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Episodic slab rollback fosters exhumation of HP–UHP rocks

Laurent Husson,[1] Jean-Pierre Brun,[1] Philippe Yamato[1,2] and Claudio Faccenna[3]

[1]*Géosciences Rennes, CNRS* UMR6118, *Université Rennes* 1, 35042 *Rennes, France. E-mail: laurent.husson@univ-rennes1.fr*
[2]*ETH-Zürich, NO-E31 Sonneggstrasse* 5, CH-8092 *Zürich, Switzerland*
[3]*Dip. Scienze Geologiche, Università degli Studi "Roma TRE", Largo S.Leonardo Murialdo* 1, 00146 *Roma, Italy*

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SUMMARY

The burial–exhumation cycle of crustal material in subduction zones can either be driven by the buoyancy of the material, by the surrounding flow, or by both. High pressure and ultrahigh pressure rocks are chiefly exhumed where subduction zones display transient behaviours, which lead to contrasted flow regimes in the subduction mantle wedge. Subduction zones with stationary trenches (mode I) favour the burial of rock units, whereas slab rollback (mode II) moderately induces an upward flow that contributes to the exhumation, a regime that is reinforced when slab dip decreases (mode III). Episodic regimes of subduction that involve different lithospheric units successively activate all three modes and thus greatly favour the exhumation of rock units from mantle depth to the surface without need for fast and sustained erosion.

Key words: Subduction zone processes; Continental margins: convergent; Dynamics of lithosphere and mantle; High strain deformation zones.

1 INTRODUCTION

The burial and exhumation cycle of rocks that underwent high pressure and low temperatures with respect to a mean crustal geotherm (HP metamorphism) is related to the subduction process. Metamorphosed stacks of blueschists or eclogites are widely found in mountain belts (e.g. Maruyama *et al.* 1996; Ring *et al.* 1999; Chopin 2003). But the fact that not all orogenic systems display high pressure (HP) or ultra high pressure (UHP) rocks at the surface is remarkable: blueschists and eclogites are essentially found in convergence zones in which the lower subducting plate was anything but a uniform oceanic lithosphere during the burial cycle: the Alps (e.g. Handy *et al.* 1999; Rosenbaum & Lister 2005), Zagros (e.g. Agard *et al.* 2006), and the Himalayas (e.g. Allègre *et al.* 1984), but also smaller systems of the Mediterranean domain (e.g. Stampfli 2000; Jolivet *et al.* 2008), like the Hellenides and Tyrrhenian systems (e.g. Brun & Faccenna 2008) encompass most of Cenozoic HP rocks occurrences, as opposed for instance to the Andes that barely show HP rocks at surface level.

Downgoing lithospheric plates convey stacks of crustal rocks at depth. These rocks are either the crustal cover of the downgoing plate or scrapped off the upper plate crust. Their downward journey into subduction zones straightforwardly follows that of the subducting slab. Conversely, the exhumation of HP rocks that follows the burial episode is less intuitive. A plethora of models, both analogue (e.g. Chemenda *et al.* 1995, 1996; Boutelier *et al.* 2004) and numerical (e.g. Pfiffner *et al.* 2000; Burov *et al.* 2001; Gerya *et al.* 2002; Gerya & Stöckhert 2002; Yamato *et al.* 2007, 2008; Warren *et al.* 2008) have been proposed to explain the second part of the cycle, in which the rock aggregate goes towards the surface, paradoxically seemingly against the overall downward flow. In all models, HP rocks are either driven upward by their own buoyancy or advected by the surrounding flow. The following severe conditions are to be met to validate the models: comprehensive analysis of HP rocks (e.g. Ring *et al.* 1999; Agard *et al.* 2009) show that HP rock slices were assembled at depth and exhumed together. The residence time at depth lasts for ~5–10 Myr; exhumation occurs within ~10 Myr or less, that is, at rates that are in the same range as rates of plate boundary displacement (e.g. Rubatto & Hermann 2001). Such rates (up to 40–50 mm/yr) are therefore significantly higher than the highest sustained erosion rates that could be expected on the long term (much less than 10 mm/yr). In fact, two-stage exhumation is often identified, with a fast exhumation at depth, up to 10 kbar (10^9 Pa), followed by a slower event that can be attributed to erosion (e.g. de Sigoyer *et al.* 2000; Ernst 2001; Rubatto & Herman 2001; Parra *et al.* 2002; Walsh & Hacker 2004; Yamato *et al.* 2008), up to surface level.

Most previous models arbitrarily consider a stationary trench location (e.g. Chemenda *et al.* 1995; Ernst *et al.* 1997; Beaumont *et al.* 1999; Pfiffner *et al.* 2000; Gerya *et al.* 2002); such choice is very unfortunate; first, because it prevents any substantial extension in the upper plate that could favour the exhumation of rocks and, second, because the associated downward flow in the wedge tends to counter an upward motion of rocks at depth. Because these models ignore the dynamics of the mantle wedge itself that may vary depending on the subduction regime, and the potential advection of the rock within the wedge, they most often invoke more complex mechanisms like for instance the so-called subduction channel (e.g. England & Holland 1979; Cloos 1982; Shreve & Cloos 1986). In fact, stationary trenches are seldom observed, regardless of the reference frame (e.g. Lallemand *et al.* 2005), and slab rollback, that is, the motion of the entire subduction system (trench and subducting slabs) towards the foreland and relative to the lower mantle is the most natural behaviour of slabs (e.g. Funiciello *et al.* 2003). In addition, the subduction of a heterogeneous plate leads to transient subduction kinematics: subduction rate, trench migration rate and slab geometry very efficiently respond to heterogeneities in the plate rheology or buoyancy and are often unsteady (Martinod *et al.* 2005; Royden & Husson 2006). Thomson *et al.* (1998) or Brun & Faccenna (2008) noticed that such transient behaviour is observed in the Hellenides and in the Mediterranean domain in general (Royden 1993). Rollback-type settings favour the exhumation of HP rocks, chiefly because upper plate extension during rollback sets free space that can be filled up by rocks from underneath and therefore causes the exhumation of HP rocks (Gorczyk *et al.* 2007; Brun & Faccenna 2008; Faccenda *et al.* 2009).

The final exhumation of HP crustal slivers occurs inside the wedge. Field relationships and tectonic reconstructions show that their way back to the surface is often accompanied by 'syn-orogenic' extensional detachments positioned on the roof of the exhumed sliver (Platt 1986, 1993; Chemenda *et al.* 1995; Ring *et al.* 1999; Hacker *et al.* 2003; Jolivet *et al.* 2003, 2008). This deformation pattern suggests that during exhumation the overall backarc area was not under compression, although convergence and subduction were at work. This is typical of the Mediterranean realm, where exhumation was produced during the formation of the arc and often accompanied by backarc spreading (Jolivet *et al.* 2003; Brun & Faccenna 2008). In such tectonic context, most favourable to exhumation, the upper plate then plays a subordinate role, passively moving and deforming under the action of the return flow.

The aim of this work is to explore the advecting power of the sublithospheric wedge (simply referred to as 'wedge' in the following) and investigate how the poloidal flow in the wedge above the slab differently affects the upward journey of rock slices towards the surface. Our model can be pertinent to explore the movement of crustal buoyant sliver units detaching from the slab, penetrating into the mantle wedge and rising up at the boundary between the upper plate and subducting slab (i.e. the first stage of exhumation). With respect to previous work dealing with the interaction of a positively buoyant rock unit with the mantle flow excited by a purely downdip slab velocity (Hall & Kincaid 2001; Gerya & Yuen 2003; Manea *et al.* 2005; Castro & Gerya 2007), our study investigates the behaviour of units of variable buoyancies within a corner flow that is excited by different kinematical conditions, including slab rollback and oscillating slab dip.

In the following, because we consider the end-member situation where the upper plate has a negligible thickness, we do not consider the exhumation stage within the orogenic wedge but instead we explore the advecting power of the sublithospheric wedge (simply referred to as 'wedge' in the following) and investigate how the poloidal flow above the slab differently affects the upward journey of rock slices towards the surface. It is argued that slab rollback is more efficient than stationary trenches to exhume HP rocks, that slab shallowing does an even better job, and that the latter settings are commonly associated to HP rocks occurrences.

2 FORCES DRIVING EXHUMATION

In the wedge above the slab, a rock slice is primarily driven by two mechanisms: the buoyancy of the rock unit with respect to the surrounding material, and the flow of the material in the wedge that may advect it.

2.1 Intrinsic velocity of the HP rock units

Although there is no comprehensive description of HP rock units in terms of size and density, it seems that the vast majority is either neutrally or positively buoyant, that is, the mean density of the rock aggregate is equal or lower than that of the surrounding material and its natural velocity in a homogeneous viscous material is upward. A handful of units for which the density is higher than that of the surrounding material, like the Alpine eclogites (Zermatt–Saas, Monviso), is reported, but those units generally are embedded within serpentinite and/or continental crust rock units of lower density (e.g. Guillot *et al.* 2004; Agard *et al.* 2009) and it is unclear what the overall buoyancy is. Units of HP rocks are generally composed of stacks of rock slices that were assembled at depth. The observed characteristic size of the assemblage is tens to hundreds of kilometers. The vertical velocity of a unit scales with its size and, for a sphere in a viscous medium, its velocity v_0 is the Stokes velocity and increases like the squared radius of the sphere. It is therefore possible that HP rocks assemblages build up at depth until the intrinsic velocity of the assemblage is high enough to make it flow upwards. (Note, however, that the intrinsic velocity from the density of a rock stack in the wedge may depart from the Stokes velocity because the actual velocity of the particle also depends on many unknown parameters like the density contrast of course, but also the viscosity and the shape of the body of HP rocks itself).

This non-linear relationship in turn also implies that for a given density contrast between the rock stack at depth and surrounding material, there is a maximum size for the aggregate, after which rock units are removed faster than they are being aggregated: rocks stacks form at depth at a rate that is proportional to the subduction rate but the vertical velocity is not proportional to the volume of the body and therefore is not proportional to the rate at which rocks aggregate at depth. Removal of rock slices at depth is thus episodic and the period of removal is characterized by the balance between the 'productivity' of the subduction, that is, the rate at which rocks can be scrapped off the downgoing plate and accumulate at depth, and the rate at which the intrinsic velocity of the rock slice increases.

As emphasized in many studies (e.g. Chemenda *et al.* 1995; Ernst *et al.* 1997; Burov *et al.* 2001), the buoyancy of the aggregate is indeed a fundamental driving mechanism. But because the associated intrinsic velocity is generally too small (a few millimeters per year, Agard *et al.* 2009) and because the buoyancy of some units—eclogites for instance—is occasionally insufficient to achieve fast exhumation, other processes should be considered. Can the flow in which the aggregate moves be an additional contributor and efficiently advect it towards the surface?

2.2 Corner flow and subduction modes

Subduction zones have variable behaviours than can either be stationary, in which case the trench remains at the same location with respect to the lower mantle, or retreating (slab rollback) when the trench moves towards the foreland (and conversely, advancing). Because subducting lithospheres can be heterogeneous, subduction zones are often in transient regimes, and slab geometries varies accordingly (Garfunkel *et al.* 1986; Martinod *et al.* 2005; Royden & Husson 2006). For instance, the slab steepens when a

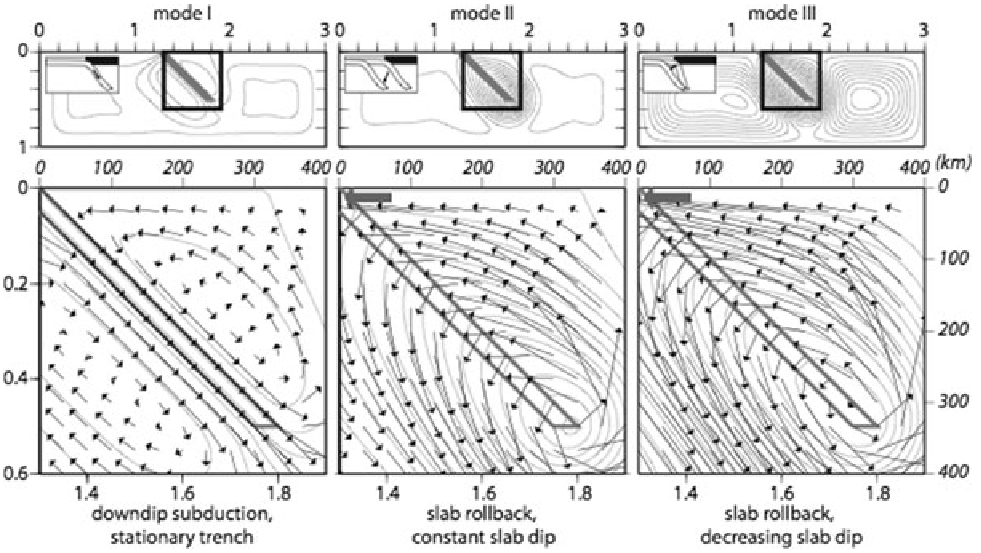

Figure 1. Flow field and streamlines in the mantle wedge for stationary trench (mode I); slab rollback (mode II); slab rollback accompanied by a decrease in slab dip (mode III). Top: cartoons and full models; bottom: zooms over the subduction wedges. Grey arrow denotes trench motion. Dimensionless and dimensional (italic) units.

unit of moderately negatively buoyant continent follows a highly negatively buoyant oceanic lithosphere. Examples can be found in the Banda and Tyrrhenian subduction zones (Royden & Husson 2009). Conversely, the subduction angle decreases when a negatively buoyant oceanic lithosphere follows the subduction of a less negatively buoyant unit like a continental island or an oceanic ridge embedded within a negatively buoyant lithosphere. The associated corner flow varies accordingly and can contribute to, or oppose, the exhumation of HP rocks. To compare the driving or resisting efficiency of the different subduction regimes, we solve for the poloidal flow of an isoviscous fluid within a two-dimensional domain (Fig. 1). It implies that return flow can always accommodate the displacement of the slab, although toroidal flow may also contribute and thus decreases the vigor of the poloidal flow (e.g. Piromallo *et al.* 2006; Stegman *et al.* 2006). The model can be naturally adimensionalized taking the subduction rate v_0, the upper mantle thickness H and the viscosity η_0 of the mantle (results are given in both dimensionless and dimensional values, computed for $v_0 = 40$ mm/yr, $H = 670$ km, and $\eta_0 = 10^{20}$ Pa s). The model represents a section of the upper mantle in which a subducting slab penetrates down to half the thickness of the upper mantle. The prescribed motion of a rigid panel that dips at 45° from the surface to a depth 0.5 (335 km) drives the flow. The fact that the slab only penetrates to half the upper mantle depth is designed to let the mantle flow freely in the poloidal field, because most small-scale slabs are dismantled at depth in the upper mantle, do not behave as consistent bodies all the way down to the top of the lower mantle, and therefore allow for poloidal flow originating at depth, around slab tails. This is opposed to many models of subduction zones (among many others, see Funiciello *et al.* 2003; Stegman *et al.* 2006; Royden & Husson 2006; Capitanio *et al.* 2007), but in fact more accurately reproduce the structure of the upper mantle as seen from geophysical observations (e.g. Faccenna *et al.* 2003 for the Mediterranean). We solve the stream function Ψ such that $\partial\Psi/\partial y = -u$; $\partial\Psi/\partial x = v$. For an incompressible fluid, Ψ verifies the biharmonic equation $\nabla^4\Psi = 0$. The stream function, and therefore the velocity, is prescribed at the boundaries and on the slab itself. The velocity at the boundaries is null and Ψ is defined on the slab such that the subduction rate v_0 is similar for all modes. The models are much simplified to allow for a comparison of the different subduction modes. To isolate the particular effect of variable corner flows, we assign the upper plate a null thickness, for it is supposed to play a passive role in the system. A thorough description of the flow in the wedge is beyond the scope of this work; we emphasize, however, that the comparison between simplified models is the most reliable way to quantify the relative contribution, in the exhumation process, of the corner flows within different modes of subduction.

The flow lines and velocity fields are shown on Fig. 1 for three different modes that highlight the contrasted, end-member flow patterns. For stationary trenches (mode I, Fig. 1a), where the slab does not change its dip or its location with respect to the mantle, slab motion is only downdip and two typical corner flow cells are well defined above and below the slab. The velocity field above the slab is downward and would not promote the exhumation of HP rocks. For purely retreating slabs (mode II, Fig. 1b), where the slab retreats with a velocity field that corresponds to a fixed foreland (the left hand side of the slab is fixed with respect to the bottom of the model), only one cell develops around the slab; above the slab the velocity field is essentially upward. The downdip velocity component along the slab is much smaller than the rollback component. Finally, for a decrease in slab dip (mode III, Fig. 1c), where the slab rotates around its tail that is anchored in the mantle, only one cell remains too, but the velocity field above the slab is strongly upward and higher than when the slab is only retreating without changing its dip. The downdip velocity component is neglected to more accurately represent the situation were only the shallowest part of the slab is dense enough to drive the subduction (see Section 4).

Amongst the three modes, two of them clearly show an upward velocity field above the slab: although a subduction zone with a stationary trench only drags the particles above the slab downward, a subduction zone with a retreating slab, and even more efficiently with a retreating slab whose dip decreases, induces an upward flow field that can only participates to the exhumation of high pressure rocks that are released from the slab at depth. Note that the velocities in the wedge are comparable in magnitude to that of the subducting slab. Other possible modes like slab steepening or trench advance are

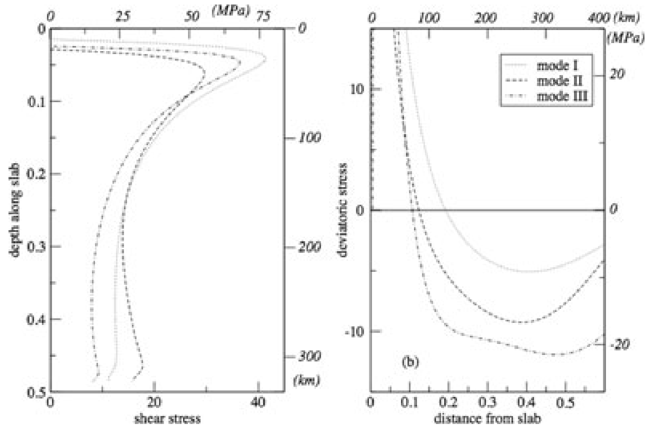

Figure 2. (a) Shear stresses along the surface of the slab and (b) deviatoric stresses at depth 0.1 (∼70 km) in front of the subducting slab. Dimensionless and dimensional (italic) units.

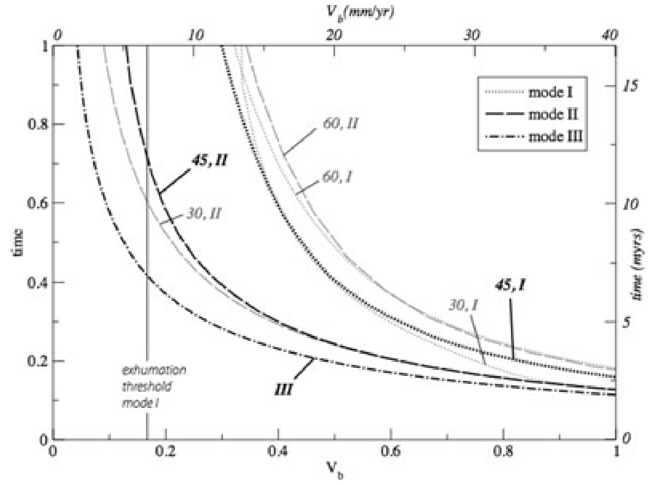

Figure 3. Delay for exhumation as a function of the intrinsic velocity of the rock unit V_b, subduction mode, and slab dip angle (labels give slab dip and mode). Vertical bar indicates the threshold under which exhumation is not achieved in mode I. Only one curve is displayed for mode III because its dip varies through time (initial dip is 90°). Dimensionless and dimensional (italic) units.

not considered here because they obviously oppose the exhumation of HP rocks.

In addition, the stress fields that are associated to the corner flows can also control the rate at which HP rocks make their way towards the surface. All three modes essentially display comparable positive shear stresses along the slab that favour the detachment of HP rock aggregates from the conveyor slab (Fig. 2a). Maximum shear stresses are found at depths lower than 0.1 (i.e. ∼70 km, typically the burial depth HP rocks reach before they are exhumed). Mode I, when the trench is stationary, favours the scrapping off rocks from the slab. Deviatoric stresses (measured in a horizontal plane) at a given depth (Fig. 2b, depth 0.1, ∼70 km) have comparable behaviours in all models, with localized strong compression (positive values) just above the slab and extension at larger distances. Horizontal extension is more than 2 times larger in mode III than in mode I, and ∼1.5 times larger than when in mode II. Extension favours the exhumation of HP aggregates throughout the wedge, rendering mode III more efficient than any other mode.

For all three modes, the very last episode of exhumation has to be driven either by extensional faulting or erosion, because the velocity field gradually becomes parallel to the surface, which of course reduces the advection capacity (Fig. 1).

3 KINEMATICS OF EXHUMATION

Once rocks are aggregated at depth and scrapped off the subducting slab, they may flow within the wedge and find their route to the surface. In the following, we test the relative influence of the buoyancy of a particle, which we characterize by its intrinsic velocity V_b, and of the wedge flow in the different modes.

3.1 Particle buoyancy and pathlines

The intrinsic velocity of the HP rock stack and the corner flow in which the aggregate is advected chiefly control the timing of exhumation. The corner flow can be driving (upward) or resisting (downward). We compare the kinematics of exhumation by tracking a particle released above the slab at a depth 0.15 (100 km) for the three modes. Unless otherwise specified, slab dip is 45° for modes I and II and the initial dip is 90° for mode III (slab dip varies in mode III and we start with the maximum dip to encompass the largest range of dip angles, from 90° to 0°).

The total time necessary for the particle to reach the surface (Fig. 3) shows that mode III is much more efficient than mode I which on the contrary slows down the exhumation process. If the intrinsic particle velocity V_b is too small with respect to the corner flow velocities ($V_b < \sim 0.17 v_0$), mode I is unable to achieve the exhumation of the particle, as opposed to modes II and III that eventually drive the particle to the surface. In any mode, steep slabs are less prone to drive the particle upwards, but more drastically in mode II (Fig. 3). The differences in the timing of exhumation are related to the pathlines of the particles within the wedge velocity fields (Fig. 4). In mode I, the slab remains at its initial location.

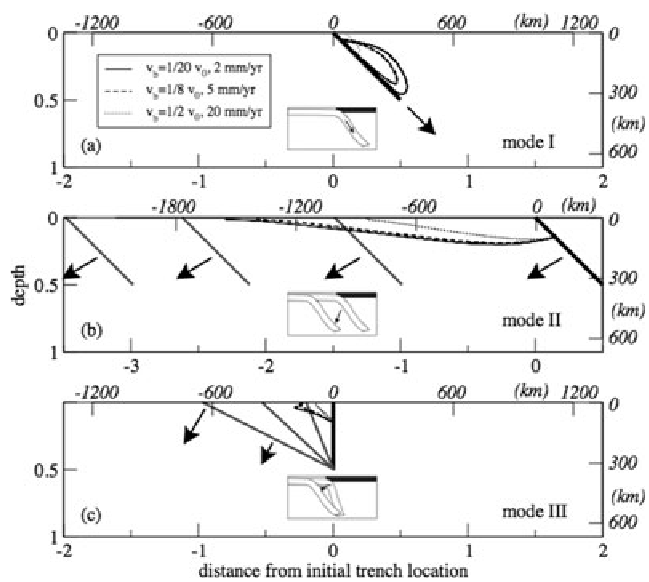

Figure 4. Flow lines for elementary rock units as a function of the ratio between intrinsic velocity of individual rock units V_b and subduction rate v_0 (1/20, solid curve; 1/8, dashed; 1/2, dotted. Dimensional values for v_0 = 40 mm/yr). Arrows show slab motion. Bold black segment shows initial slab location, grey segments in modes II and III are the final locations. Overprinted path for V_b = 1/20 and V_b = 1/8 in mode I shows the multiple cycles. Dimensionless and dimensional (italic) units.

During subduction, the particles remain at a short distance from the slab until they reach the surface. But low buoyancy particles are in a first stage driven to large depths before they reach the surface. Because this result is inconsistent with the vast majority of observed maximum burial depths of presently outcropping rocks, it suggests that essentially very positively buoyant units can be exhumed in mode I. This nevertheless is in agreement with the fact that deeper exhumed rocks are rather of continental origin (e.g. Chopin 2003; Liou *et al.* 2004). Note that, as opposed to modes II and III for which brittle extension is expected at the surface, mode I can only fully achieve the burial–exhumation cycle if erosion is efficient enough.

Very low buoyancy (or neutrally buoyant) particles are not exhumed in mode I and remain in the mantle wedge cell (Fig. 1a). In modes II and III, the particles are gradually exhumed, and even low-buoyancy particles eventually reach the surface. Pathlines are shorter in mode III than in modes I and II (Fig. 4).

3.2 Delay of exhumation

Dimensional units make it easier to compare model results to natural examples, and we keep dimensional values in the following. The total delay of exhumation (Fig. 5) essentially depends on the buoyancy of the particle and the flow in the wedge. In an inactive subduction ($v_0 = 0$), the delay is simply D times V_b, where D is the initial depth of the particle. In the following, D is set to 100 km; because the velocity field tends to parallel the surface near surface level, we consider a depth of 6.5 km as the final depth (for otherwise total time tends to infinity if the particle has no intrinsic velocity); it also means that this final exhumation process needs to be attributed to another mechanism such as erosion or crustal extension (e.g. Yamato *et al.* 2008). Depending on the location of the particle in the wedge, the flow advects the particle with a variable vigour. It can either help or resist the ascension of the particle towards the surface. The combination often produces complex behaviours.

Mode I is almost systematically resisting: the faster the subduction, the longer the total time before exhumation (Fig. 5). If the intrinsic velocity of the particle cannot overcome the downward wedge flow, the particle permanently remains in the mantle wedge cell. In mode I, exhumation does not occur, even at low subduction rates, unless the particle has an intrinsic velocity V_b higher than ~5 mm/yr (Fig. 6). Under some circumstances in mode I, the particle benefits from the upwelling mantle, or return flow (Fig. 1), that balances the downwelling effect. This is for instance outlined by the total time before exhumation of a particle that has an intrinsic velocity of 5 mm/yr in mode I (Fig. 5): for subduction rates that range from ~22 mm/yr to ~28 mm/yr the particle follows a peculiar pathline because it takes advantage of the return flow; as a consequence, the total delay of exhumation becomes shorter than for subduction rates lower than 22 mm/yr.

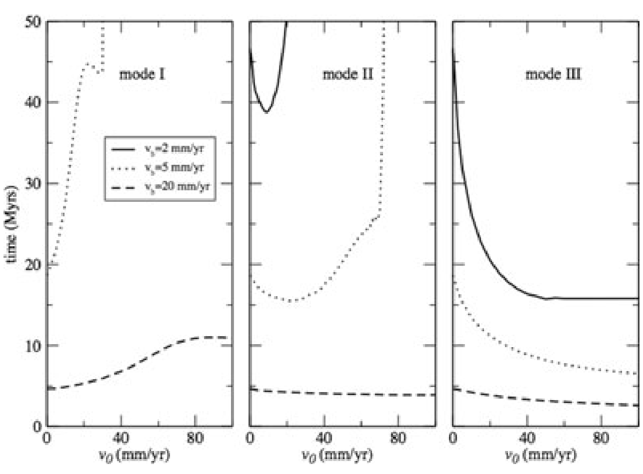

Figure 5. Total exhumation time for the three subduction modes, as a function of the intrinsic velocity of individual rock units V_b and subduction rate v_0. Dimensional units.

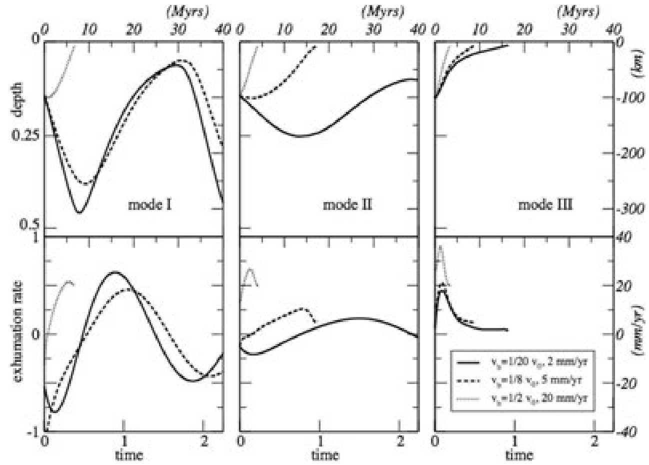

Figure 6. Burial depth (top) and exhumation rates (bot) of the rock units as a function of time and of the ratio between intrinsic velocity of individual rock units V_b and subduction rate v_0 (1/20, solid curve; 1/8, dashed; 1/2, dotted. Dimensional values for $v_0 = 40$ mm/yr). Dimensionless and dimensional (italic) units.

Mode II also shows a complex pattern (Fig. 5). Because at short distance from the slab the flow is downward, if subduction rates reach high values, the particle is dragged along with the slab and remains in the subduction cell. For instance, exhumation of a particle with an intrinsic velocity $V_b = 2$ mm/yr is fostered by subduction rates that are lower than ~10 mm/yr, but higher rates increase the total exhumation delay. At rates higher than ~28 mm/yr, the particle is never exhumed. Such scheme also holds for particles that have a higher intrinsic velocity: with $V_b = 5$ mm/yr, exhumation never occurs for subduction rates higher than ~70 mm/yr.

Mode III is always helping exhumation. For a particle with $V_b =$ 2 mm/yr, the total delay of exhumation is divided by a factor 2 with a subduction rate of ~10 mm/yr (from 50 to 25 m.yr between $v_0 =$ 0 mm/yr to $v_0 = 10$ mm/yr). A decrease in slab dip therefore very efficiently contributes to exhume HP rocks from depth.

3.3 Burial and exhumation

Because of these interactions between the vertical motion of a particle excited by its own intrinsic velocity and the wedge flow in which the particle is advected, the burial history is not monotonic (Figs 5 and 6). The most dramatic case is that of low buoyancy particles in mode I, that are stuck in the wedge cell. They are first driven to large depths before they are brought back to moderate depths and drown to large depths again, in a cyclic behaviour. The shape of the cell bounds the oscillation between depths of ~300 and ~50 km. The period of the cycle is controlled by the subduction rate v_0 (e.g. ~30 m.yr for $v_0 = 40$ mm/yr). The vertical velocities are high (Fig. 6), comparable in magnitude to the tectonic velocities. In mode II, particles that have low intrinsic buoyancies are also caught in a comparable cyclic behaviour, although the vertical velocities are lower (<10 mm/yr) because the burial depths are constrained within a thinner domain (between depths of ∼60 and ∼160 km). Such behaviour can be relevant to real Earth in the description of the wedge flow, but it would prevent the exhumation of HP rocks; of course, no observation can likely report such a pattern yet. Only if the positive buoyancy of the particle makes it overcome the advection in the wedge the particle reaches the surface. In that case, exhumation rates increase as the particles move away from the downwelling (see Fig. 1). The ascension eventually slows down as the particles approach the surface. Note that this is true in any mode because at surface level the velocity vectors tend to be parallel to the surface. In mode III, the vertical motion is always directed towards the surface, the larger the intrinsic velocity of the particle the faster it reaches the surface. With $v_0 = 40$ mm/yr, the fastest exhumation rates range between 20 and 40 mm/yr for particles with 2 mm/yr $< V_b <$ 20 mm/yr and gradually slow down to lower values as the particles approach the surface.

4 DISCUSSION

These models outline the first order behaviour of three subduction modes during the exhumation process of HP rocks. When the trench is stationary with respect to the lower mantle (mode I), the subduction zone is characterized by a powerful downwelling that drags to depth the HP rock aggregate released on the Benioff zone. It is therefore more efficient than any other mode to bury crustal material that may even be positively buoyant at large depths, but is rather inefficient to drive rocks to the surface except in cases implying high buoyancy material. Conversely, when the trench retreats during subduction (modes II and III), the wedge flow tends to advect the rock aggregate towards the surface. The vertical velocities can reach values that are comparable to tectonic velocities, that is, the velocity at which the plate subducts in the mantle. This result solves the apparent paradox based on observations that states that blueschists metamorphic rocks are often exhumed at a rate that is comparable to the rate at which the subduction panel enters the upper mantle (e.g. Thomson *et al.* 1998; Rubatto & Hermann 2001).

When trench retreat is associated to a decrease in slab dip (mode III, as opposed to mode II, where the slab uniformly retreats during subduction), the exhumation process is even more efficient. The timing of exhumation can typically be divided by a factor of two if the subduction rate increases from $v_0 = 0$ mm/yr to $v_0 = 40$ mm/yr when mode III is excited. We conclude that slab rollback accompanied by a decrease in slab dip is the most efficient yet simple mechanism for HP rock exhumation, simply because it pumps material upwards. The closer to the surface, the more efficient this process is.

Because our simple models only address a single aspect of the exhumation process and neglect the rheological complexity of subduction zones, we emphasize that the qualitative results as well as the comparison of the models relative to each other hold, but the quantitative results should be considered with care, that is, as orders of magnitude. For instance, toroidal flow may decrease the vigour of the upward, poloidal flow, by a factor of 2 (Piromallo *et al.* 2006). Similarly, radial and lateral viscosity variations, or the presence of erosion, may distort our quantitative conclusions, but would not discard the return flow as a significant contributor for HP rocks exhumation. In our models the boundary conditions are that of a fixed upper plate, that is, backarc extension occurs when the trench retreats; changing the ‘upper plate’ boundary conditions to either free slip or fixed velocity (set to trench velocity) modifies the flow field (e.g. Yamato *et al.* 2009), but in a way that do not alter our conclusions because the upward flow near the surface is also close to the subducting slab. Our results indeed suggest that only slab rollback can provide enough power to drive the exhumation of rock aggregates that have low or neutral positive buoyancies at rates that are comparable to tectonic velocities, as inferred from P–T–t paths (e.g. Duchêne *et al.* 1997; Gebauer *et al.* 1997; Rubatto & Hermann 2001; Agard *et al.* 2009) and from the dynamics of real Earth systems (Brun & Faccenna 2008).

Our analysis compares models at a given subduction rate. However, because the buoyancy and viscosity structures of subducting plates are heterogeneous, subduction dynamics may vary significantly. Alternatively, the power—literally, the rate of energy spent to move the surrounding mantle around the slab—could have been used as a reference. Equal-power comparison would give slightly different results: mode II and mode III are the least and the most energy consuming regimes, respectively, possibly making mode II more efficient than mode III to advect HP rock aggregates towards the surface within a short delay. However, equal-power comparisons are not very satisfying either, because of the association of the modes to subduction velocities. For instance, mode III is likely associated to increasing subduction rates, for instance when a dense unit of oceanic lithosphere enters the subduction (e.g. Royden & Husson 2006). Likewise, mode I requires specific conditions that may slow down subduction.

The three modes are currently found on Earth, but mode I should be considered as an oddity, in which coincidentally the lower plate is pushed towards the upper plate at a rate that is equal to the subduction rate. A steady subduction is unlikely to prevail during the 20–40 Myr long burial–exhumation cycle. In many cases, in particular where subduction zones are narrow, the behaviour of the trenches and slabs are transient. Modes II and III would thus naturally occur more often than mode I. For instance, the termination of the subduction of the African plate beneath Eurasia is characterized by the many small-scale Mediterranean subduction zones in which the incoming lithosphere is heterogeneous, which leads to a chaotic behaviour of subduction zones, that may subsequently retreat, advance or remain stationary (e.g. Royden & Husson 2009). The Mediterranean subduction zones are remarkable in that sense. One can also establish similar observations for the SE Asian subduction zones assemblage. Complex settings like those, where subduction zones are believed to occur in a succession of different stages, generally yield HP rocks. Well-documented examples include the Tyrrhenian and Hellenic subduction zones (e.g. Jolivet *et al.* 2003), Oman (e.g. Breton *et al.* 2004) or Papua New Guinea (e.g. Baldwin *et al.* 2004). Conversely, modern blueschists and eclogites metamorphic rocks are seldom found in subduction zones that undergo a steadier regime, like the long-lived, massive circum Pacific subduction zones. Many of these examples where HP rocks outcrop—particularly the Mediterranean ones—also correspond to case studies for slab rollback (e.g. Malinverno & Ryan 1986; Royden 1993). This support the idea that slab rollback promotes exhumation for two reasons. The first reason is that the overriding plate is thinner: modes II and III that prevail during rollback drive the rock unit up to shallow depths before it hits the base of the upper plate. Only mild erosion and extension suffice for the final stage of exhumation. Our simplified model considers an upper plate of negligible thickness; this assumption holds for subduction zones where significant phase of trench retreat occurred prior to the release of the rock unit at depth. Nevertheless, the thickness of the overriding plate is thought to be thinner than 100 km, and generally about 60 km (Currie & Hyndman 2006) because of the effects of enhanced corner flow and slab dehydration (e.g. Arcay *et al.* 2006)

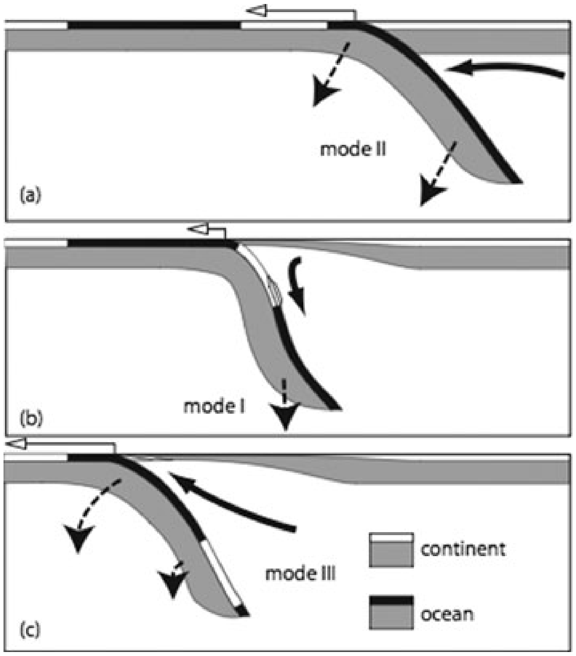

Figure 7. Sketch showing an episodic subduction triggering the burial–exhumation cycle of HP rocks. White arrow denotes trench migration rate, dashed arrows indicate slab motion and bold arrows show mantle flow.

and destabilization of the backarc lithosphere (Currie *et al.* 2008) and may tend to 0 km where backarc basins are active. Indeed, in the Mediterranean domain, overriding plates are thinned due to slab rollback (Royden 1993; Jolivet *et al.* 1994). Conversely there is, to our knowledge, no proven example where HP rocks are clearly associated with thick overriding lithospheres during the exhumation process: upper plates are thin in modern examples and older examples like the Alps or Himalayas are being debated. The second reason that we emphasize is that chaotic, or better-said episodic behaviour of subduction zones greatly promote the exhumation of HP rocks in a multi-stage story: following a subduction episode of dense oceanic lithosphere during which the trench retreats at a fast rate, in mode II (Fig. 7a); a fragment of less negatively buoyant continental lithosphere enters the subduction (Fig. 7b). The trench retreats slower and slab dip increases (although it seems counter intuitive, slab dip increases because negatively buoyant units at depth continue to sink, whereas the shallower, more buoyant units, resist subduction, Martinod *et al.* 2005; Royden & Husson 2006), entering mode I. The continental crust is buried and metamorphosed at high pressure and low temperatures. Because the wedge shears the Benioff zone and because the continental slices that are stacked in an aggregate of HP rocks have a constantly increasing upward force, the aggregate eventually detaches from the slab, at a depth at which shear stresses overcome the yield stress of the rock unit (e.g. Seno 2008). More negatively buoyant lithosphere enters the subduction and the slab rolls back again (Fig. 7c), and the dip of the slab decreases in mode III, inducing a wedge flow that triggers the exhumation of HP rocks from depth, with an upward velocity that is comparable to tectonic velocities and trench migration rate. The final exhumation stage is then promoted by the extensive strain in the upper plate. Throughout the entire cycle, the upper plate, therefore, never hampers the exhumation process. This cyclic episode can be followed by several other cycles that make it easy for HP rocks to be exhumed. More generally, any subduction zone that has a transient behaviour due to the presence of heterogeneities in the incoming lithosphere likely promotes the same mechanism.

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