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Up the down escalator: the exhumation of (ultra)-high pressure terranes during on-going subduction

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Abstract

The exhumation of high and ultra-high pressure rocks is ubiquitous in Phanerozoic orogens created during continental collisions, and is common in many ocean-ocean and ocean-continent subduction zone environments. Three different tectonic environments have previously been reported, which exhume deeply buried material by different mechanisms and at different rates. However it is becoming increasingly clear that no single mechanism dominates in any particular tectonic environment, and the mechanism may change in time and space within the same subduction zone. In order for buoyant continental crust to subduct, it must remain attached to a stronger and denser substrate, but in order to exhume, it must detach (and therefore at least locally weaken) and be initially buoyant. Denser oceanic crust subducts more readily than more buoyant continental crust but exhumation must be assisted by entrainment within more buoyant and weak material such as serpentinite or driven by the exhumation of structurally lower continental crustal material. Weakening mechanisms responsible for the detachment of crust at depth include strain, hydration, melting, grain size reduction and the development of foliation. These may act locally or may act on the bulk of the subducted material. Metamorphic reactions, metastability and the composition of the subducted crust all affect buoyancy and overall strength. Subduction zones change in style both in time and space, and exhumation mechanisms change to reflect the tectonic style and overall force regime within the subduction zone. Exhumation events may be transient and occur only once in a particular subduction zone or orogen, or may be more continuous or occur multiple times.

1 Introduction

Global exposures of high- and ultra-high-pressure (HP and UHP) metamorphic rocks mark regions where crustal materials were subducted to mantle depths and exhumed back to the surface at some point in the geological past (Chopin, 1984; Smith, 1984;

Ernst et al., 1997). Previous work has categorised exhumation of these rocks into three main tectonic environments: accretionary prism (producing mainly blueschists), serpentinite subduction channel (producing mainly quartz-eclogites) and continental (producing quartz- and coesite-eclogites) (Guillot et al., 2009). These different tectonic environments appear to exhume high-pressure rocks at different rates and by differing mechanisms. Exhumation mechanisms and rates appear to be internally consistent for accretionary prism and serpentinite subduction channel environments. However it has recently become apparent that the exhumation rate and mechanism of deeply subducted continental crustal material appears to vary, with significant differences between relatively small terranes (e.g. Alps and Himalayan examples) and relatively large terranes (e.g. Western Gneiss Region, Norway and Dabie Sulu, China; Kylander-Clark et al., 2012).

Continental (U)HP terranes vary in outcrop size, tectonic and structural setting and age, but share a number of common features including a commonly upper- to mid-crustal origin, a volumetrically insignificant amount of mafic eclogite with respect to the volume of host felsic gneisses or metasediments, and a post-exhumation structural position close to the continental suture zone (Liou et al., 2004). Geochronological data suggest that (U)HP metamorphism proceeded during, or shortly after, the transition from oceanic subduction to continental collision, and that exhumation proceeded during on-going subduction: "*up the down escalator*" (e.g. Rubatto and Hermann, 2001; Parrish et al., 2006). Exhumation rates appear to vary bimodally: volumetrically small $<50\,\mathrm{km}^3$ terranes such as those found in the Alps and Himalayas appear to have exhumed at $\mathrm{cm\,a}^{-1}$ rates (Rubatto and Hermann, 2001; Parrish et al., 2006). In contrast, huge terranes such as the Western Gneiss Region ($>50\,000\,\mathrm{km}^3$) appear to have exhumed more slowly and/or stalled at lower-mid crustal depths during exhumation (Kylander-Clark et al., 2012 and references therein). Two episodes of subduction and exhumation of the same terrane (termed yo- yo subduction) appear to have been recorded from HP rocks in the Alpine Sesia Zone (Rubatto et al., 2011). These data imply that episodic exhumation during orogenesis depends on the subtle balance between buoyancy and traction forces within the subduction channel.

Despite an ever-increasing database of metamorphic, structural, and geochronological data, the processes and mechanisms driving the exhumation of UHP material, and the cause of the variations seen in different orogens, are still debated. This paper aims to review the mechanisms by which subducted continental crust subducts and exhumes to determine if any general conclusions may be made about exhumation mechanisms in different tectonic settings where the subduction of continental crustal material takes place.

2 Types of exhumation mechanism

Exhumation mechanisms may be divided into those in which a force internal to the exhuming terrane drives the upwards motion, e.g. the buoyancy of the bulk terrane (Ernst et al., 1997) (Fig. 1a) or the assistance of a buoyant serpentinite matrix (Guillot et al., 2001), and those in which an external force drives motion, for example channel, corner or cavity-driven flows (Cloos, 1982; Platt, 1993; Warren et al., 2008b; Fig. 1b), extensional collapse (e.g. Dewey et al., 1993; Thompson et al., 1997), compression or squeezing of weak material between two stronger blocks (e.g. Thompson et al., 1997) or plunger exhumation involving the insertion of stronger crust into a channel of weaker material (Warren et al., 2008b, 2011; Fig. 1c). Combinations of these two end-members have also been proposed, e.g. buoyancy in combination with erosion and tectonic processes (Chemenda et al., 1995).

In simple mechanical terms, shear traction between the crust and mantle drives the subduction of buoyant crustal material to UHP depths. This competes against the buoyancy forces that act to return subducted material to neutrally-buoyant depths (Ernst et al., 1997). Subducted crust will detach from the down-going slab when the buoyancy force overcomes its strength (Raimbourg et al., 2007; Warren et al., 2008a, c). These workers discussed exhumation in terms of an exhumation number, E, which expressed the balance and competition between the downwards-acting subduction (Couette) flow and the upwards acting exhumation (Poiseuille) flow:

$$E = (\partial P/\partial x)h^{*^2}/\eta_\mathrm{e}U \tag{1}$$

Where P is the effective down-channel pressure gradient, x is the horizontal distance along the channel, h^* is a function of channel thickness, η_e is the effective viscosity and U is the subduction velocity (Fig. 2).

Strong, buoyant continental crust may therefore be subducted to great depths due to its attachment to stronger, denser, underlying lithosphere ($E \ll 1$). Progressive decoupling of the subducting crust during/after metamorphism to high pressure assemblages takes place if buoyancy forces increase or as shear traction is reduced. Once detached, the crust may stagnate if the buoyancy forces are not great enough to overcome the boundary stress ($E \approx 1$), or exhume if the buoyancy forces exceed the boundary stress ($E \gg 1$; Raimbourg et al., 2007; Warren et al., 2008a, c).

Buoyancy is generally assumed to be the dominant controlling force driving exhumation (Ernst et al., 1997). The contribution of additional assistance and/or resistance from boundary and/or tectonic forces remains unclear. This paper aims to review the factors that may control decoupling and subsequent detachment and exhumation of subducted continental crustal material, and discuss these with regard to commonly suggested exhumation mechanisms. These factors may also apply in full or in part to oceanic crust that has been subducted in intra-oceanic or oceanic-continental subduction zones. They may be loosely sub-divided into those that act to weaken the subducting crust, those which affect the buoyancy of the subducting crust, and external tectonic forces that may act to modify the mechanics of the subducting system.

3 How does subducted crust weaken?

Examination of exposed continental UHP terranes shows that they are either pervasively deformed (e.g. Terry and Robinson, 2004) or consist of low-strain regions or blocks on a variety of scales separated by high strain shear zones (e.g. Labrousse et al., 2002; Jolivet et al., 2005). Despite their rapid burial and exhumation along a lithosphere-scale shear zone, there are many examples of both continental and oceanic UHP rocks that have accumulated remarkably little strain: well preserved magmatic fabrics have been reported in (U)HP granites (e.g. Wallis et al., 1997), gabbros (e.g. Zhang and Liou, 1997; Krabbendam et al., 2000) and pillow basalts (e.g. Bearth, 1959; Puga et al., 1995; Oberhänsli et al., 2002). In these localities, all the deformation during burial and exhumation appears to have been accommodated along localized shear zones, many of which formed during exhumation rather than at UHP conditions. The preservation of primary textures also implies low stress conditions within the subduction zone. Although HP shear zones have been described from many localities (e.g. Pognante et al., 1985; Austrheim, 1987; Boundy et al., 1992; Camacho et al., 1997), UHP shear zones are much rarer (see e.g. Lenze and Stockhert, 2007). UHP shear zones have been reported from the Dabie Sulu region in China (Zhao et al., 2003). The lack of evidence for structures forming at UHP conditions may be due to metamorphic or deformational overprinting, continuous development and reactivation during exhumation, or an unspecific and/or unrecognizable microstructural record (Stöckhert, 2002; Zhao et al., 2003).

Whilst the location, timing of initiation and mechanism of propagation of the high-strain zones responsible for the detachment of subducted crust and its transport back up to mid-crustal levels of exhumation are poorly constrained, experiments suggest that such shear zones are significantly weaker than the host rock and remain weak once formed (Holyoke and Tullis, 2006). The levels of weakening inferred from natural shear zones associated with UHP rocks may be up to a factor of 100 (Raimbourg et al., 2007).

3.1 Strain weakening

Experimental strain weakening data are most commonly determined from mono-mineralic starting materials. The data suggest weakening of up to 25–50 % for minerals such as olivine, anhydrite and calcite at low shear strains (Bystricky et al., 2000; Heidelbach et al., 2001; Barnhoorn et al., 2004). Data from strain weakening experiments on quartz (the majority mineral in continental crust) is more difficult to interpret as it mainly deforms in the (semi)brittle, rather than ductile, field under laboratory conditions and timescales (Hirth and Tullis, 1992, 1994; Schmocker et al., 2003).

Outside the laboratory, most rocks are polymineralic, and do not show the same rheological behaviour as monomineralic charges in laboratory deformation experiments. The comparison between numerical models based on monomineralic flow laws and the polymineralic reality is approximately valid if the mineral is sufficiently weak or abundant enough to dominate the rheology (Handy, 1990). Most commonly, however, several minerals collectively define the rheological properties of a polymineralic rock, and the rheology-defining mineral may change under changing conditions. Strong minerals may form a load-bearing framework which dominates the strength behaviour, the rheology may be controlled by one or two low-strength minerals which form elongate boudins within the rock, or a single weak mineral may control the rheology while the stronger minerals form clasts (Handy, 1990). Strength vs. composition relationships appear to be highly non-linear (Jordan, 1988; Handy, 1990).

In summary, therefore, whilst strain arguably causes weakening in natural rocks, the amount of weakening will depend on the mineralogy and composition of the overall terrane, as well as the degree of heterogeneity within it. Numerical models of continental collision zones designed to investigate aspects of UHP terrane formation and exhumation commonly apply strain weakening as a numerical proxy for other weakening mechanisms such as grain size reduction, hydration and metamorphic reactions (e.g. Babeyko and Sobolev, 2005; Sobolev and Babeyko, 2005; Warren et al., 2008a, c). In these models, weakening is applied to the bulk crust, which is effectively treated as being homogeneous. At present it is still unclear whether strain weakening can weaken a terrane enough to allow it to flow on a regional scale, as suggested by numerical models (Gerya et al., 2002; Warren et al., 2008a) or to exhume only as a rigid block with weak boundaries, as suggested by field studies (e.g. Labrousse et al., 2002). A combination of these two end-members probably operates at all scales.

3.2 Melt weakening

Partial melting allows rocks to weaken rapidly and effectively. Experiments have shown that there is an exponential decrease in rock strength with increasing proportions of melt (Rutter and Neumann, 1995). Many UHP terranes show evidence for migmatization in the mafic eclogite bodies as well as their host rocks, suggesting bulk weakening on a regional scale. In the Western Gneiss Region of Norway, partial melting is widespread and recent high-precision dating and geochemical analysis suggests that melting initiated during high-pressure metamorphism and continued during exhumation-related decompression (Labrousse et al., 2002, 2011). Further work in, for example, the Woodlark Basin (e.g. Hill et al., 1995), the Dabie Sulu region (e.g. Wallis et al., 2005), the Kokchetav Massif (e.g. Ragozin et al., 2009) and the Greenland Caledonides (e.g. Lang and Gilotti, 2007) suggest that the initiation of melting at UHP conditions and the continuation of melting during exhumation is a common phenomenon in UHP terranes. Partial melting must therefore be considered a viable mechanism for the bulk weakening of deeply subducted crust, and potentially the cause of exhumation initiation.

The ultimate end-member of how weakening may facilitate exhumation is a case where the subducted crust melts, detaches and rises as a diapir through the mantle rather than exhuming back along the subduction channel. This model has been suggested for the evolution of the still actively exhuming UHP continental crustal rocks exposed on the D'Entrecasteaux Islands, Papua New Guinea (Fig. 3; Ellis et al., 2011). The exhumation of these UHP rocks cannot be explained by syn-convergent extrusion of UHP material in an active subduction channel, because exhumation occurred ca. 20–30 Ma after collision ceased (Baldwin et al., 2004; Monteleone et al., 2007). Instead, structural, metamorphic, and geochronological data suggest that they exhumed rapidly and vertically following partial melting of the felsic protolith (Little et al., 2011).

First-order 2-D and 3-D modeling suggests that the exhumation of this terrane may be explained by diapiric flow of partially molten felsic crust, assisted by a propagating extensional rift (Ellis et al., 2011).

3.3 Hydration weakening

Weakening of the mantle wedge forming the roof of the subduction zone by hydration and ultimately by serpentinisation is one of the most commonly invoked weakening and buoyancy-inducing mechanisms for assisting the exhumation of subducted oceanic and continental crust (e.g. Guillot et al., 2001; Pilchin, 2005). Oceanic crustal eclogite may reach densities greater than the mantle, so a buoyant matrix is required to assist its exhumation (Agard et al., 2009). Exhumed oceanic crustal terranes such as the Monviso/Zermatt-Saas in the Alps contain km-cm scale blocks of metabasites within a sheared serpentinite matrix. The serpentinite appears to act as a low-density "carrier" for the higher density oceanic crustal eclogite blocks (e.g. Philippot and van Roermund, 1992; Blake et al., 1995; Schwartz et al., 2001).

As well as acting as a buoyancy-increasing agent, serpentinites may also act as a lubricant by forming a mechanically weak zone at the roof of the subduction zone (Guillot et al., 2001). This weak zone assists subduction and subsequent exhumation by decreasing the viscosity of the wall of the subduction channel. Many of the smaller and more geologically recent continental HP and UHP terranes are exhumed structurally beneath the continental suture zone, and are associated with mantle-wedge-derived serpentinites (Guillot et al., 2001; Pilchin, 2005; Beaumont et al., 2009). This association appears to be less common in large UHP terranes such as the WGR or Dabie Sulu.

Fluid migration in subducted crust is suggested by the formation of veins bearing eclogite-facies minerals (Philippot and Kienast, 1989; Rubatto and Hermann, 2003), and Caledonian-aged eclogite-facies shear zones bounding Grenvillian-aged granulites in the Bergen Arcs region of Norway (Jolivet et al., 2005). These shear zones suggest that hydration weakening occurred under eclogite-facies conditions. Furthermore, water-filled inclusions associated with UHP plastic deformation structures in omphacite suggest that hydrolytic weakening may play a major role in the weakening of omphacite (Su et al., 2003, 2006). Fluids may additionally assist the formation of relatively weak, foliation-forming metamorphic minerals such as phengite, biotite and lawsonite. The crystallization of these minerals in high strain zones may help localize deformation and initiate decoupling of buoyant crust from the subducting slab. The formation of discrete weak shear zones may additionally protect stronger lenses and boudins of UHP material from penetrative deformation, assisting in the preservation of UHP indicator minerals (e.g. Guillot et al., 2009).

3.4 Grain size reduction

Minerals in shear zones commonly show a reduction in grain size compared with the original protolith, with an inverse relationship between the amount of strain and the grain size (resulting in the formation of mylonites). The mechanisms responsible for deformation-induced grain size reduction include cataclasis, metamorphic reactions or dynamic recrystallization (e.g. De Bresser et al., 2001 and references therein). Cataclasis is a brittle grain-size – reducing mechanism and is therefore not relevant to the discussion of high-pressure rock exhumation which initiates in the ductile field.

Eclogite-facies (HP) shear zones have been documented from a number of locations including the Western Gneiss Region and Bergen Arcs in Norway, Australia, the Western Alps (e.g. Pognante et al., 1985; Austrheim, 1987; Boundy et al., 1992; Camacho et al., 1997). In the Bergen Arcs, mylonitic eclogite-facies shear zones transect coarser, apparently unaltered, granulite-facies rocks, suggesting that deformation, and arguably fluid, were necessary for triggering the eclogite-forming reactions (Austrheim and Griffin, 1985). What is still unclear is whether the deformation triggered the metamorphic transformation or whether fluid triggered the metamorphic reactions, thereby forming a weak zone, hence allowing further deformation and grain size reduction to proceed. Once initiated, deformation was partitioned preferentially into those zones.

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Dynamic recrystallization leads to weakening and strain localization by generating a change from dislocation creep (which is insensitive to grain size) to diffusion creep (which is sensitive to grain size; De Bresser et al., 2001). However significant weakening by grain size reduction may only be possible when caused by syntectonic reaction recrystallization or cataclasis rather than dynamic recrystallization (De Bresser et al., 2001). Alternatively, weakening may only occur if grain growth is inhibited.

Element solubility is enhanced at high pressures. Dissolution–precipitation creep and grain-boundary sliding have therefore also been proposed as likely mechanisms for rock deformation at UHP conditions due to a continuous fluid supply from dehydration reactions and high concentrations of solutes (Stöckhert, 2002). Such mechanisms would imply grain-size-sensitive behavior and a Newtonian (linear) dependence of strain rate on stress (Rutter, 1983). The expected effective viscosities of rocks undergoing such flow are still poorly constrained by experimental results.

The effect of increasing temperature on decreasing viscosity may be counterbalanced by a temperature-related increase in grain size (Stöckhert, 2002). Further investigation into the causes, and effects on viscosity, of grain size reduction in shear zones is needed, especially in polymineralic rocks.

3.5 Development of foliation

Strain partitioning between the mineral phases in a polymetamorphic rock may lead to the crystallization and/or rotation of planar minerals such as micas. The formation of foliation lowers the bulk strength of the rock by increasing the distance between stronger clasts (Handy, 1990). Foliation development, grain size reduction and/or hydration weakening may all act contemporaneously at different stages of the subduction/exhumation cycle.

3.6 Discussion

The preceeding section has summarized ways in which different mechanisms may act to weaken subducted crust, thereby allowing it to detach from the subducting slab and allowing the potential for exhumation. These different mechanisms operate at different spatial and temporal scales and at different times during the evolution of the subduction system. They variably depend on pressure, temperature, mineralogy, amount of hydration and any pre-existing heterogeneities within individual lithologies and between different geological units or terranes. More work is needed regarding the rates at which these processes operate, the amount by which they weaken the crust, the depth of detachment and whether differences can be linked to the composition of different terranes.

4 Changes in the density of subducted crust

Metamorphic reactions that affect the density and strength of crustal material depend on, amongst others, pressure, temperature, time, deformation and the availability of fluids. The rate of achievement of equilibrium to the stable assemblage at any point on the P-T-t path in rocks of differing bulk composition in different tectonic settings is still under debate (e.g. Peterman et al., 2009). Fully transformed metabasaltic eclogite is denser than the mantle at UHP conditions (e.g. Ernst et al., 1997), which may be one of the reasons why remnants of eclogitised oceanic crust are so rarely exhumed. However continental crust (with an average composition of coesite-bearing granitic gneiss, and <10 % mafic material by volume) is less dense than the surrounding mantle at equivalent conditions (e.g. Ernst et al., 1997). Density calculations based on the composition of the Norwegian Western Gneiss Region crust show that even if the entire slab had transformed to dense minerals during subduction (which Krabbendam et al. (2000) and Wain et al. (2001) consider unlikely), it would still have been less dense than the surrounding mantle at UHP conditions (Walsh and Hacker, 2004; Fig. 4).

Whether the felsic continental crust completely transforms to a mineral assemblage stable at eclogite facies conditions or whether lower pressure minerals persist is an unresolved issue in the study of subducted and exhumed continental crust. Evidence from numerous localities, including the Bergen Arcs and Western Gneiss Region in Norway, and the Western Alps, suggests that granulite facies rocks can persist metastably through a subduction-exhumation cycle so long as they remain dry and/or undeformed (e.g. Wain et al., 2001 and references therein). What is less clear is whether "wetter" continental crust behaves equally metastably under subduction conditions. A recent study of garnets in the quartzofeldspathic gneisses of the Norwegian WGR showed that the cores grew mostly grew during prograde metamorphism (but only up to ca. 1.7 GPa) and the rims grew mainly during the amphibolite-facies overprint that postdated UHP metamorphism (Peterman et al., 2009). Very little garnet appears to have grown during the HP-UHP stage, implying that much of the WGR country rock did not transform to eclogite facies-stable mineralogy during subduction. This observation may also have implications for the geochronology of the HP-UHP stages, especially when using garnet Sm-Nd or Lu-Hf chronology. Zircon, commonly used to date the timing of peak pressure metamorphism, may only have grown during pre-HP prograde or during retrograde amphibolite-facies conditions. Careful trace element analyses of any dated zircon should help to determine the conditions under which it crystallized (e.g. Rubatto, 2002; Rubatto and Hermann, 2007).

Similar observations on incomplete transformation of subducted crust have been reported from the western Alps, where the Brossasco granite in the Dora Maira Massif appears on the macroscale to have remained undeformed and unreactive during subduction and exhumation (Lenze and Stockhert, 2007). Microstructural evidence from quartz suggests that it transformed to coesite and back to quartz during subduction and exhumation (Lenze and Stockhert, 2007). Laboratory experiments suggest that this transition takes place within hours (Lenze et al., 2005). Randomly oriented twins in jadeite and kin-bands in kyanite suggest that deformation at UHP conditions was driven by the volumetric change from coesite to quartz rather than any far-field tectonic stress (Lenze and Stockhert, 2007). This evidence suggests that even though some minerals remain unreactive and metastable, the quartz-coesite transition takes place instantaneously, at least on geological timescales.

Sluggish reaction kinetics during the transformation of continental crust in subduction zones will therefore reduce the expected density of the subducted crust. This means that it will be more difficult to subduct the crust to great depths, unless it is particularly strong and can remain attached to the downgoing slab. As discussed in the previous section, many of the crust-weakening processes require hydration and/or mineral recrystallization, so if the crust is particularly dry then the decoupling mechanisms may also proceed more slowly. More research is needed into the rate and completion rate of metamorphic reactions and the factors contributing to reaction overstepping and metastability to improve knowledge of material pathways in subduction zones.

5 External tectonic forces

Numerical models of the transition from oceanic subduction to continental collision show that tectonic forcing mechanisms such as plunger expulsion and driven cavity (forced return) flow are both physically plausible and may operate at different depths and at different times in the subduction channel (Burov et al., 2001; Warren et al., 2008b). Proving the operation of these mechanisms, however, requires careful interpretation of structural and geophysical data, and metamorphic P-T-t data may not provide unambiguous proof.

5.1 Plunger expulsion

This mechanism involves the expulsion of weaker (hotter) material due to the insertion of stronger (colder) material into the subduction channel (e.g. Warren et al., 2008b; Fig. 1b). Entrance of stronger crust into a subduction channel forces a strong downwards flow of weaker material ahead of it. Exhumation flow is generated when the subducting flow is constricted by a "choke point" at the base of the subduction channel. Numerical models suggest that in order for the plunger mechanism to operate, the plunger must be considerably stronger than the material in the subduction channel (Warren et al., 2008b). Furthermore, the along-channel pressure gradient driving the return flow must be sufficient to overcome the traction forces at the top of the channel and along the roof of the plunger. For a system subducting material of heterogeneous strength, the plunger model predicts episodic exhumation during the subduction of the stronger units. This mechanism has been suggested for the exhumation of cryptic lower crustal granulitised eclogites in the eastern Himalaya (Kellett et al., 2010; Grujic et al., 2011; Warren et al., 2011), but its operation may be difficult to prove in ancient collisional settings.

5.2 Driven cavity (forced return) flow

Driven cavity flow is induced by the traction of the subducting material along the base of the channel (Fig. 1c). This traction drives a circulatory or eddy flow that exhumes material out of the channel. Its higher structural level equivalent, corner flow, was proposed in the 1980s to help explain the exhumation of blueschists in subduction zone mélanges (Shreve and Cloos, 1986; Cloos and Shreve, 1988). Using numerical models Burov et al. (2001) and Warren et al. (2008b) showed that a similar mechanism could also explain the exhumation of UHP material.

To drive efficient exhumation by driven cavity flow, subducting crust must detach from the subducting plate and accrete in the subduction channel. Exhumation is efficient when the subducting material and accreted channel material are strongly coupled – if not, then the material in the channel will stagnate. Driven cavity flow will exhume material which is neutrally or only weakly positively buoyant, but this mechanism does not, at least in the models, produce extremely rapid exhumation rates (Warren et al., 2008b). This mechanism can, in theory, produce continuous exhumation. The operation of this mechanism in fossil subduction zones would be difficult to prove, but may explain the exhumation of mélanges of blocks recording different P-T-t paths and variable timing of attainment of peak metamorphism.

6 How is space created for exhuming material?

As already discussed, in order for deeply subducted material to exhume “up the down escalator”, the upwards-acting forces must overcome the downwards-acting forces. One way to reduce the traction forces is to reduce the coupling between the upper and lower plates by separation, thereby creating space, and a weak zone, into which the exhuming material can move (Dewey, 1980; Malusà et al., 2011). This may be achieved by slab rollback or upper plate retreat in two-dimensional space or by transtension in three-dimensional space.

6.1 Slab rollback

During slab rollback the trench retreats away from the upper plate, causing it, and the accretionary wedge, to extend and thin. This creates an opportunity for buoyant high-pressure rocks to exhume into the created space (e.g. Dewey, 1980; Jolivet et al., 1994; Malusà et al., 2011). Exhumation of HP (but not necessarily UHP) rocks in locations such as the Aegean and Calabria-Appenine belts appear to be associated spatially and temporally with slab rollback events (Brun and Faccenna, 2008).

Slab roll-back occurrence depends on the force balance between the density of the subducting slab,the coupling strength of the subduction zone and the viscosity of the mantle lithosphere that the slab is rolling back into. Subduction velocity is also involved – slower subduction rates allow gravity to exert more of a dominating force on the slab, creating a more vertical trajectory, and decoupling the slab from the upper plate e.g. shown in the numerical models of Warren et al. (2008b). The (transient) insertion of thicker continental material into the subduction zone may trigger a decrease in the subduction rate, hence allowing the subducting slab to steepen and roll back (Brun and

Faccenna, 2008; Fig. 5). The ensuing trench retreat would therefore create space for detached subducted material to exhume.

Alternatively, other numerical models suggest that surface extension is caused by the upwards-acting force of the exhuming material. In cases where the exhuming material (e.g. Fig. 1) is particularly buoyant and/or moving at high velocity, it “punches” through the overlying material and forces lateral flow (Warren et al., 2008c; Beaumont et al., 2009; Butler et al., 2011). In such cases subsequent re-working of the exhumed material during lateral transport may obliterate clues about its exhumation history (Butler et al., 2011).

6.2 Upper plate retreat

Extension along the subduction channel may also be created by the retreat of the upper plate relative to the trench. The main difference in outcome between slab rollback vs. trench retreat is suggested to be the final structural position of the exhumed HP units (Fig. 6) – more towards the upper plate in the case of upper plate retreat and more towards the subducting plate in the case of slab rollback. Upper plate retreat has been suggested for the Eclogite Belt of the Western Alps (Malusà et al., 2011), but more work is needed to strengthen the suggestion that the final structural emplacement of the exhuming high-pressure rocks is unambiguously linkable to the relative motion between the subducting and upper plates.

Alternatively, the emplacement of the exhuming (U)HP material on either side of the accretionary wedge may be related to whether the upper plate deforms or acts as a backstop (Butler et al., 2011). Further detailed structural, geochronological and regional tectonic information is needed to determine whether either of these scenarios is likely in different subduction zone settings.

6.3 Transtension

Transtension involves both extensional and transverse shear, i.e. a combination of normal and strike-slip faulting. In this way, space is made available for exhuming material in three dimensions, whereas slab rollback and subduction zone divergence operate in two dimensions. Exhumation in a transtensive region is achieved in a similar manner to slab rollback or subduction zone divergence but diachronously along strike, as the orogen “unzips”. Transtensional and rifting mechanisms have been proposed for the Miocene-Pliocene Papua New Guinea eclogites (discussed above and by Ellis et al., 2011) as well as the Devonian Western Gneiss region in the Norwegian Caledonides (Fossen, 2010).

In the Norwegian Caledonides, high and ultra-high pressure rocks are exposed in a series of gentle corrugational folds beneath a major flat-lying extensional shear zone (Root et al., 2005; Fossen, 2010). Recent reconstructions suggest that Devonian-aged extension in the Caledonides was concentrated in a lozenge-shaped region, with maximum extension between the Western Gneiss Region in Norway and the Fjord Region of East Greenland (Fossen, 2010; Fig. 7a). This reconstruction suggests that the corrugational folding of the exhuming plate and focused exhumation within that region may have been caused by the transtensional tectonics as shown by recent analogue experiments (e.g. Venkat-Ramani and Tikoff, 2002). The combination of high strain, and hot, partially molten rocks may have locally accelerated the exhumation of the Western Gneiss Region to at least mid-crustal levels. Later extension at higher crustal levels appears to have facilitated the final exhumation to the surface as well as creating the space for large Devonian-aged depositional basins (Fig. 7b).

7 Combinations of exhumation mechanisms

The exhumation of large tracts of oceanic crust subducted to, and exhumed from, UHP conditions is rare, in part because eclogitised oceanic crust is negatively buoyant with respect to the mantle. However the fact that UHP tracts of oceanic crust are exposed at the surface shows that mechanisms exist to return considerable volumes of dense material to the surface. The Monviso and Zermatt-Saas units of the western Alps are arguably the two best-documented oceanic crustal UHP terranes (Agard et al., 2009). Both of these units wrap continental crust-derived “Internal Crystalline Massifs” such as the Monte Rosa (Fig. 8), and the Dora Maira massifs, suggesting that buoyant assistance from an underlying exhuming block or plume of continental material helps its exhumation. Support for this hypothesis comes from similar exhumation rates and timings for both the oceanic and continental units in the Western Alps (Agard et al., 2009 and references therein).

Blocks and slices of HP (and rarely UHP) oceanic crustal material are nearly ubiquitously associated with a weak matrix – either serpentinites, which possibly originate from the mantle wedge or the slab mantle (Guillot et al., 2001, 2007, 2009; Agard et al., 2009), or weak sediments (e.g. Guillot et al., 2009). These are thought to provide a weak buoyant matrix that assists the exhumation of denser eclogitic blocks within it (Pilchin, 2005).

8 Discussion

A recent review (Guillot et al., 2009) suggested that high pressure terranes may be classified into three main types:

1. accretionary (mainly exhuming blueschist-facies accretionary-wedge derived metasediments),
2. serpentinite subduction channel (exhuming blocks of blueschist and eclogite facies metabasalt and metasediment in a serpentinite matrix during oceanic crust subduction), and

3. continental (exhuming large tracts of relatively coherent high and ultra-high pressure continental crust during the transition from oceanic subduction to continental collision).

These three types may coexist along the same subduction zone or transition from one to the other during oceanic closure and continental collision. The mechanism(s) driving exhumation in each case may also vary in space and time. In order to determine the most likely dominant mechanism or how dominance varies with time, it is useful to assess the relative buoyancy of the exhuming material, its relative strength, the amount of material exhumed and the overall tectonic setting.

There are still uncertainties about the timescales over which exhumation takes place in the exhumation types described above. Is exhumation a transitory "pulse" or a continuous "flow" in each of the three types? Do deeply subducted terranes only have one "opportunity" for exhumation or are there cases where multiple pulses of exhumation of the same material may be demonstrated (Rubatto et al., 2011)? What is the balance between buoyancy and tectonic forces in driving exhumation in the three types and how do these change with time? What limits the timescale(s) over which HP and UHP rocks are exhumed? How, where and when does exhumation change from being dominated by buoyancy, to being dominated by tectonics, to being dominated by surface processes?

9 Conclusions

Despite our understanding of crustal subduction, metamorphism and exhumation to and from depths >100 km developing hugely since the discovery of natural coesite in crustal rocks (Chopin, 1984; Smith, 1984), there are still major uncertainties about the mechanisms by which such buoyant material is transported down and back up a subduction channel. In order to subduct to great depths, buoyant crust must stay attached to a denser, stronger substrate, yet must weaken, detach, and be at least initially buoyant in order to exhume. Continental crust appears to remain inherently buoyant compared to the mantle to depths of ~120 km, but oceanic crust appears to require either a more buoyant matrix such as serpentinite or the exhumation of more buoyant continental crust beneath it in order to assist exhumation.

Exhumation rates on the order of cm a^{-1} have been described from many orogens, with rates appearing to slow as the exhuming material reaches mid crustal levels. In many cases such as in the western Alps and western Himalaya, exhumation appears to initiate within a few Ma of subduction. In others such as in the Norwegian Caledonides or in Papua New Guinea, exhumation appears to initiate as many as 20–30 Ma after subduction. Questions still remain about how and why these rocks stay at mantle depths for so long without recording their history.

Clearly in many cases a combination of buoyancy and tectonic forces operate either in tandem or at different times to exhume deeply subducted material. The dominant mechanism and resulting exhumation rate in each case depends on the density difference between the exhuming material and surrounding rocks, the viscosity of the subducting and exhuming material (itself dependent on temperature, fluid concentration, melt proportion, mineralogy and microstructure), shear traction, velocity of subduction, and the coupling between the upper and subducting plates which influences the amount of space available for surface-directed motion. The determination of how, when and where the force balance within a subduction zone changes over time remains one of the outstanding questions in understanding how deeply buried material is returned to the surface "up the down escalator".

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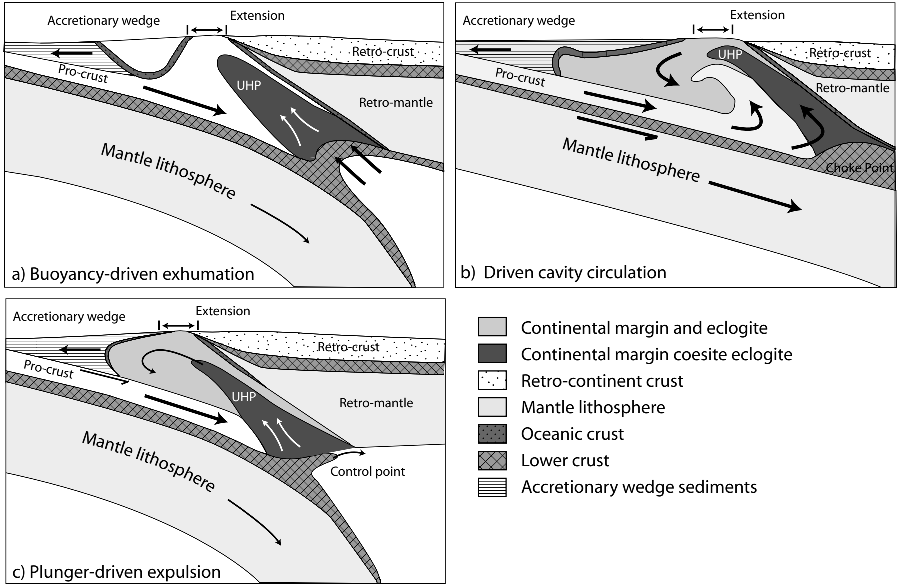

Fig. 1. Schematic diagram showing example styles of exhumation. **(a)** Buoyancy-driven exhumation, where upwards motion is driven primarily by the buoyancy force of the exhuming material; **(b)** driven-cavity flow, where upwards motion is driven by circulatory flow initiated by the traction of the subducting plate; and **(c)** plunger-driven expulsion whereby weaker material in the channel is expelled upwards between a choke point at the base of the channel and stronger crust entering the channel. Modified from (Warren et al., 2008b).

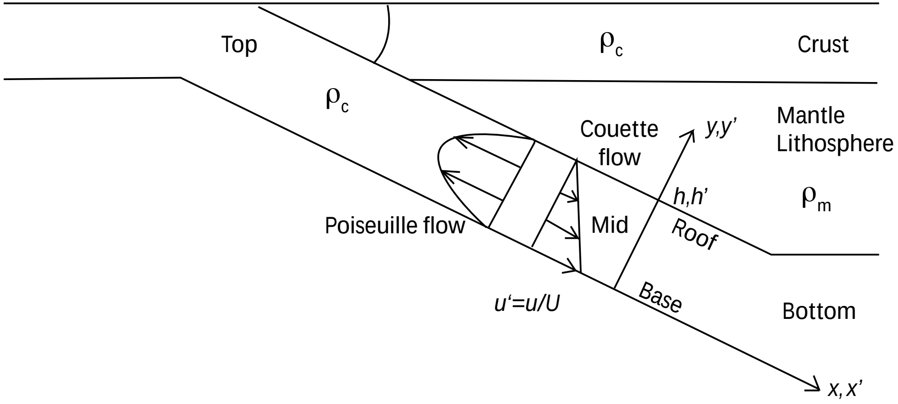

Fig. 2. Schematic diagram showing the nomenclature of subduction/exhumation channel flow behavior in terms of dominating Couette (subduction) and Poiseuille (exhumation) flows. Figure is modified from Warren et al. (2008a, c).

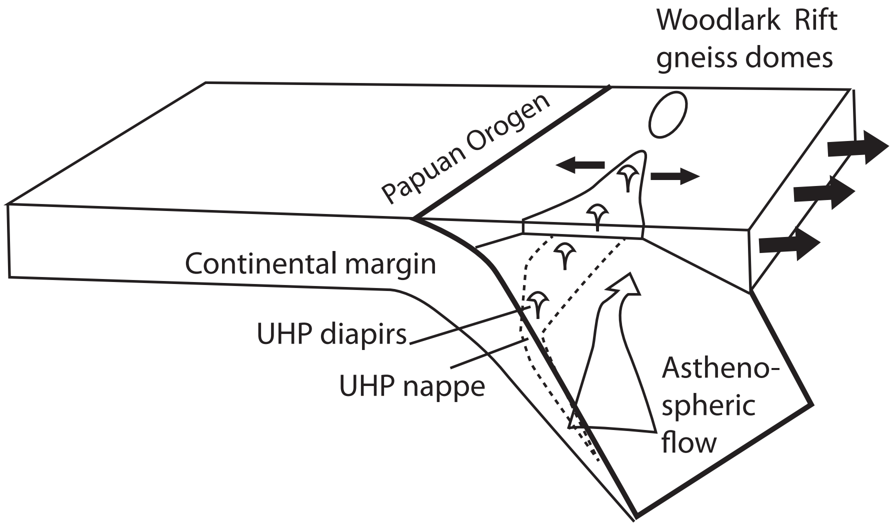

Fig. 3. Cartoon showing the suggested evolution of the D'Entrecasteaux Islands UHP terrane modified from Little et al. (2011). Rifting resulted in asthenospheric flow ahead of a spreading ridge. Hot mantle material may have heated the previously subducted crust, and/or supplied fluids that allowed the material to recrystallize in the eclogite facies. Subsequent partial melting may have resulted in the formation and upwelling of diapirs, which rose through the mantle and caused doming in the overlying crust.

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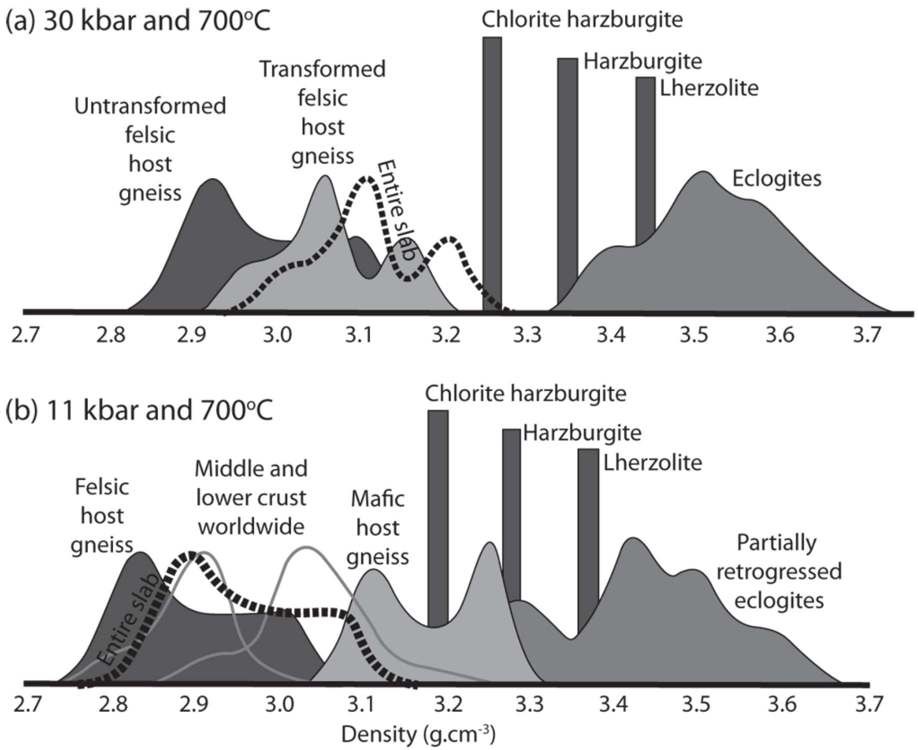

Fig. 4. Figure modified from Walsh and Hacker (2004) showing the calculated densities of the WGR at **(a)** UHP conditions and **(b)** during the amphibolite-facies overprint, using the formalism of Hacker and Abers (2004). Mafic rocks were estimated to form 10 % by volume of the subducted slab.

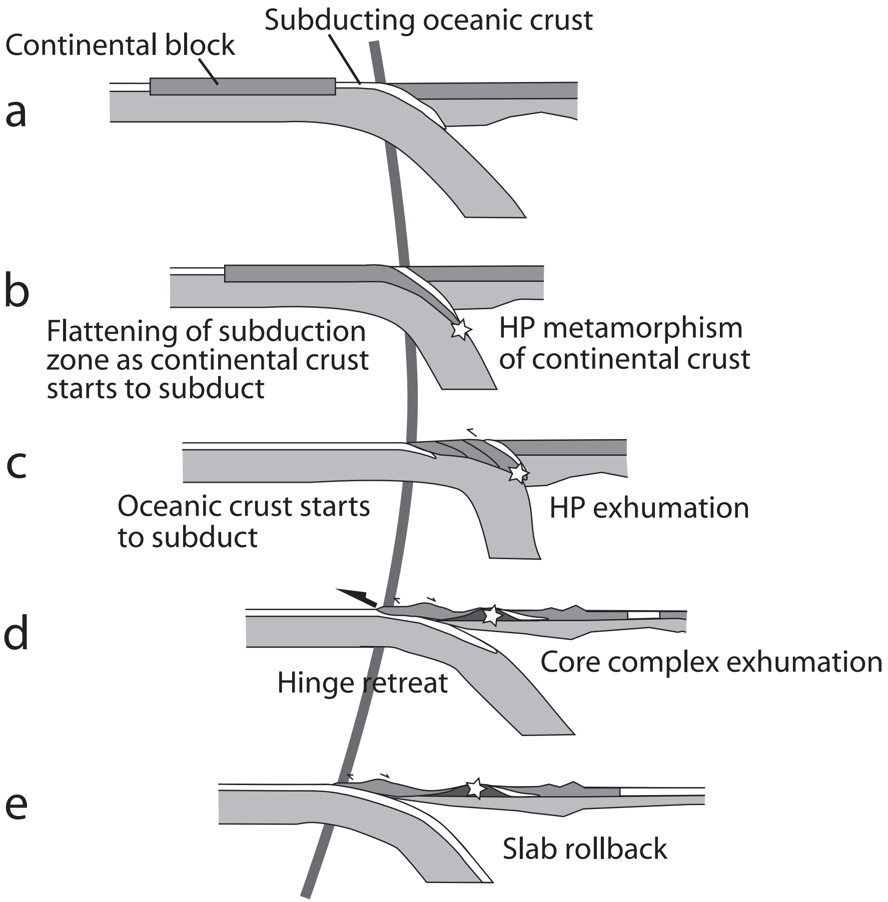

Fig. 5. Figure modified from Brun and Faccenna (2008) showing the interpreted development of slab rollback tectonics and the exhumation of high pressure rocks in domal culminations within that framework.

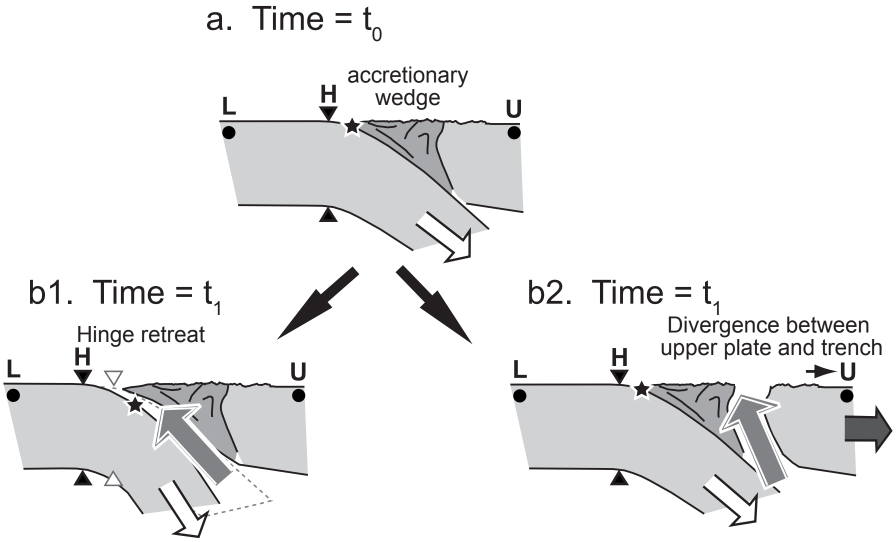

Fig. 6. Figure modified from Malusà et al. (2011) showing a suggested difference in structural position of exhumed UHP units depending on the divergence of the upper and lower plates above the exhuming high-pressure rocks: **(a)** subduction zone before exhumation; **(b1)** retreat of subduction hinge, with high-pressure rocks exhumed on the lower-plate side of the orogen; **(b2)** Upper plate motion away from the trench, with high pressure rocks exhumed on the upper-plate side of the orogen. L = lower plate, U = upper plate; black dots indicate fixed positions on those plates. H = subduction hinge.

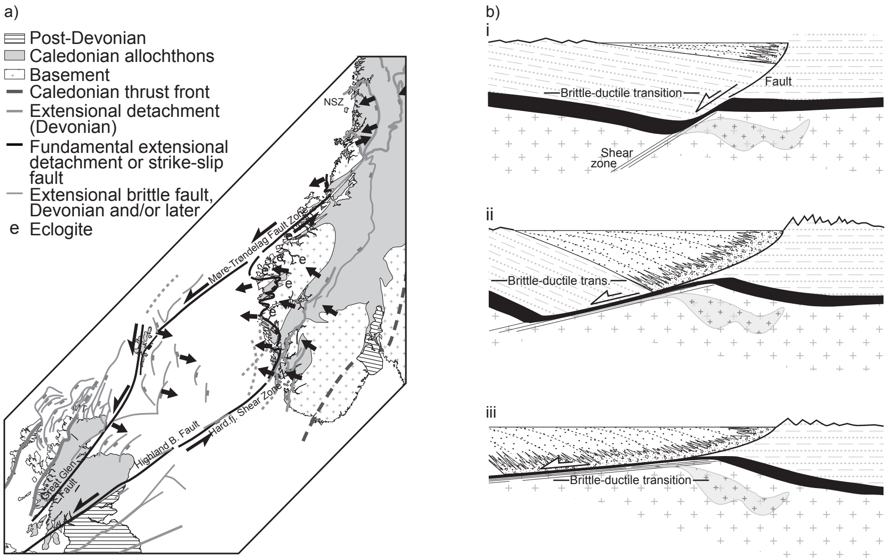

Fig. 7. Figures modified from Fossen (2010) showing the suggested role of transtension in the exhumation of the Caledonian ultra-high-pressure Western Gneiss Region in Norway: **(a)** sketch structural map of western Norway and Scotland showing the major strike-slip and detachment faults, gross geology and location of major eclogite bodies; **(b)** illustration of how low-angle detachments may form initially as high-angle faults that rotate to lower angles at increasing strain. This allows rotating beds to develop in hanging wall basins, such as the Devonian Hornelen Basin.

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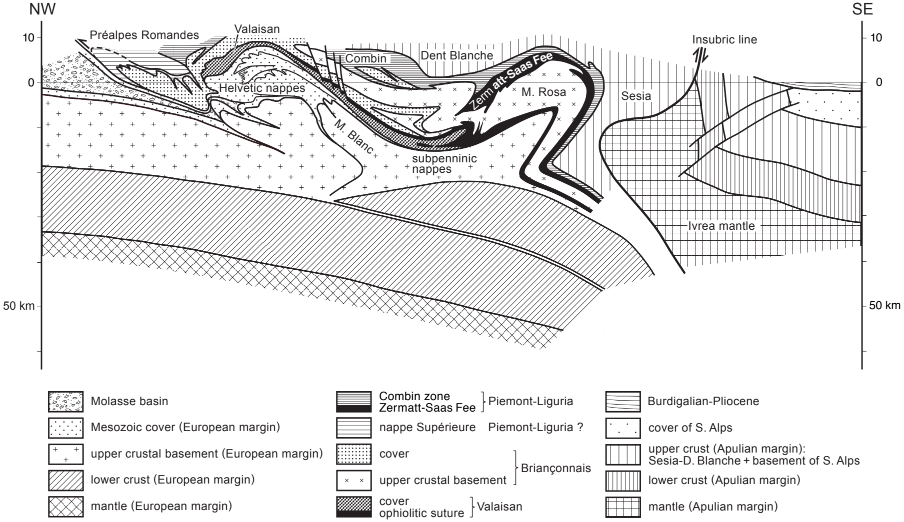

Fig. 8. Cross section through the Western Alps, modified from Schmid et al. (2004) showing the continental crustal Monte Rosa unit wrapped above and below by the Zermatt-Saas and Ligurian ophiolite sequences. It is suggested that the Zermatt-Saas ophiolite, which was metamorphosed under UHP conditions, had buoyant assistance during exhumation from the underlying continental-crustal Monte Rosa terrane (Agard et al., 2009).