantle wedge (Guillot et al., 2000) may replace the role of hydrated sediments at these greater depths and act as the lubricant for the exhumation of eclogitic rocks. This proposal is supported by the common occurrences of serpentinites with eclogitic rocks (Guillot et al., 2000). In the internal Piemonte zone of the Western Alps (Monviso ophiolitic massif), eclogite lenses of several km long are surrounded by serpentine melange (Blake et al., 1995; Schwartz et al., 2000). A similar situation can be observed for the Ligurian Alps (Scambelluri et al., 1995).

The exhumation of high-density eclogitic rocks (up to 3500 kg m^{-3}; Le Pichon et al., 1997) in a low-density matrix (2600–3000 kg m^{-3} for serpentinites and metasediments; Le Pichon et al., 1997; De Bremond d'Ars et al., 1999) requires dynamic fluid flow in the matrix, and the maximum size of the exhumed eclogitic blocks is controlled by Stoke's law (Cloos, 1982). The aim of this paper is to numerically test the possibility that eclogites can be exhumed in a serpentinized mantle wedge in a subduction zone using the physical properties of Piemonte eclogites of the Western Alps. We first present the geological setting of the internal Western Alps, showing the geological characteristics of the Monviso ophiolitic massif. Then, we will present a 1D numerical model in which we will test the physical parameters (geometry, density, viscosity, size of blocks) that control the possible existence of a serpentinized accretionary wedge.

2. Geological setting

The southern part of the Piemonte zone of the Western Alps (Fig. 1) consists of three major tectono-metamorphic units formed during the closure of the Liguro–Tethyan ocean in the Late Cretaceous and

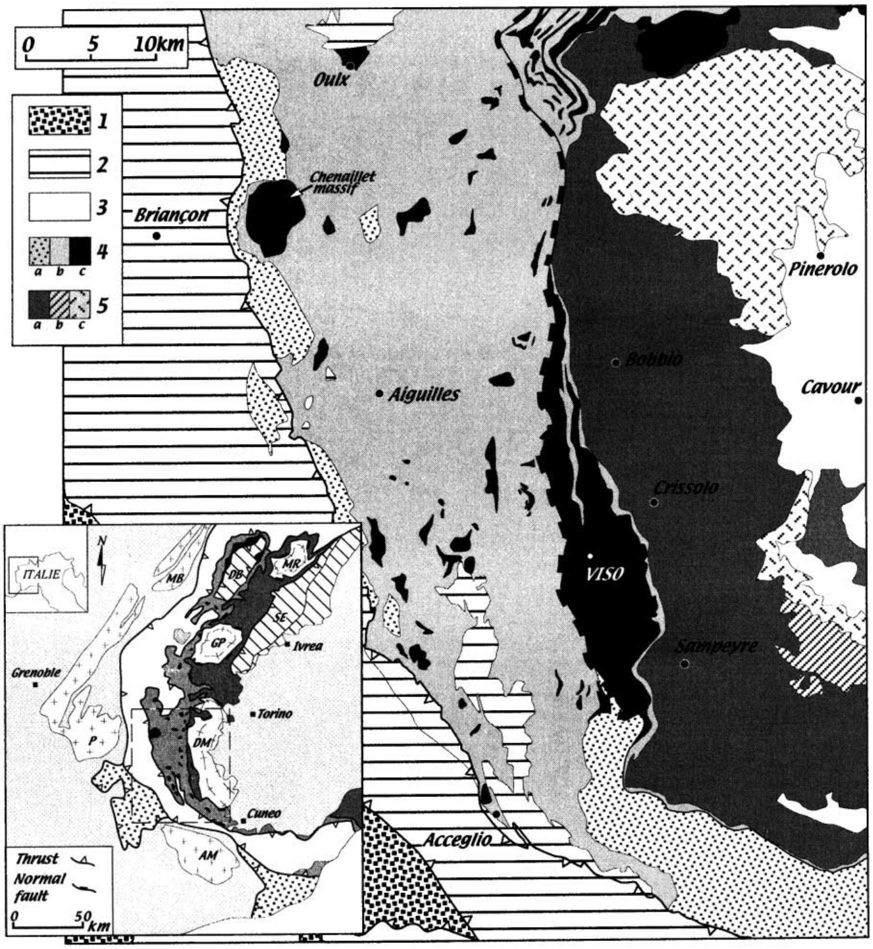

Fig. 1. Geological map of the southern part of the Piemonte zone of the western Alps. 1 — Helminthoïd flysch nappes; 2 — Briançonnais zone; 3 — Tertiary Po plain sediments and Dauphinois zone; 4 — Piemonte zone (a — External Piemonte units; b — Schistes lustrés; c — ophiolitic bodies); 5 — Dora Maira massif (a — Eclogitic units; b — Coesite bearing units; c — Pinerolo–Sanfront units). In insert, localisation of the Piemonte zone in a tectonic sketch map of the western Alps with the main External (AM = Argentera–Mercantour; P = Pelvoux; MB = Mont Blanc) and Internal crystalline massifs (DM = Dora Maira; GP = Gran Paradiso; MR = Monte Rosa) and Austroalpine units (DB = Dent Blanche; SE = Sesia).

Early Tertiary (Ernst, 1973; Caron, 1977; Pognante, 1991; Caby, 1996). The uppermost unit (Chenaillet massif) corresponds to a low-grade metamorphic ophiolite obducted onto the European continental margin (Mével et al., 1978). The intermediate unit corresponds to the Queyras "Schistes Lustrés" unit (Deville et al., 1992). It consists of metric to kilometric lenses of ophiolite embedded in dominant Jurassic to Cretaceous oceanic metasediments (De Wever and Caby, 1981; Lemoine et al., 1987; Lagabrielle et al., 1984). They are metamorphosed under blueschist-facies conditions (Caron, 1977; Caby, 1996). The Queyras "Schistes Lustrés" is considered as a crustal-scale tectonic accretionary wedge in which the oceanic sediments and oceanic lithosphere we scrapping off at the toe of the overriding plate (Schwartz, 2000). The structurally lowest eclogitic unit (Monviso ophiolitic massif) is separated to the west from the blueschist "Schistes Lustrés" by a ductile normal fault located within the serpentinites (Ballèvre et al., 1990) and also to the east from the continental eclogitic units of Dora Maira by a second normal ductile fault (Blake and Jayko, 1990). The central part of the massif is well studied (Fig. 2). The upper part consists of imbrication of kilometric to decakilometric sheets of oceanic lithosphere where the mafic and ultramafic rocks are in lithological contact (Lombardo et al., 1978; Lagabrielle and Lemoine, 1997) and dominant over the metasediments. They correspond to the Traversetta, Costa Ticino, Passo Gallarino and Viso Mozzo units. The basal unit of the Monviso ophiolitic massif is interpreted as a serpentinite melange including metric to kilometric lenses of eclogites such as the Lago Superiore unit (Philippot and Van Roermund, 1992; Blake et al., 1995) (Fig. 2). In the central part of the massif, the basic rocks correspond to various eclogitic metagabbros, depleted Mg–Al metagabbros, and chromiferous and enriched Fe–Ti metagabbros (Lombardo et al., 1978; Kienast, 1983; Nisio, 1985). The metagabbros are associated with metabasalts. The metagabbros and the massive metabasalts form metric to kilometric rigid lenses striking north–south and embedded with a matrix of strongly foliated serpentinites or prasinites (Figs. 2 and 3). Based on the example of the Lago Superiore eclogitic unit, Philip-

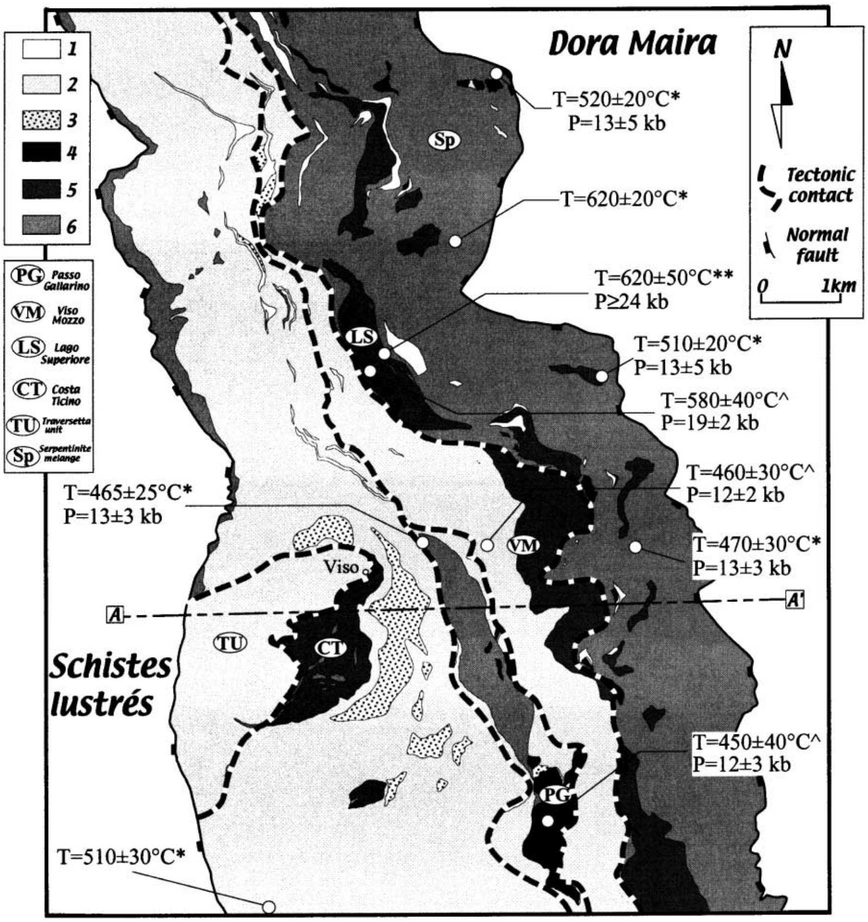

Fig. 2. Geological map of the central part of the Monviso ophiolitic massif (after Philippot, 1988). The different lithotectonic units are separated by major tectonic contacts. 1 — Metasediments; 2 — Prasinites; 3 — Pillow lavas; 4 — Fe – Ti metagabbros; 5 — Mg – Al metagabbros; 6 — Serpentinites. The $P-T$ estimates of the eclogitic facies conditions are reported in the different units (data from: (*) Blake et al., 1995; (**) Messiga et al., 1999 and (^) Schwartz et al., 2000). The $P-T$ conditions are heterogeneous at the scale of the massif. A–A′ represents the transect of the cross-section presented in Fig. 3.

pot and Van Roermund (1992) also suggested that eclogitic shear zones develop during subduction, and subsequently act as a zone of detachment during exhumation.

The metamorphic evolution of the Monviso ophiolitic massif is well constrained (Lombardo et al., 1978; Lardeaux et al., 1986; Philippot, 1993; Schwartz et al., 2000). Three successive metamorphic events are recognized all along the massif: eclogitic, blueschist and greenschist (Lardeaux et al., 1987; Philippot, 1988). The eclogitic facies is well preserved in the metagabbros and the massive metabasalts lenses. The metamorphic pressures and temperatures are independent of the composition of the rocks, but vary between different eclogite lenses. They range from 450 ± 40 °C and 12 ± 3 kbar in the Passo Gallarino unit to 620 ± 50 °C and >24 kbar in the Lago Superiore unit (Fig. 2) (Nisio et al., 1987; Blake et al., 1995; Messiga et al., 1999; Schwartz et al., 2000).

The retrograde metamorphism under blueschist–facies conditions was homogeneous at the scale of the massif at 420 ± 30 °C and 7.5 ± 1.5 kbar (Schwartz et al., 2000). The greenschist-facies conditions are localized within hectometric normal shear bands made of prasinites and serpentinites (Blake and Jayko, 1990). These shear bands overprinted the eclogitic- and blueschist-facies conditions and surround well-preserved eclogitic lenses (Philippot and Van Roermund, 1992; Schwartz et al., 2000) (Fig. 3).

Based on the rock exposures on the maps of Lombardo et al. (1978), Philippot (1988) and Blake et al. (1995), we estimate that mafic rocks constitute 56%, serpentinites 39% and metasediments less than 5% of the surface of the Monviso ophiolitic massif. As the maximum thickness of each unit is of about 1 km (Fig. 4), the volumes of different lithotectonic units are estimated. The Passo Gallarino unit has a volume of 3 km^3. The Costa Ticino unit is the largest eclogitic unit with a volume of 46–47 km^3. Serpentinites are abundant with total volume of 55 km^3, and the eclogitic lenses in the serpentinite mélange constitutes less than 1 km^3 (Philippot and Van Roermund, 1992).

The origin of serpentinites is not well understood. They are commonly associated with discontinuous calcschists (Lombardo et al., 1978; Philippot, 1988; Blake and Jayko, 1990). By analogy with the Chenaillet ophiolite (Mével et al., 1978) and the mid-Atlantic ridge (Lagabrielle and Lemoine, 1997), it is considered that the serpentinites with the metabasites and metagabbros correspond to Tethyan peridotites (Philippot, 1993; Philippot et al., 1998). They may have been hydrated by seafloor hydrothermal activity before subduction. In contrast, Blake et al. (1995) suggested that the basal unit corresponds to a serpentinitite melange representing highly attenuated upper mantle that structurally overlay the UHP rocks during subduction, a situation very similar to those described by Guillot et al. (2000) in the Ladakh, Himalaya. Whatever the origin of the serpentinites within the Monviso ophiolitic massif, the intimate relationships between eclogitic lenses embedded with a serpentinite matrix suggest that the latter may have played a major role in exhumation of the HP rocks.

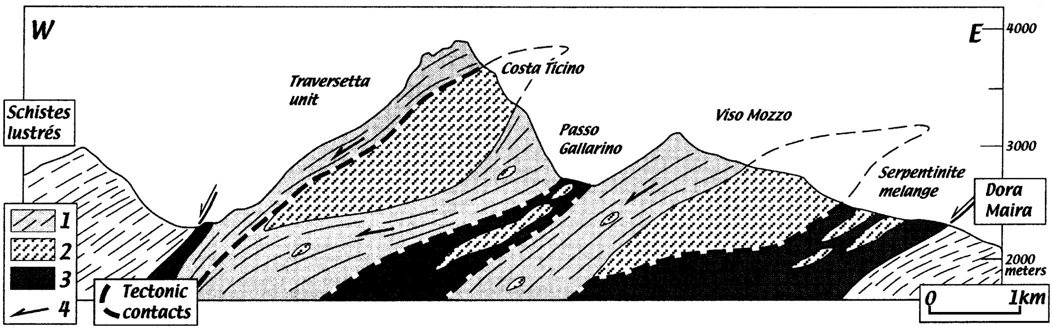

Fig. 3. Cross-section of the ophiolitic Monviso massif showing the different units with eclogitic lenses embedded within the serpentinite. The tectonic contacts between the different units correspond to normal shear zones under greenschist facies conditions. 1 — Greenschist foliated metabasalts (prasinites); 2 — Eclogitic lenses composed of undifferencied metagabbros, massive metabasalts and pillow lavas; 3 Serpentinites; 4 — Kinematics motion under greenschist facies conditions.

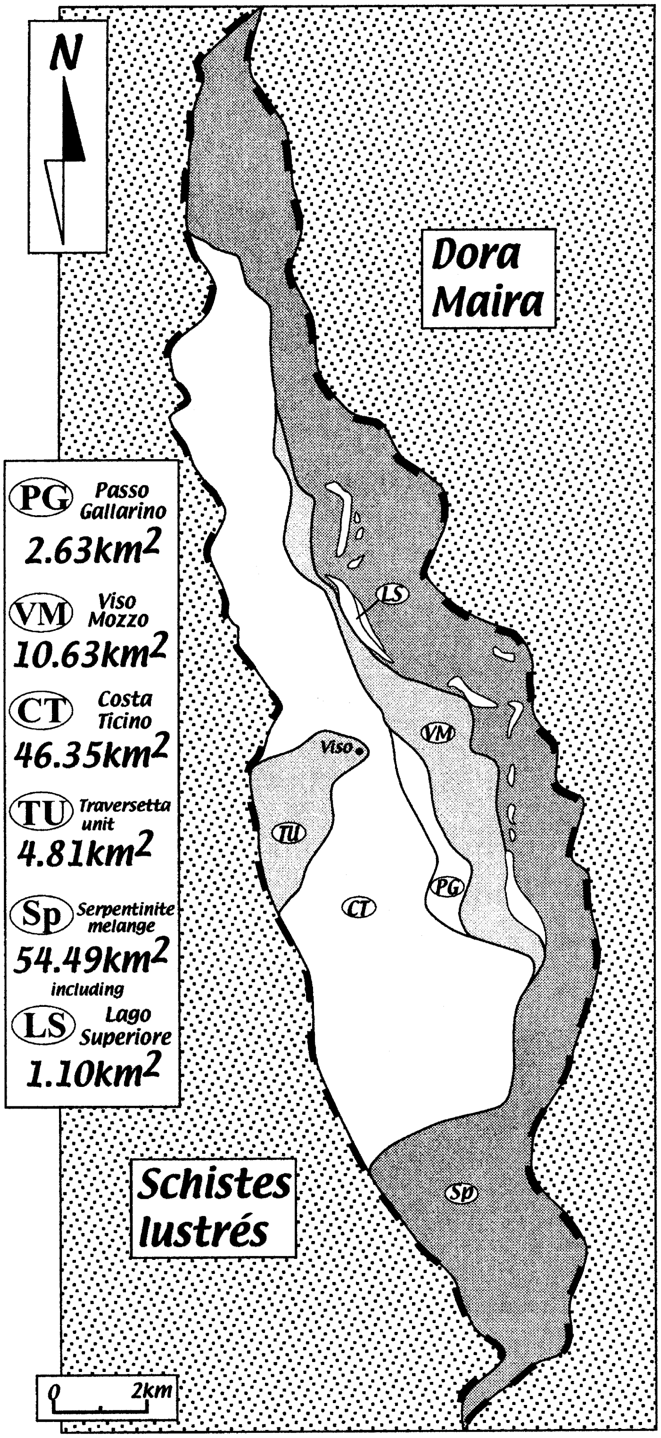

Fig. 4. Simplified geological map of the Monviso ophiolic massif showing the main tectonic units (modified after Blake et al., 1995) and their surface estimated by image analysis.

The age of the eclogitization is estimated to be 49 ± 2 Ma using the Ar/Ar method by Monié and Philippot (1989) and Lu/Hf method by Duchêne et al. (1997b), and 62 ± 9 Ma using Sm/Nd method by Cliff et al. (1998). Metamorphic temperatures recorded at different depths suggest a paleogeotherm of about 5 ± 1 °C/km (Schwartz et al., 2000), which is similar to the geotherm in active subduction zones (Peacock, 1993). Juxtaposition of the different eclogitic units occurred during their exhumation at a depth of about 20 km at the blueschist- to greenschist-facies transition (Schwartz et al., 2000). The exhumation rate was fast at the beginning ($\sim$1 cm year^{-1}) and slowed at the blueschist–greenschist-facies transition ($\sim$1 mm year^{-1}; Schwartz et al., 2000). The collection of the evidences above is compatible with the evolution of a deep accretionary wedge where eclogitic rocks are buried and partly exhumed within a serpentinite melange during active subduction at different depths. Then, the different eclogitic units were stored at 25-km depth under blueschist conditions before their final and common exhumation in a collisional context (Schwartz et al., 2000).

3. Numerical model of a serpentinized accretionary wedge

The geology of Piemontese zone suggests the contemporaneous development of two wedges. The upper sediment wedge now contains hectometric blocks of ophiolite that were metamorphosed under blueschist conditions, and the lower wedge contains kilometric blocks of ophiolites that were metamorphosed under eclogitic conditions. The dynamics of the sedimentary accretionary wedge has been numerically tested by Allemand and Lardeaux (1997) and will not be investigated here. We test the dynamics of the lower wedge and the possible mechanisms of exhumation of eclogitic blocks from this serpentinized lower wedge. The results of numerical calculations are then compared with the mechanical characteristics of different units in the mantle wedge.

3.1. Geometry of the model

The geometry of the system is based on geophysical observations made by Sato (1992) for the Japanese subduction zone, and by Clowes et al. (1987) along the Vancouver Island wedge. It is similar to the general model of subduction zone proposed by Wang et al. (1994). The dip of the subduction zone is arbitrary fixed at 45° (Fig. 5). As the model is 1D, the system is considered as a channel of serpentinized mantle (Fig. 5), which extends from the base of the continental crust to the depth at which serpentinite becomes unstable.

3.2. Serpentinization processes

Serpentinites associated with eclogites are considered to be relics of hydrated subcontinental lithospheric mantle exposed on the ocean floor and preserved during the cold subduction path (e.g., Liguria, Scambelluri et al., 1995; Zermatt-Saas zone, Barnicoat and Fry, 1986; Cerro de Almirez, Sierra Nevada, Trommsdorf et al., 1998). Some partially serpentinized peridotites may represent fragments of the mantle wedge overlying the subduction zone (Liou et al., 1998) by dehydration of the subducting oceanic plate at the depth of 20 to 60 km (Peacock, 1991). This opinion is supported by the occurrence of a low-

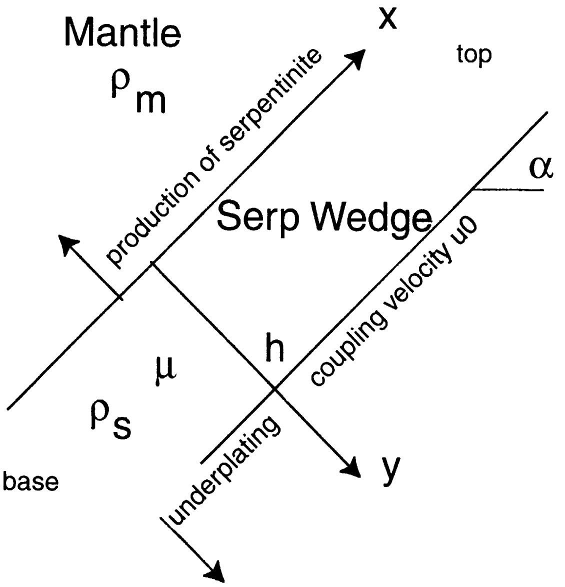

Fig. 5. Characteristics of the channel model (μ: viscosity of serpentinite), u_0: coupling velocity, α: dip angle of subduction, h: width of the channel.

resistivity zone above the subducting plate in Japan (Furukawa, 1993, 1999). Two models of fluid migration have been proposed (Poli and Schmidt, 1995, Schmidt, 1999): (1) homogenous transfer of fluid in which all peridotites are transformed into serpentinites, (2) heterogeneous transfer of fluids in channels. In the homogeneous transfer model, 10 to 15 m^2 of peridotites are totally transformed per year for a subduction velocity of 1 cm $year^{-1}$ (Schmidt, 1999). The surface area of serpentinites is identical in the heterogeneous and homogeneous models, but in the former model, only peridotites along the fluid channels are serpentinized. Thus, the total surface of peridotite partly affected by the serpentinization is higher in the heterogeneous transfer model. In the following, three cases will be modelled: (1) the homogeneous case, (2) an heterogeneous model in which the serpentinized channels represent 50% of the total surface is affected by the serpentinization (corresponds to a production of 20–30 m^2 $year^{-1}$ of partially serpentinized peridotite for a velocity of subduction of 1 cm $year^{-1}$); and (3) a heterogeneous model in which 12% of the total surface is affected by the serpentinization (corresponds to a production of 100–120 m^2 $year^{-1}$ of partially serpentinized peridotite at the subduction velocity of 1 cm $year^{-1}$). The lower boundary of the serpentinite wedge is determined from the thermal stability of serpentine below 650 °C (Evans et al., 1976). In a subduction zone, the maximum stability limit is reached at 80- to 100-km depth (e.g., Peacock, 1992).

3.3. Viscosity and density

The viscosity is assumed constant within a domain because of large difference between different domains. The viscosity of a completely serpentinized peridotite is around 10^{19} Pa at 550 °C and ambient pressure (Carter and Tsenn, 1987; De Bremond d'Ars et al., 1999). The viscosity of a mixture of serpentinite and peridotite is not available, and the value is estimated using an exponential law of two phases (Farris, 1968). The viscosity of anhydrous peridotite in a subduction zone is 10^{23} Pa (Carminati et al., 1999). A mixture containing 50% serpentinites yielded a viscosity of 10^{20} Pa and that with 12% serpentine 10^{21} Pa.

The density of anhydrous peridotite is 3300 km m^{-3}, and it decreases with increasing serpentinization. In the homogeneous percolation model, the density of the peridotite is that of pure serpentinite, 2650 kg m^{-3} (De Bremond d'Ars et al., 1999). Two cases were considered for the density in the heterogeneous percolation model: (1) peridotite containing 50% serpentinite, with a density of 2975 kg m^{-3}, and (2) peridotite containing 12% serpentinite, with a density of 3200 kg m^{-3}.

Viscosity and density are correlated (Table 1). Completely serpentinized peridotite has low viscosity (10^{19} Pa) and low density (2650 kg m^{-3}). Less serpentinized peridotites have high viscosity (10^{21} Pa) and high density (3200 kg m^{-3}).

3.4. Velocity field

The serpentinized wedge is in contact with the subducting plate, and a fraction of the subduction velocity is transmitted to the wedge (Wang and Suyehiro, 1999). When the coupling between the wedge and the subducting plate is complete, the velocity at the base of the wedge is equal to the velocity of the subducting plate. However, the velocity at the base of the wedge can represent only a part of the subducting velocity. In that case, the coupling is partial. In the following, the velocity applied at the base of the wedge is called the coupling velocity.

3.5. Forces

The serpentinite wedge can produce a flow by (1) surface forces applied by the subducting plate, or by (2) volume forces due to the density difference between the serpentinite domain and the surrounding unserpentinized mantle. The effect of surface forces is only considered here as the effect of the coupling velocity.

Table 1
Petrophysical parameters used in the calculations

	Density (kg m^{-3})	Viscosity (Pa)
Continental crust	2700	10^{23}
Sedimentary wedge	2600	10^{18}
Anhydrous mantle	3300	10^{23}
100% Serpentinized mantle	2650	10^{19}
50% Serpentinized mantle	2975	10^{20}
12% Serpentinized mantle	3200	10^{21}

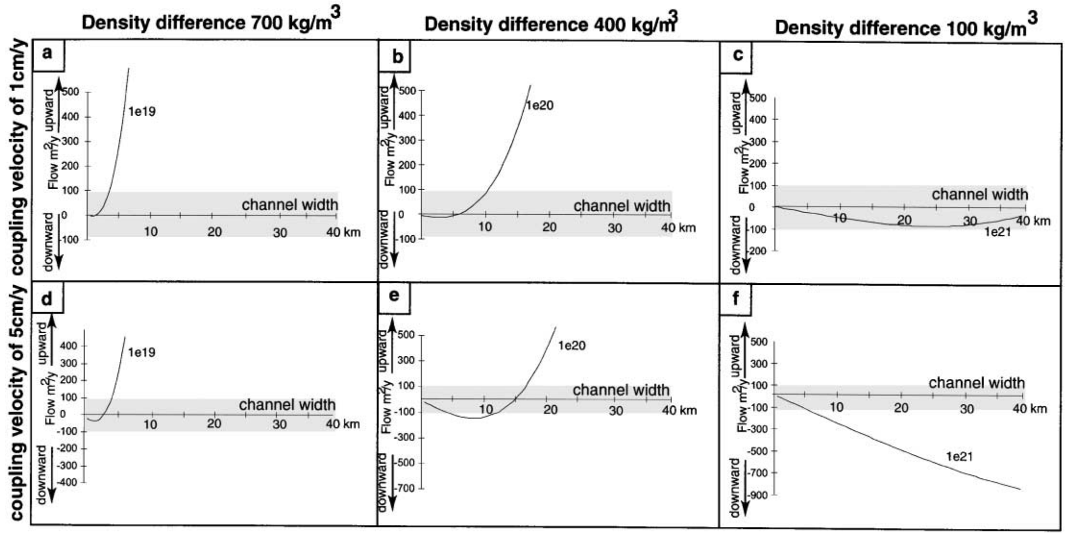

Fig. 6. Net flow in the channel model relative to the width of the channel. The dashed areas represent the possible flow of serpentinite added by hydratation of the mantle or by underplating. The model is acceptable if the flow in the channel is lower or equal than the maximum production of serpentinite.

3.6. Governing equations

The different density rates between a serpentinized wedge and the surrounding mantle induces an upward volume force. In the following calculations, a wedge is considered as a viscous channel submitted to a pressure gradient between the base and the top (Fig. 5). The width of the channel is considered as constant in order to simplify the calculation. The pressure gradient between the base and the top of the channel is expressed by:

$$\frac{\mathrm{d}P}{\mathrm{d}x} = \Delta\rho g \sin\alpha \tag{1}$$

The velocity profile in the channel is equal to (Turcotte and Schubert, 1982):

$$u = \frac{1}{2\mu}\frac{\mathrm{d}P}{\mathrm{d}x}(y^2 - hy) - \frac{u_0 y}{h} + u_0 \tag{2}$$

The flow of material through the channel is equal to:

$$Q = \int_0^h u \mathrm{d}y \tag{3}$$

The maximum upward velocity in the channel can be found by calculation of the position where the derivative of the velocity relative to y is equal to zero:

$$u_{\max} = -\frac{\left(\frac{h^2}{2}\frac{\mathrm{d}P}{\mathrm{d}x} - \mu u_0\right)^2}{4\mu h^2 \frac{\mathrm{d}P}{\mathrm{d}x}} \tag{4}$$

4. Results

The flow in a serpentinite channel is presented in Fig. 6 according to the width of the channel. For example, in the case of a density contrast of 400 kg m^{-3} and a coupling velocity of 1 cm $year^{-1}$ (Fig. 6b), the net flow in the channel is downward (i.e., negative) if the channel width is lower than 7 km. For larger channel width, the net flow is upward (i.e., positive) and reaches 500 m^2 $year^{-1}$ for a channel width of 17 km. If the density difference is greater and thus the viscosity is lower (Fig. 6a), the net flow in the channel increases more rapidly. When the density difference is low with high viscosity, the net flow is equal to -20 m^2 $year^{-1}$ for a channel width of 40

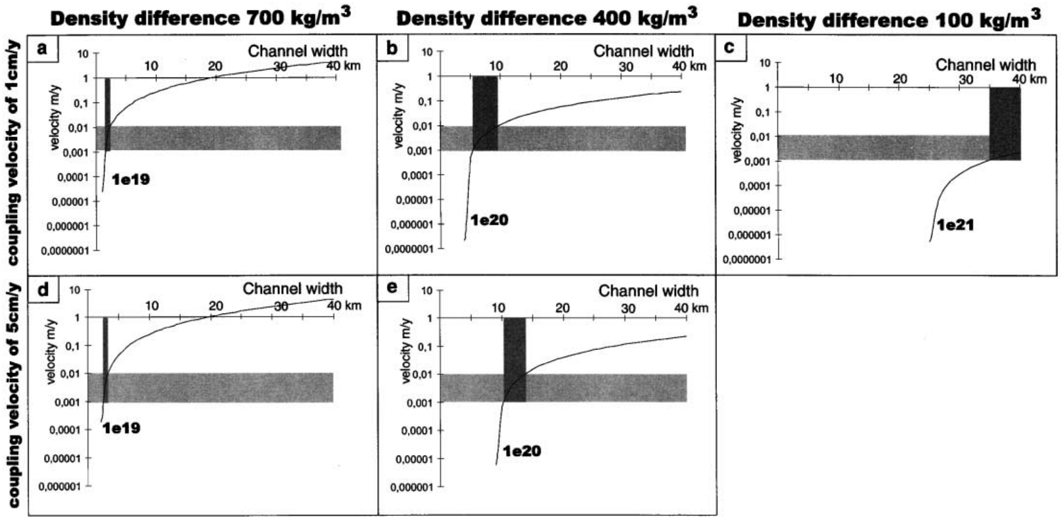

Fig. 7. Maximum velocity in the channel model. The horizontal dashed rectangles represent the range of exhumation velocities registered in eclogites. The vertical dashed rectangles represent the acceptable values of width of the channel.

km (Fig. 6c). An increase in the coupling velocity with a constant channel width (Fig. 6d, e and f) causes a decrease in the net flow in the channel.

When the net flow in the channel is not zero, the width of the channel cannot be constant because the channel is not infinite. The net flow has to be compensated by an addition of serpentinites (Fig. 5). This can be achieved by additional hydration of the peridotite above the channel or by underplating of oceanic serpentinite at the base of the channel. The production of serpentinite can vary from 10 to 120 m^2 $year^{-1}$ (Schmidt, 1999). An addition of oceanic serpentinite by underplating would increase the width of the channel. The width of the channel can be at steady state as far as serpentinites are added to the channel. A realistic value of addition of serpentinite is around 100 m^2 $year^{-1}$.

Maximum upward velocities are related to the channel width (Fig. 7). As the velocity of eclogitic blocks is close to the velocity of the flow, we chose the values ranging from 10^{-3} to 10^{-2} m $year^{-1}$ as a realistic velocity (Duchêne et al., 1997a). Such velocities are obtained in narrow channels when the density contrast is large (3 km width for $\Delta r = 700$ kg m^{-3} and $\mu = 10^{19}$ Pa, Fig. 7a and d). For intermediate density difference, ~ 400 kg m^{-3}, the channel width is lower than 10 km if the coupling velocity is 1 cm $year^{-1}$ and is around 15 km for a coupling velocity of 5 cm $year^{-1}$. For a low-density difference, ~ 100 kg m^{-3}, the width of the channel should be at least of 40 km for a coupling velocity of 1 cm $year^{-1}$.

From the preceding calculations of flow (Fig. 6) and maximum velocity (Fig. 7) in the viscous channel, possible geometrical and mechanical conditions for the existence of a stable channel are as follow. In the case of high-density difference and low viscosity, the width of the channel should be around 3 km. This width is probably too small to allow the transport of eclogitic bodies of several km. For high-viscosity and low-density contrast, a channel width of 10–20 km or wider than 35 km is feasible when the coupling velocity is around 1 cm $year^{-1}$. In the case of wider channel and fast coupling velocity, it is difficult to maintain a constant width of channel. In the intermediate case, a width from 10 to 15 km is possible for high coupling velocity. A width around 10 km is feasible for low coupling velocity.

5. Application to the Monviso ophiolitic massif

The eclogites in the Monviso massif are used to examine the model developed here. Mafic eclogites have densities on the order of 3400–3500 kg m^{-3} (Le Pichon et al., 1997), denser than serpentinite.

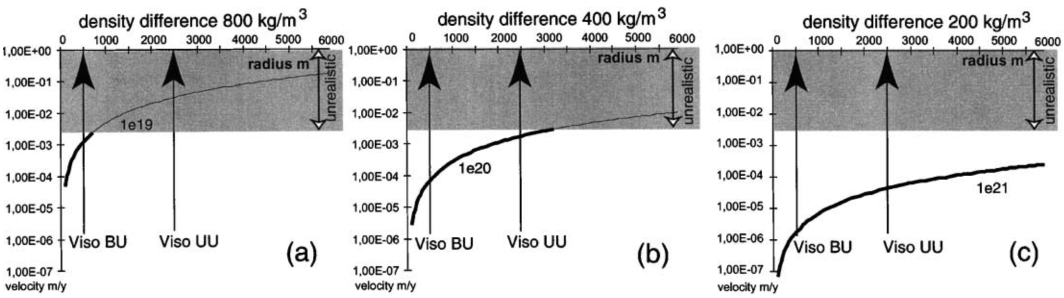

Fig. 8. Downward velocity of a particle in a fluid at rest. The dashed areas represent the range of velocities that cannot be sustained by channel flow. Viso Upper Units UU (Traversetta, Costa Ticino, Passo Gallarino and Viso Mozzo units) with their maximum width. Viso Basal Unit BU: width of eclogitic bodies in the serpentinite melange localised at the base of the Monviso.

Mafic eclogites would sink without upward flow in the mantle wedge. Assuming the eclogitic blocks as spherical rigid objects, the minimum velocity of upward viscous flow can be obtained using the Stokes equation (Turcotte and Schubert, 1982):

$$u = u_f - \frac{2(\rho_e - \rho_s)gr^2}{9\mu} \tag{5}$$

where u_f is the velocity of serpentinite flow, ρ_e and ρ_s are densities of eclogite and serpentinized domain, respectively, r is the radius of the particle and μ is the viscosity of the serpentinized domain. The spherical shape of eclogites may not be valid because the eclogitic units are lenticular and flattened during exhumation, as shown on the map (Fig. 4). The flattening will reduce the exhumation velocity by dissipating a part of the energy of the system, but the shape effect will increase the upward velocity because of increased surface of the object compared to spherical bodies. The two effects likely cancel each other out, and spherical shape is used for the calculations.

Fig. 8 shows the downward velocity of a particle in function of its radius in a fluid at rest, according to various density contrast. As in the previous calculations, the density contrast is related to the viscosity of the serpentinite wedge. The velocity increases with the radius of the particle. The velocity is obviously higher when serpentinite viscosity is low. Schwartz (2000) shows that the exhumation velocity of Monviso units is around 1 cm year^{-1}. To be exhumed, a particle should have a smaller downward velocity than the upward flow. So, particles with a downward velocity larger than 0.5 cm year^{-1} are very difficult to exhume. When the viscosity is 10^{19} Pa, the radius of the particle should be less than 700 m. When the viscosity is 10^{20} Pa, particles with a diameter of 3 km could be exhumed. Larger units can be exhumed when serpentinites have greater viscosities.

In the case of the upper Monviso units, the largest eclogitic unit (Costa Ticino, Fig. 4) has a volume equivalent to a sphere of 2.5-km radius. Such a unit will rise at the velocity of serpentinite flow if the viscosity of the matrix is larger than 10^{20} Pa and if the density difference is smaller than 400 kg m^{-3}. This suggests that the exhumation of such large eclogites is possible in a partly serpentinized wedge. In contrast, eclogitic blocks in the serpentinite mélange are small, volume equivalent to spheres with less than 500-m radius. Such small blocks could have been exhumed independent of the degree of serpentinization. The fact that the Monviso serpentinite wedge can be only partially hydrated is supported by stable isotopic data obtain on the Monviso ophiolitic massif (Philippot, 1993; Philippot et al., 1998) showing that the fluids coming from the altered oceanic crust are partly stored in the eclogitic rocks, and consequently they are only partially transferred to the mantle wedge.

6. Conclusions

Our numerical model shows that viscous channel in a serpentinized mantle wedge could exhume dense eclogitic bodies from 100 to 40 km depths. The kinematics and the geometry of the Monviso ophiolitic massif impose the following constrains for the exhumation of eclogites by serpentinites:

1. The viscosity of the serpentinized wedge should be between 10^{20} and 10^{21} Pa.
2. The density difference between the eclogitic bodies and the partially hydrated peridotites should be on the order of 100–400 kg m^{-3}.
3. The peridotite should be partially hydrated (between 10% and 50% serpentinization).
4. The width of the serpentinite wedge is about 10–20 km.

Small eclogitic blocks (< km^3) may be exhumed in completely hydrated serpentinite wedge, but there is no geophysical evidence for a large hydrated domain in a subduction wedge (e.g., Furukawa, 1993, 1999). Therefore, it is not likely that a large portion of mantle wedge is completely serpentinized.

Our results suggest that buoyancy induced by density difference between the mantle peridotite and the serpentinite wedge could be an efficient force for the exhumation of high-pressure units.

The existence of a deep partially hydrated mantle wedge is consistent with the close association of ultra-high-P rocks with serpentinites and hydrated peridotites in many active and past subduction zones such as the Voltri massif in the Ligurian Alps (Scambelluri et al., 1995), the Kokchetav massif in northern Kazakstan (Mayurama et al., 1997) or Dabie Shan in east-central China (Zhang and Liou, 1994).

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