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Review Article

Paradigms, new and old, for ultrahigh-pressure tectonism

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ABSTRACT

Regional ultrahigh-pressure (UHP) metamorphic terranes exhibit a spectrum of lithological, structural and petrological characteristics that result from the geodynamic processes that formed and exhumed them. At least six geodynamic processes can be envisioned to have carried continental rocks to mantle depths: i) continental margin subduction, ii) microcontinent subduction, iii) sediment subduction, iv) intracontinental subduction, v) subduction erosion, and vi) foundering of a crustal root. Most of these processes have been investigated through numerical or analog models and most have been invoked for one or more specific occurrences of UHP rocks. At least six geodynamic processes can be envisioned to have exhumed UHP continental rocks: i) eduction, ii) microplate rotation, iii) crustal stacking, iv) slab rollback, v) channel flow, and vi) trans-mantle diapirs. Most of these processes have also been investigated through numerical or analog models and all have been invoked to explain the exhumation of at least one UHP terrane. More-detailed and systematic field investigations are warranted to assess the predictions of numerical models, and more-sophisticated and realistic numerical models are required to replicate and explain the petrological, structural, and chronological data obtained from UHP terranes.

Contents

1. Introduction

The two discoverers of regional metamorphic coesite, Chopin (1984) and Smith (1984), immediately deduced that subduction of continental crust was responsible for the formation of this unusual high-pressure form of silica. This paradigm reigned for more than two decades and may well be correct for most ultrahigh-pressure (UHP) terranes (regional areas of rock containing coesite or other evidence of equivalent pressures, Coleman and Wang, 1995), but here we review evidence and ideas for other geodynamic mechanisms by which UHP terranes may have formed. Exhumation of UHP terranes has always been ascribed to positive buoyancy of these dominantly

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quartzofeldspathic terranes with respect to the mantle. For many years the prevailing assumption was that UHP terranes had to be exhumed rapidly before the coesite could break down or before wholesale melting could occur; this led to early sketch models based on the exhumation of relatively coherent slabs by extrusion or eduction. Here we review a subsequent blossoming of observations and ideas showing that some UHP terranes are large and some are small; some were exhumed slowly and some quickly; and some were exhumed with almost no melting, whereas others were exhumed with vast amounts of melt. This variety of terrane types implies formation and exhumation via a wide variety of geodynamic mechanisms; see also the recent paper by Warren (2013).

This paper focuses entirely on quartzofeldspathic UHP terranes and does not discuss UHP bodies that are exclusively mafic or ultramafic, which tend to be considerably smaller. We choose this focus because quartzofeldspathic UHP terranes—with a few percent mafic and ultramafic rocks—are by far the dominant type.

2. Formation of UHP terranes

There are at least six tectonic settings/mechanisms by which quartzofeldspathic rocks can reach mantle depths (Fig. 1): i) continental margin subduction, ii) microcontinent subduction, iii) sediment subduction, iv) intracontinental subduction, v) subduction erosion, and vi) foundering of a crustal root. Whether the upper plate is oceanic or continental in any of the first three settings is irrelevant to whether UHP rocks *form*, and subduction erosion of continental rocks can even be caused by an oceanic lower plate (Stöckhert and Gerya, 2005; von Huene and Scholl, 1991). That most UHP rocks have been found in continent collision zones may have something to do with how the rocks were exhumed, but says nothing a priori about how UHP rocks form.

Presently active continental margin subduction is exemplified by subduction of the Australian margin beneath the Banda Arc (Hamilton, 1979; Harris, 2003) and New Guinea (Quarles van Ufford and Cloos, 2005); notably, the upper plate is oceanic. Ancient examples include the Triassic UHP Dabie Shan of eastern China, where Sino–Korean craton passive-margin sedimentary and volcanic sequences are preserved (Schmid et al., 2003), and the Cretaceous subduction of the Arabian continental margin beneath the Samail ophiolite to near-UHP depths (Searle et al., 1994). Microcontinent subduction of the Yakutat terrane of southeastern Alaska may be ongoing (Eberhart-Phillips et al., 2006), and was suggested for the Paleozoic Kokchetav massif (Dobretsov et al., 1995). Sediment subduction is occurring in arcs around the world (Scholl and von Huene, 2007; von Huene and Scholl, 1991) and is recognized in the compositions of arc lavas (Plank and Langmuir, 1993); an ancient UHP example has not been identified. Intracontinental subduction may be underway beneath the Pamir (Burtman and Molnar, 1993; Sippl et al., 2013) and may have produced Carboniferous UHP rocks in Greenland (Gilotti and McClelland, 2007). Subduction erosion is occurring in arcs around the globe (Scholl and von Huene, 2007; von Huene and Scholl, 1991), and may have been responsible for Miocene xenoliths erupted in the Pamir (Ducea et al., 2003; Hacker et al., 2005). Both subducted sediment and crystalline rocks may rise through the mantle diapirically and may have formed Phanerozoic UHP terranes (Behn et al., 2011; Gerya and Stöckhert, 2006; Yin et al., 2007). Gravitationally unstable portions of continental lithosphere sinking beneath the Pamir (Burtman and Molnar, 1993) may be carrying quartzofeldspathic rocks into the mantle to UHP depths; an ancient UHP example has not been identified.

3. Types and characteristics of UHP terranes

A number of review papers of UHP terranes characterize their distribution and their lithological, structural and petrological characteristics (Kylander-Clark et al., 2012; Liou et al., 2012; Massonne and O'Brien, 2003; Schertl and Sobolev, 2012). UHP terranes have recently been divided into two end-member types: small terranes formed and exhumed quickly, and large terranes formed and exhumed slowly (Kylander-Clark et al., 2012); these two types might form during the early and late stages of continent collisions, respectively, but further work on this topic is needed because other explanations are possible. Systematic observations from UHP terranes are fundamental to constraining exhumation mechanisms. To be most meaningful, such datasets must integrate structural geology, petrology, and geochronology to produce deformation–pressure–temperature–time–space records that can be used to build and test numerical models. Characteristic features of interest include the rate of burial and how it varied spatially; the magnitudes, distributions, ages and durations of peak temperatures and pressures and their spatial variations during subduction and exhumation; the magnitudes, kinematics, ages, durations and spatial variations in deformation during subduction and exhumation; the types and volumes of igneous activity during subduction and exhumation; and the tectonic relationships with respect to surrounding units, such as lower pressure rocks and volcanoplutonic arcs. As is usual in geologic studies, tying sedimentological, structural, petrological, and chronological data can range from challenging to impossible in UHP rocks. Fortunately, the high metamorphic pressures help investigators in at least two ways: 1) the absolute uncertainties typical of geobarometers wreak less havoc than they do when trying to understand Barrovian metamorphism, and 2) many crustal minerals have the potential to disappear during compression and reappear during decompression, providing strain markers (e.g., Peterman et al., 2009) or chronometers (e.g., Spencer et al., 2013) with unusually specific petrological significance. On the other

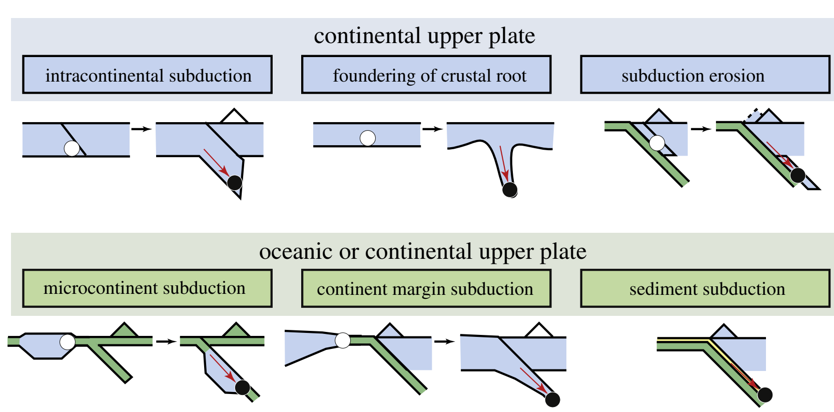

Fig. 1. UHP terranes can form in a variety of settings, some involving a continental upper plate, others involving an oceanic or continental upper plate. The unfilled arc triangle in continental subduction settings indicates that the magmatism may be minimal in such settings.

hand, the possibility of deviatoric-stress induced variations from lithostatic pressure of a few hundred MPa in quartzofeldspathic UHP terranes (Li et al., 2010) injects a certain level of caution in interpreting pressures and pressure gradients recorded in rocks.

4. Forces and controls during exhumation

The main forces that operate during the formation and exhumation of UHP rocks are well understood and can be modeled quantitatively (see overviews in Molnar and Gray, 1979; Gerya and Meilick, 2011): global tectonic forces transmitted by plate motions, and local body forces derived from the buoyancy of subducted rocks. The first type of force is typically responsible for the subduction of UHP-rock precursors, whereas the second often (but not always) drives various styles of exhumation.

Buoyancy is affected by pressure and temperature, composition (so-called "chemical buoyancy") and phase transformations. At the most-rudimentary level, why UHP continental crust is exhumed to the Moho—or to Earth's surface in oceanic settings—is not difficult to understand: at modest temperatures (≤800–900 °C), continental crust is positively buoyant with respect to the mantle up to pressures of at least 4 GPa (Massonne et al., 2007). This is true for a quartzofeldspathic terrane with a few percent mafic or ultramafic rock regardless of whether transformation to high-pressure phases occurs (Peterman et al., 2009; Walsh, 2003). At higher temperatures, melting asserts its influence on buoyancy: if quartzofeldspathic rocks undergo significant melting and the melt migrates, the residue may be insufficiently buoyant to rise out of the mantle (Hacker et al., 2011). This has been suggested as one of the reasons why so few UHP terranes have peak P–T conditions in excess of 800 °C (Hacker, 2006). Why quartzofeldspathic UHP terranes have only a few percent mafic or ultramafic rocks must be a feature of their original composition, rather than a limit imposed by buoyancy, because even a 50/50 mixture of quartzofeldspathic rock and eclogite is still neutrally buoyant with respect to the mantle at typical UHP conditions.

Body forces are not the only relevant controls on exhumation, however: surface tractions, pressure gradients, and rheology play a role (Chemenda et al., 1996; Heuret and Lallemand, 2005; Scholz and Campos, 1995). Why UHP material is exhumed to mid–upper crustal levels within continental settings may have less to do with buoyancy than surface tractions, pressure gradients, or local tectonic plate motions. For both buoyancy and rheology, radiogenic, conductive, and viscous heating may play determinative roles. Transformational weakening—that is, weakening associated with phase transformations (White and Knipe, 1978)—may be especially important to the formation and exhumation of UHP terranes (Warren, 2013) because the large (≥2 GPa) increases from typical crustal pressures to ultrahigh pressures favor substantial densification (Semprich et al., 2010).

Models of UHP terrane exhumation are fundamental to constraining exhumation mechanisms. To be most meaningful, such models must produce deformation–pressure–temperature–time–space predictions that can be tested by integrated structural geology, petrology, and geochronology field studies. Numerical thermomechanical models of the exhumation of UHP rocks deal naturally with this testability requirement, though three-dimensionality, high resolution and self-consistent plate motions remain as challenges (Gerya, 2011; Gerya and Meilick, 2011; Sizova et al., 2012). On the other hand, three-dimensional analog models cannot yet do an adequate job of representing time-dependent changes in temperature, temperature-dependent rheology (including melting), and pressure-induced changes in density. Analog models are relevant in situations where the conductive lengthscale is large and phase transformations are minor.

5. Exhumation mechanisms

A number of different mechanisms have been proposed to account for the exhumation of UHP terranes. Some are specifically related to how the UHP rocks formed, whereas other exhumation mechanisms are independent of the mode of formation (Fig. 1; Table 1). Some exhumation mechanisms have been extensively modeled; others have rarely, or never, been modeled.

5.1. Eduction

'Eduction' has been used to mean exhumation of a subducting plate by reversal of plate motion with relatively little internal strain (Fig. 2) (Andersen et al., 1991). The Western Gneiss region (Andersen and Austrheim, 2008) is the archetype for exhumation by eduction for several reasons: i) there seems to be no foreland thrust fault that roots beneath the UHP rocks, suggesting that the overlying Laurentia plate was drawn off the top of the subducted Baltica plate (Andersen et al., 1991);

Table 1
Geologic characteristics of terranes exhumed by different mechanisms.

	a) Structural	b) Petrological	c) Chronological	d) Length scale	e) Example
Eduction ("Andersen model")	• Relatively weakly deformed • No thrust fault at base	• Monotonic down-dip gradient in peak P & T	• Up to 10 Myr subduction & exhumation in models • Monotonic down-dip gradient in ages	• Thickness of educting lithospheric section	Western Gneiss region
Microplate rotation	• Rotation of lineations in space and time • Possible thrust fault at base with increasing offset from rotation axis	• P & T gradient with respect to rotation axis	• Not yet modeled • Age gradient with respect to rotation axis	• Thickness of rotation lithospheric section, unless diminished by basal thrust	Dabie Shan
Crustal stacking ("Chemenda model")	• Relatively coherent slab • Thrust fault at base above another crustal section	• Monotonic down-dip gradient in peak P & T	• Up to 20 Myr in models • Monotonic down-dip gradient in ages	• Crust	Dora Maira(?)
Slab rollback	• Microcontinent • Thrust fault at base	• Associated back-arc spreading	• 15 Myr in Mediterranean • Monotonic down-dip gradient in ages	• Microcontinent crust	Not yet(?) demonstrated for UHP rocks
Channel flow	• Nappes or strong mixing	• Mixing of domains of different pressures • Possible pressure cycling of individual domains	• A few Myr to tens of Myr in models • Mixing of domains with different ages	• Meters to kilometers	Unknown
Trans-mantle diapirs	• Radially symmetric structures • Dome within upper plate • No basal fault	• Significant local melting • Mixing of domains of different pressures • Concurrent magmatism	• Rapid (<1 Myr) ascents of diapirs over a period of tens of Myr	• 10–20 km diapir radius	N Qaidam

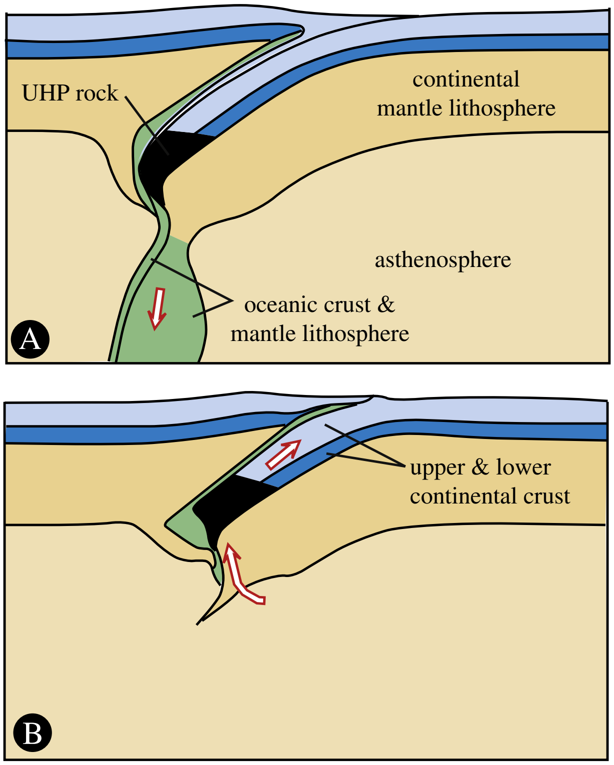

Fig. 2. Eduction, after Andersen et al. (1991) and Duretz et al. (2012). A) A continent attached to oceanic lithosphere follows the latter to UHP depth. At some point, slab pull exceeds slab strength, initiating necking. B) The positively buoyant portion of the subducting plate reverses direction and rebounds, exhuming the UHP rocks. If the continent is sufficiently strong, it undergoes little strain.

ii) most of the Western Gneiss region underwent rather minor strain during the eclogite–facies metamorphism; and iii) the metamorphic pressure and temperature gradients within the Western Gneiss region show near-monotonic increases—apart from some late folds—toward the core of the orogen (Hacker et al., 2010). If there is a foreland thrust that roots beneath the UHP rocks (e.g., Tucker et al., 2004), the Western Gneiss region is not the archetype for eduction.

If a continental slab is subducted because it is attached to downgoing oceanic lithosphere, at some time and location the downward slab pull force exceeds the strength of slab, and necking of the slab initiates (van Hunen and Allen, 2011). The positive buoyancy of the continental slab—in opposition principally to ridge push—can then drive exhumation at a rate and mode determined by plate geometry and the rheology of the materials (Duretz et al., 2012). Duretz et al. (2012, 2013) used thermo-mechanical models with spontaneously moving plates to demonstrate that eduction is favored by strong coupling of the subducted crust to the underlying mantle and the rapid subduction of old oceanic lithosphere that is capable of pulling the continent to UHP depth; if the subducted crust is sufficiently strong, it undergoes little internal deformation during subduction and exhumation. Continent subduction up to 15 Myr and exhumation through mantle depths as long as a 7 Myr is possible in the models (Duretz and Gerya, 2013; Duretz et al., 2012). These timescales are shorter than recorded in the Western Gneiss region (Kylander-Clark et al., 2009), indicating a mismatch between the existing model outcomes and the interpretation of geologic data.

5.2. Microplate rotation

A different means of exhuming a UHP terrane by reversal of plate motion is if the plate to which the subducted continental material is attached begins to rotate in response to changing boundary conditions or body forces, and the rotation is such that it exhumes the UHP rocks (Fig. 3). This is a 3D—rather than a 2D—exhumation model, and could occur if, for example, the subducting plate is small enough that continent subduction markedly changes the orientation and magnitude of slab pull or if the plate is being consumed by more than one subduction zone pulling in different directions. Characteristics of a UHP terrane exhumed by microplate rotation include i) a relatively coherent terrane, perhaps with a thrust fault at the base that shows increasing offset away from the pole of rotation; ii) a gradient in metamorphic pressures increasing away from the rotation pole; and iii) stretching lineations compatible with rotation.

Perhaps the ancient UHP terrane to which this process might best be ascribed is the Triassic Dabie Shan orogen of eastern China, where exhumation-related stretching lineations and gradients in metamorphic pressure indicate rotation of the exhuming terrane (Hacker et al., 2000). Subduction-driven rotation of the Woodlark microplate has also been proposed as the explanation for the exhumation of the Miocene UHP terrane in eastern Papua New Guinea (Webb et al., 2008). There are no analog or computational models of UHP exhumation by microplate rotation.

5.3. Buoyancy-driven crustal delamination and stacking ("Chemenda" model)

If a subducting plate consists of a weak buoyant layer atop a stronger negatively buoyant layer, the former will detach at the depth where the

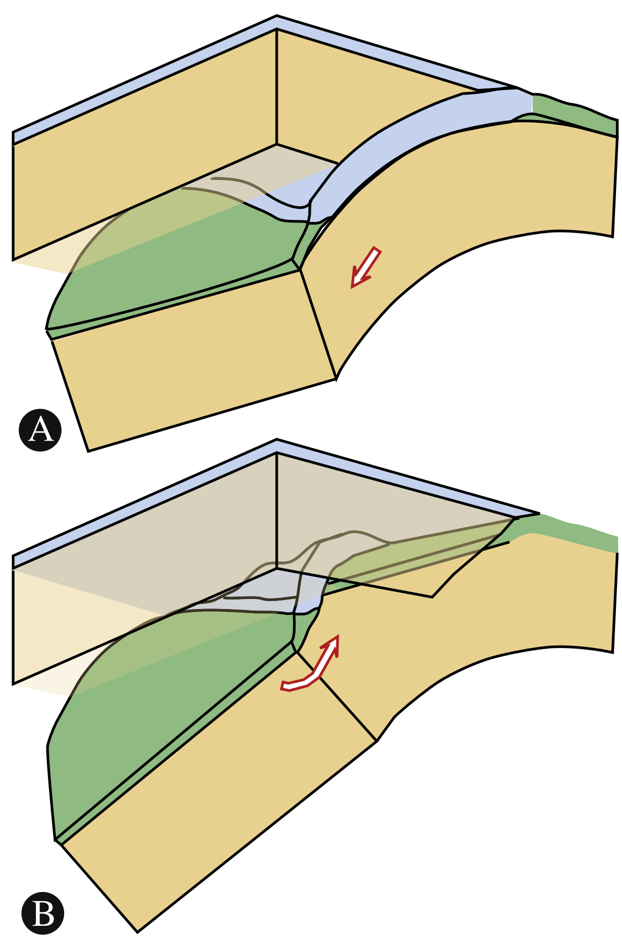

Fig. 3. Microplate rotation to exhume UHP rocks (after Hacker et al., 2000). If the changes in force that occur in response to continent subduction vary along the length of the subduction zone, these lateral gradients may drive plate rotation that exhumes UHP rocks.

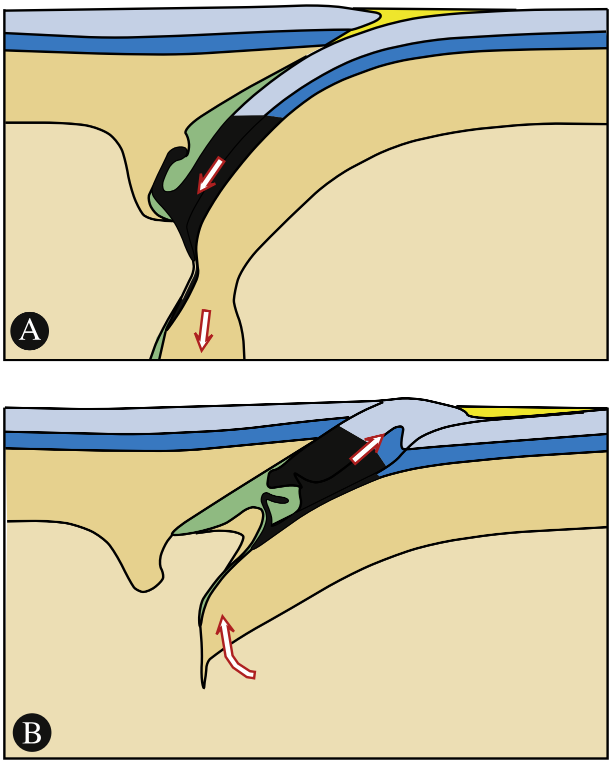

Fig. 4. Buoyancy-driven crustal delamination and stacking ("Chemenda" model) after Duretz and Gerya (2013). A weak buoyant layer atop a stronger negatively buoyant layer detaches where buoyancy exceeds slab pull, and extrudes upward as a semi-coherent sheet. The delaminated crust is thrust upward over the downgoing plate.

buoyancy force exceeds slab pull. The buoyant material may extrude upward as a semi-coherent sheet (Fig. 4). This type of delamination and stacking was proposed by Chopin (1987) to explain exhumation of the Dora Maira massif and by Okay and Sengör (1992) to explain exhumation of the Dabie Shan, and then demonstrated with analog experiments by Chemenda et al. (1995). None of these examples are wholly convincing as either the geologic record is incomplete, the early structures are significantly reworked, or the basal contact of the UHP unit cannot be identified.

Sizova et al. (2012) reproduced the "Chemenda model" using numerical experiments with spontaneously moving plates involving a long and heavy oceanic slab that drives deep subduction of thick and strong continental crust with a narrow passive margin. Large-scale crustal stacking in these models is initiated by brittle/plastic failure along the cold, deeply subducted continental Moho: the delaminated crust is then thrust over the downgoing plate. Strong thermal feedback from shear heating controls further lubrication and exhumation of crustal-scale UHP nappes; exhumation driven by crustal buoyancy is enhanced further when the subducting lithosphere tears off. In the Sizova et al. models, less oceanic subduction led to less cooling and more-distributed, less slab-like exhumation of only the subducted upper crust; a wider passive margin led to diapiric ascent of the subducted crust through the upper plate, rather than up the subduction channel.

Duretz et al. (2012, 2013) used thermo-mechanical models to demonstrate that delamination of subducted crust from its mantle substrate is favored by slow subduction (1–2 cm/yr) as well as by a thinned subducted continental margin; if the plate is sufficiently strong, it undergoes little strain. Continent subduction up to 10 Myr and exhumation through mantle depths up to 7 Myr are possible in the models. Duretz et al. noted that the thrust underlying the UHP rocks might be obscured by other structures, and that this model could apply to the Western Gneiss region of Norway.

5.4. Slab rollback

Brun and Faccenna (2008) noted that the buoyancy of a microcontinent locally slows the rollback of subducting mafic lithosphere, causing the slab to steepen (Fig. 5). If the mafic lithosphere on either side of the microcontinent continues to roll back, a buoyant portion of the microcontinent may detach, allowing the retarded portion of the slab to roll quickly back, driving arc extension and making room for the continental crust to exhume. This model was developed to explain repeated cycles of subduction and exhumation of high-pressure rocks documented in the Aegean and Calabria–Apennine orogens. Exhumation by slab rollback has not been used to explain the exhumation of an *ultra*high-pressure terrane, but it has been

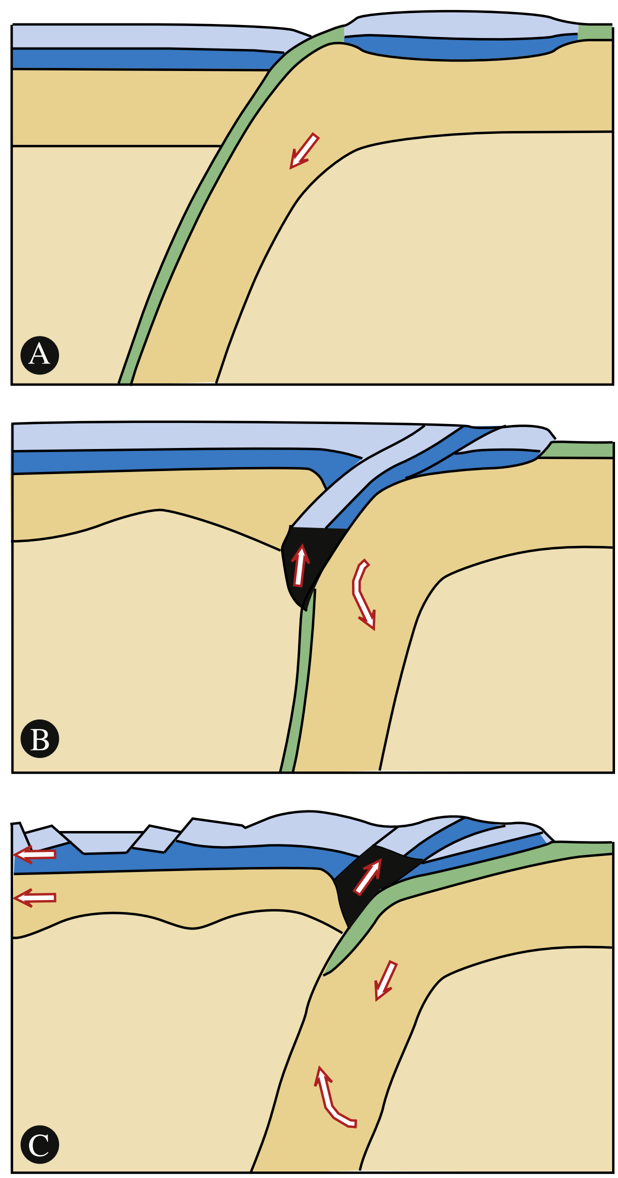

Fig. 5. Slab rollback (Brun and Faccenna, 2008). The buoyancy of a microcontinent slows slab rollback & steepens the slab. If the mafic lithosphere on either side of the microcontinent continues to roll back, a buoyant portion of the microcontinent may detach, allowing the retarded portion of the slab to roll quickly back, making room for the UHP continental crust to exhume and driving back-arc extension.

reproduced in numerical experiments of Apennine-style collisions (Faccenda et al., 2009) and microcontinent accretion (Tirel et al., 2013; Vogt and Gerya, 2012).

5.5. Subduction channel flow

If buoyant material—either sediment, material removed by subduction erosion (von Huene et al., 2004) or—is subducted within a confined channel, the material tends to undergo circulation driven by tractions along the base of the channel and the relative buoyancy of rocks inside the channel (Cloos and Shreve, 1988; England and Holland, 1979; Raimbourg et al., 2007). Distinct from crustal delamination and stacking, in which the exhumed sheet is semi-coherent, subduction channel flow can be complex, generating nappes or mélange (Fig. 6) (Beaumont et al., 2009; Burov et al., 2001; Gerya et al., 2008; Li and Gerya, 2009; Warren et al., 2008; Yamato et al., 2008). The material within the channel can be exhumed if: i) continuous introduction of new material into the channel driven by traction of the subducting plate pushes old channel material upward; ii) buoyancy in the channel exceeds subduction-related traction and the channel is pushed upward by asthenospheric mantle intruding between the plates; or iii) a strong indenter squeezes the channel and extrudes the material within (Gerya et al., 2008; Warren et al., 2008). In the Gerya et al. (2008) thermomechanical models, the UHP material in the subduction channel is exhumed in the hinterland of the upper plate by the arrival of a strong continental indenter, whereas in the Li and Gerya (2009) models the mixed UHP body is extruded up the subduction channel. In contrast, Butler et al. (2011) showed that reducing the strength of the upper plate can divert the exhumation of UHP material from the subduction channel up into the upper plate. Exhumation by channel flow is a natural outcome of models with prescribed plate convergence (Beaumont et al., 2009; Li and Gerya, 2009; Warren et al., 2008; Yamato et al., 2008), and is not common in models with spontaneously moving plates, in which continental subduction slows plate convergence (Sizova et al., 2012).

Lardeaux et al. (2001) suggested that the UHP rocks of the Massif Central were exhumed within an active subduction channel. Beaumont et al (2009) proposed that the UHP Tso Morari massif is a strongly deformed terrane that was subducted and exhumed within a channel. No UHP terrane known to us shows the degree of mixing of metamorphic pressures that might be considered diagnostic of formation and exhumation within a channel.

5.6. Trans-mantle diapirs

Stimulated by the small size of UHP terranes in the Alps and the formation of some Alpine UHP terranes prior to continent collision, Stöckhert and Gerya (2005) and Gerya and Stöckhert (2006) postulated that some UHP terranes might be coalesced material derived from subduction erosion (Fig. 7). In some of their models, subducted crustal material rises in plumes beneath the hinterland of the orogen to form a sheet (Gerya and Stöckhert, 2006) of UHP mélange. Yin et al. (2007) calculated that 20–40 km diameter diapirs could form from a 200–400 m thick subducted sediment layer and rise through an arc mantle wedge in a few Myr, and Currie et al. (2007) and Gerya et al. (2008) presented models of such diapirs accumulating to form UHP terranes. This model was suggested for the early Paleozoic North Qaidam UHP terrane of Tibet to explain the long duration of UHP metamorphism during arc magmatism (Yin et al., 2007). Little et al. (2011) invoked short-duration diapiric rise of a much larger subducted continental body to explain the exhumation of the Miocene Papua New Guinea UHP terrane.

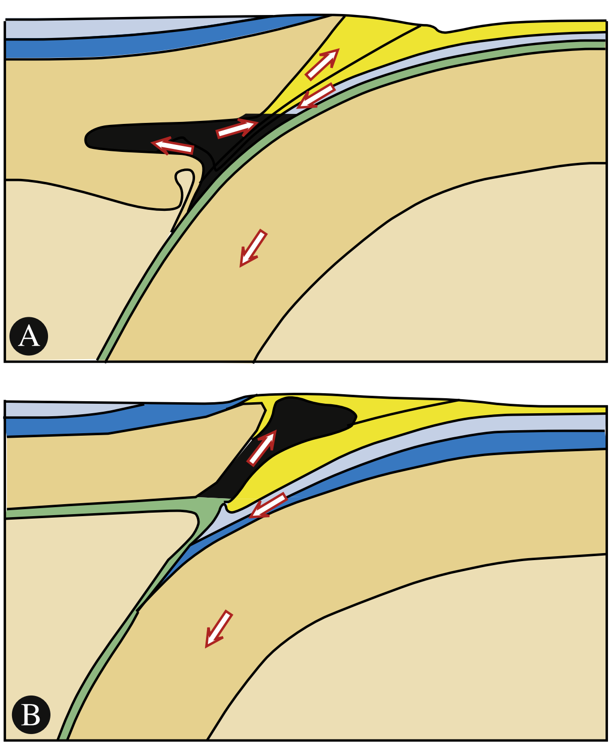

Fig. 6. Subduction channel flow (Li and Gerya, 2009). Crustal material subducted in a confined channel circulates, driven by traction along the base of the channel and the buoyancy of rocks in the channel. Material in the channel can be exhumed if: i) new material pushes old material up; ii) buoyancy in the channel exceeds traction; or iii) an indenter squeezes channel.

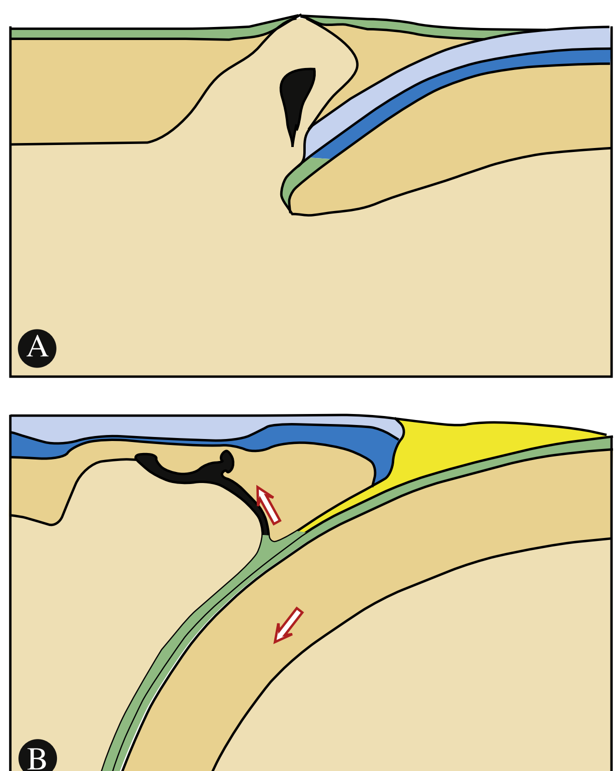

Fig. 7. Some UHP terranes might be coalesced material derived from subduction-sourced diapirs of sediment or material removed by subduction erosion (Gerya and Meilick, 2011; Little et al., 2011).

The trans-mantle diapir and subduction-channel models both may involve extensive mixing of i) upper plate sediment and crystalline material removed by subduction erosion, ii) subducted sediment, iii) upper plate mantle or crust that may mix into the diapir during ascent or into the channel by mechanical mixing. Trans-mantle diapirs should have distinctive characteristics, including i) domal structure showing emplacement into the upper plate; ii) no basal fault; iii) concurrent magmatism in the upper plate (Yin et al., 2007); and iv) significant local melting (the Papua New Guinea UHP rocks are intruded by abundant syn-exhumation igneous rocks, Gordon et al., 2012).

5.7. Relamination (non-exhumation)

Certainly not all subducted crustal material returns directly from the mantle to the crust. At one extreme, Scholl and von Huene (2007) used the general paucity of UHP rocks to suggest that 95% of subducted continental material returns to the mantle. However, as the number of recognized UHP terranes continues to grow year by year, and because all are overprinted by amphibolite- to granulite-facies metamorphism that tends to obliterate the UHP record, this 95% estimate looks increasingly questionable. It is entirely possible that most subducted continental material was not returned to the mantle, but was relaminated to the base of continents (Hacker et al., 2011). Buoyancy alone may be insufficient to drive exhumation of UHP rocks to Earth's surface if the overlying material is lower density, continental rocks. Arrest and spreading at the Moho are likely unless other forces are available to force the UHP rocks upward (Walsh and Hacker, 2004). The large-scale transfer of subducted crustal material into the lower crust has been termed relamination (Fig. 8) (Hacker et al., 2011).

5.8. Identifying different formation and exhumation mechanisms in the rock record

The different mechanisms by which UHP rocks might form and the different mechanisms by which they might be exhumed are not necessarily independent (Fig. 9). Trans-mantle diapirs, for example, might form from subduction erosion, foundering of a crustal root, intracontinental subduction, microcontinent subduction, continent-margin subduction, or sediment subduction. Other exhumation processes require specific mechanisms to form the UHP rocks—slab rollback being perhaps the singular example.

The different formation and exhumation mechanisms could leave identifiable structural, petrological and/or chronological fingerprints in UHP terranes. Table 1 lists these characteristics, which in general augment or supplant those of Yin et al. (2007). Each of the different exhumation models makes specific predictions about the geologic characteristics of a UHP terrane; those predictions are separated into 4 columns in the table. a) The structural characteristics that are most critical include i) whether the terrane is planar or domal; ii) whether there is a thrust fault at the base of the terrane; iii) the degree of internal deformation; and iv) whether the structures are parallel, curved, or radial/tangential. b) The petrological characteristics most useful to assess include i) whether the metamorphic pressures increase monotonically (allowing for kinetic differences among domains) or vary stochastically from domain to domain; ii) the degree and distribution of melting; and iii) whether there is concurrent arc or backarc magmatism. c) Diagnostic chronological characteristics focus on whether i) prograde or retrograde metamorphic age gradients are monotonic or vary from domain to domain, and ii) are millions of years or tens of millions of years. d) The minimum dimension (or length scale) of the UHP terrane affects the timescale for thermal diffusion and can thus be inferred from

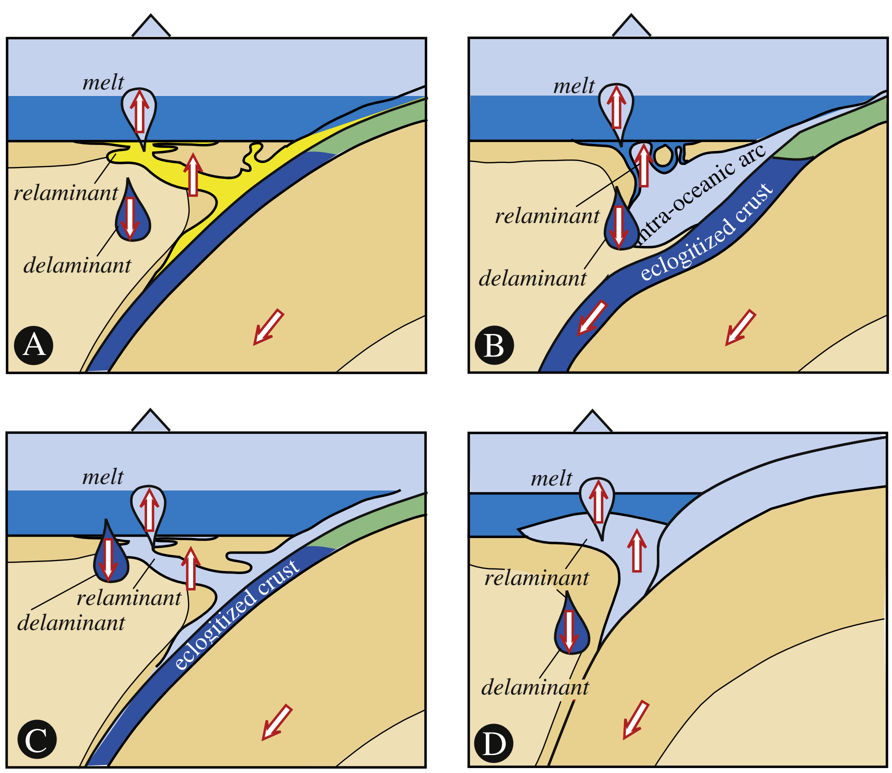

Fig. 8. Transfer of subducted crustal rock into the base of the upper plate is termed 'relamination'. A) Relamination of subducted sediment (Currie et al., 2007). B) Relamination of subducted intra-oceanic arc. C) Relamination of crust removed by subduction erosion (Stöckhert and Gerya, 2005). D) Relamination of subducted continental crust (Walsh and Hacker, 2004).

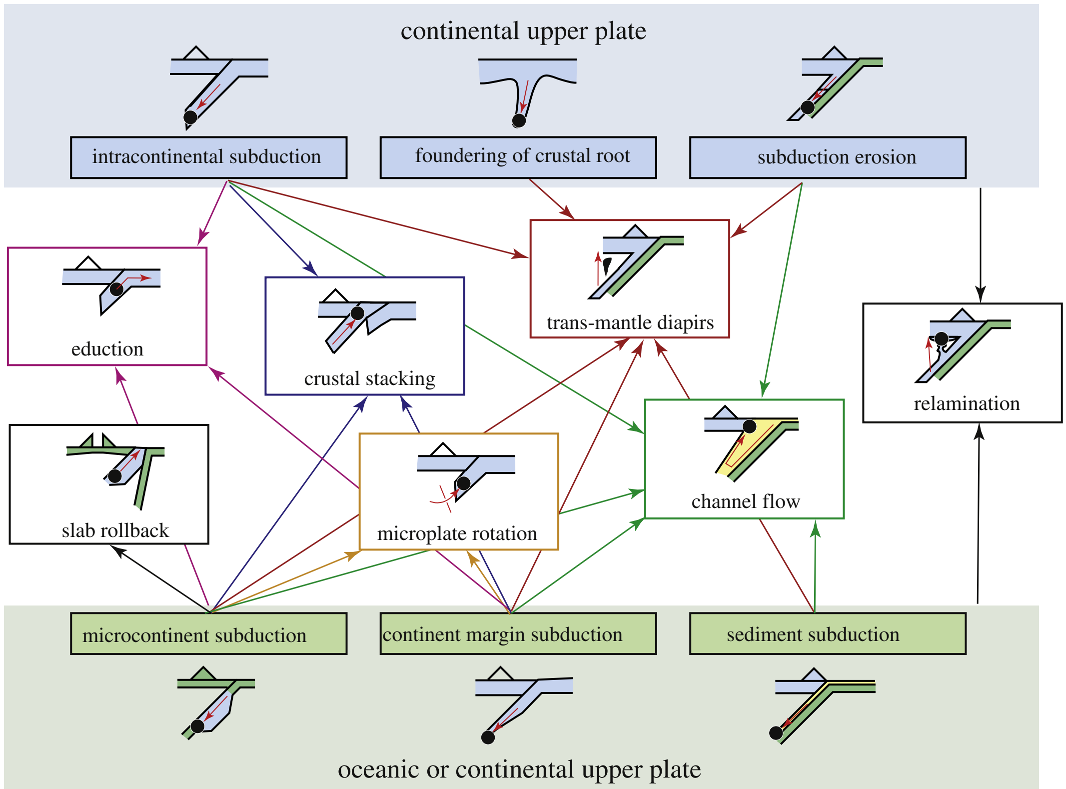

Fig. 9. Range of possible formation and exhumation mechanisms for UHP terranes.

geochronology. e) Examples of UHP terranes that might have formed by each of these mechanisms are listed in the final column. Not one of the listed examples is truly a perfect match, indicating that further geologic work is required to measure and interpret the histories of these orogens.

6. Future work

The diversity of *observations* from UHP terranes has led to the realization that there must have been different processes of formation and exhumation, and attempts have been made to address these differences through geodynamic modeling. The diversity of *models* of UHP terranes has expanded the range of formation and exhumation scenarios being tested through field geology.

We see the following tasks as exciting and relevant topics for future study. 1) Understanding what form of tectonism occurred in lieu of UHP tectonism prior to the Phanerozoic (Sizova et al., 2013). In addition to natural observations, systematic exploration of numerical models for Precambrian crustal and mantle conditions is required (Gerya, 2012). 2) Producing realistic 3D geodynamic models that attempt to replicate all of the most-specific geologic data from well-studied UHP terranes (e.g., the very long timescales for subduction and exhumation of the giant UHP terranes (e.g., the Western Gneiss region of Norway) remain unaddressed by geodynamic models. If models cannot replicate the observations, perhaps the observations are in error? Alternatively, perhaps the models lack some important physics involved in UHP tectonism? 3) Looking in detail at the specific predictions of geodynamic models and testing these models by acquiring field and laboratory data. 4) Imaging actively exhuming UHP terranes (e.g., Papua New Guinea)—something patently impossible in ancient orogens. 5) Assessing the fluxes of continental material returned to the mantle, exhumed to Earth's surface, and relaminated to the base of continents (Hacker et al., 2011).

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