Formation and Exhumation of Ultrahigh-Pressure Terranes

The exhumation of Norwegian eclogites, in the footwall, was aided by the Nordfjord-Sogn Detachment Zone (e.g. Johnston et al. 2007)

Bradley R. Hacker[1], Taras V. Gerya[2], and Jane A. Gilotti[3]

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The reigning paradigm for the formation and exhumation of continental ultrahigh-pressure (UHP) terranes is the subduction of crust to mantle depths and the return of crustal slices within the subduction channel—all at plate tectonic rates. Additional processes beyond the paradigm are needed to explain the diversity of geological observations gathered from the growing study of UHP terranes—for example, variations in the size, degree of deformation, petrologic evolution, timing of UHP metamorphism, and exhumation rates. Numerical models that evaluate physical parameters in time and space have produced new insights into the formation and exhumation of UHP terranes.

Keywords: ultrahigh pressure, exhumation, channel flow, eduction, diapir

INTRODUCTION

The two discoverers of coesite in regional metamorphic rocks, Chopin (1984) and Smith (1984), immediately deduced that subduction of continental crust was responsible for the formation of this unusual high-pressure form of SiO_2. This led naturally to the conclusion that continental ultrahigh-pressure (UHP) terranes form from the subduction of continental margins. Exhumation of continental UHP terranes has typically been ascribed to positive buoyancy of these dominantly quartzofeldspathic rocks with respect to the mantle, and one of the earliest ideas for the mechanism of exhumation—detachment of a crustal sliver (Fig. 1)—held sway for many years. The preservation of metamorphic coesite was originally judged to be so rare that it was assumed that unusual processes were critical to its preservation. This led to the prevailing assumption that UHP terranes had to be exhumed at plate tectonic rates and that exhumation without overprinting is an unusual process.

Challenges to understanding the formation and exhumation processes involved in UHP metamorphism arise because structures formed at mantle depths are commonly overprinted or excised by younger structures. Numerical models help explore possible scenarios because they can predict rock behavior for a range of boundary conditions and forces. Here we review a blossoming of observations and ideas showing that some UHP terranes are large and some are small; some were exhumed at plate tectonic rates and some more slowly; some were exhumed with almost no melting, whereas others were exhumed with vast amounts of melt; and others were never exhumed at all. This variety implies that UHP terranes formed and were exhumed via a wide array of mechanisms, some of which have not yet been imagined.

RAPID SUBDUCTION AND EXHUMATION OF A CONTINENTAL SLIVER: THE REIGNING PARADIGM

The earliest models for UHP tectonism assumed that it occurs during subduction of a continental margin because the metamorphic pressure–temperature (P–T) conditions of UHP rocks are typical of subduction zones and not of overthickened continental collision zones, such as the Tibetan Plateau. A second point in favor of a subduction zone model is that a subduction zone can provide a pathway for conveying crustal rocks back to Earth's surface without exceeding the moderate temperatures (<800 °C) observed in most continental UHP terranes. The need for such cool temperatures to be maintained by either continued, deeper-level subduction refrigeration or rapid, near-adiabatic exhumation has led to the general dominance of a single model. In this model, a relatively thin slice of UHP continental crust becomes detached from the subducting lithosphere at a depth of ~100 km and is rapidly exhumed up the subduction zone during continued convergence (Fig. 1). The requirement to have continental rocks reach mantle depths has led to the assumption that most UHP terranes formed where continental margins were subducted at the end of ocean closure. The presence of UHP rocks in continent collision zones has caused most workers to assume that the upper plate of the subduction zone was continental. The subduction of a continent is assumed to eventually cause the downgoing slab to break off (Davies and von Blanckenburg 1995), triggering a range of specific tectonic processes such as volcanism and uplift. To many observers, this overall paradigm of rapid continental-margin subduction during the early stages of continental collision satisfies most of the geologic constraints teased from UHP occurrences. The dominance of this paradigm has been further solidified by an imaginative and evocative series of analog experiments by Chemenda and coworkers (1995), which demonstrated that large, coherent slices of crust—bounded by a thrust below and a normal fault above—could be exhumed in one piece (Fig. 1). The exhumation of a crustal slice, or the Chemenda model as it has come to be known, remains a popular model for the exhumation of some UHP terranes.

1 Department of Earth Science, University of California
Santa Barbara, CA 93106, USA
E-mail: hacker@geol.ucsb.edu

2 Geophysical Fluid Dynamics Group
Institute of Geophysics, Department of Earth Sciences
Swiss Federal Institute of Technology (ETH Zürich)
Sonneggstrasse, 5, 8092 Zürich, Switzerland

3 Department of Earth and Environmental Sciences
University of Iowa, Iowa City, Iowa 52242, USA

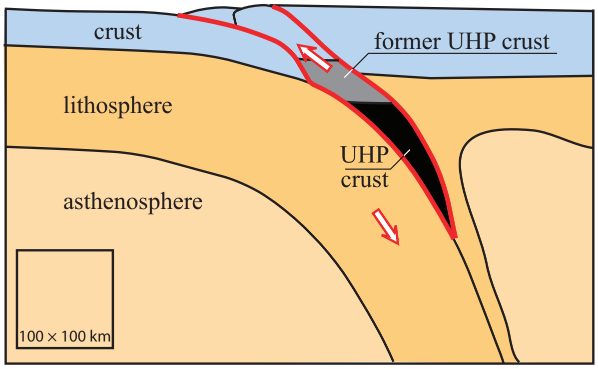

FIGURE 1 Most early models of UHP-terrane formation and exhumation called upon rapid subduction and exhumation of a relatively coherent sheet during continued convergence. This drawing—after one of Chemenda et al.'s (1995) analog experiments—shows a coherent slab of continental crust that has broken free from the downgoing lithosphere and is rising to crustal levels from UHP depths by slip along two faults (red lines).

FORMATION OF UHP TERRANES: NUMERICAL MODELS

Numerical and physical analog models are tools that can be used to understand the formation and exhumation of UHP terranes. These models use estimates of rheology, density, plate-convergence rates, and physical conditions to produce realistic scenarios for a large range of conditions and tectonic settings. Numerical models in particular can portray the changing geodynamic situation over time, and they can follow single rocks from near Earth's surface to mantle depths and back, tracking their pressure–temperature–time (*P*–*T*–*t*) history.

Forces and Controls

The main forces that operate during the formation and exhumation of UHP rocks—that is, global tectonic forces transmitted by plate motions and local body forces derived from the buoyancy of subducted rocks—are well understood and can be modeled quantitatively (see overviews in Warren et al. 2008; Duretz et al. 2012; Sizova et al. 2012). Tectonic forces are typically responsible for the subduction of UHP-rock precursors, whereas local body forces often (but not always) drive various styles of exhumation. At the most rudimentary level, why UHP continental crust is exhumed to the continental Moho—or to Earth's surface in oceanic settings—is not difficult to understand: although mafic eclogite is denser than peridotite, eclogite facies continental crust is positively buoyant with respect to the uppermost mantle, and former eclogite facies continental crust is positively buoyant with respect to oceanic crust. Buoyancy is affected by composition and phase transformations (so-called "chemical" buoyancy), pressure, and temperature. Melting is a particularly important type of phase transformation in that whether the melt remains with, or separates from, the solid may significantly change the buoyancy. Body forces are not the only relevant controls on exhumation: surface tractions, pressure gradients, rheology, and local tectonic plate motions also play a role. For both buoyancy and rheology, radiogenic, conductive, and viscous heating may play determinative roles. Transformational weakening—that is, weakening associated with phase transformations—may be especially important to the formation and exhumation of UHP terranes because the large pressure variations and high temperatures accentuate the roles of phase transformations, including melting.

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. Characteristic features of interest include the rate of burial and how it varied spatially; magnitudes, distributions, ages, and durations of peak temperatures and pressures and their spatial variations during subduction and exhumation; magnitudes, kinematics, ages, durations, and spatial variations in deformation during subduction and exhumation; types and volumes of igneous activity during subduction and exhumation; and tectonic relationships with respect to surrounding tectonic units, such as lower-pressure rocks and volcanoplutonic arcs.

Numerical thermomechanical models of the exhumation of UHP rocks deal naturally with this testability requirement, although three-dimensionality, high resolution, and self-consistent plate motions remain as challenges. On the other hand, three-dimensional analog models cannot do an adequate job of representing time-dependent changes in temperature, temperature-dependent rheology (including melting), and pressure-induced changes in density. These models are only relevant in situations where the conductive length scale is large and phase transformations are minor.

A Numerical Scenario for the Formation and Exhumation of UHP Rocks

Numerical investigations of UHP-rock formation and exhumation processes are based on conducting systematic calculations that explore the effects of variations in major physical parameters, such as external and internal forces, boundary conditions, plate structures, and rock properties. Based on these experiments, the physical parameters for different UHP formation and exhumation scenarios are defined.

FIGURE 2 illustrates the results of a numerical investigation that produced exhumation via Chemenda-style, large-scale crustal stacking (FIG. 1). The model (Sizova et al. 2012) simulates subduction of a continental plate following closure of an ocean basin (FIG. 2A). The incoming continental passive margin subducts in a coherent manner, reaching depths of 100–150 km within 5.8 My (FIG. 2B). Buoyancy of the deeply subducted continental crust creates large deviatoric stresses that trigger brittle or plastic failure along the subducted continental Moho. A large, coherent, crustal-scale block of continental crust then separates from the subducting plate and is thrust back over the subducting plate along a major shear zone; the exhumation of the UHP rocks is extremely rapid, occurring within 0.2 My (FIG. 2C). Shortly after, subduction is terminated by slab breakoff in the continental part of the subducting plate at a depth of ~300 km.

To exemplify the *P*–*T*–*t* evolution of subducted crustal rocks during this UHP tectonism, three distinct rock markers within the upper part of the incoming continental crust are traced in FIGURE 2 with colored squares. The orange marker is located closest to the margin at shallow depth within the sedimentary cover; these sedimentary cover rocks (orange line) are rapidly subducted to diamond-stable depths of >150 km, where they are scraped off the top of the crust, are heated by the overlying asthenospheric mantle to temperatures up to 750 °C, and rise rapidly in a relatively thin subduction channel (FIG. 2B). When the first large crustal segment detaches from the slab, it rapidly exhumes these subducted sedimentary rocks to lower–middle crustal levels (FIG. 2C). The green marker, initially located farther from the margin below the sedimentary cover, has a distinctly different evolution. It is part of a small segment of the continental margin that stays attached to the oceanic slab even after the slab breaks; thus, even positively buoyant continental rocks can be recycled into the mantle during subduction. The purple upper-crustal marker is initially located farthest from the margin. This rock reaches coesite-

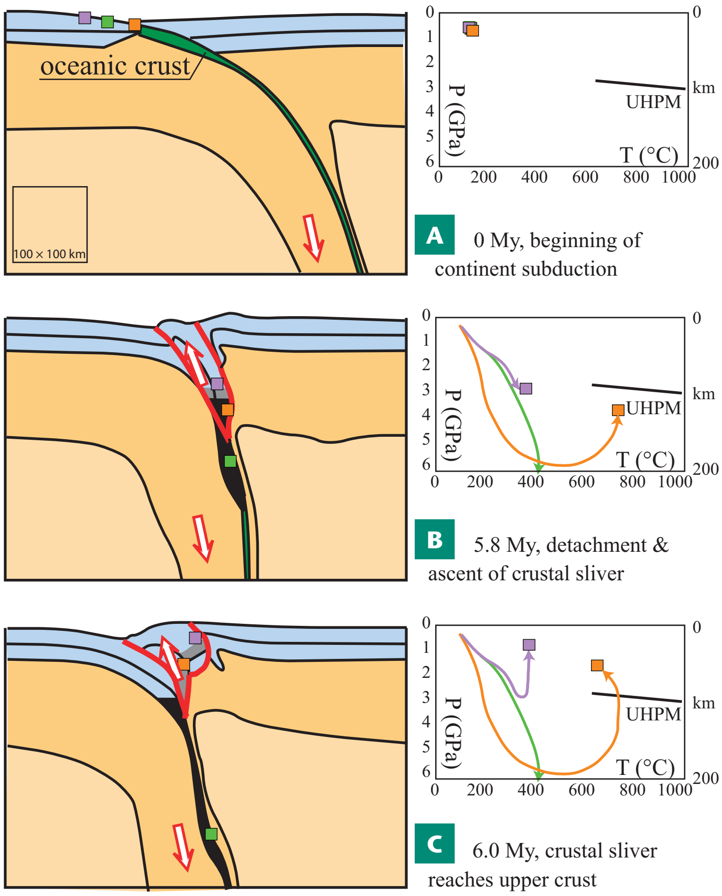

Figure 2 A numerical model of the formation and exhumation of UHP rocks during continent–continent collision (after Sizova et al. 2012). Cross sections (colors same as in Figure 1, except as noted) show that 5.8 My after the beginning of continent subduction (**B**), a relatively coherent block of continental crust abruptly detaches from the downgoing slab and rises to crustal levels in <1 My (**C**). *P–T* diagrams show that UHP rocks with dramatically different *P–T* paths are juxtaposed by the end of the orogeny. Colored squares link *P–T* conditions to the corresponding positions in the cross sections. The continental crust in divided into upper and lower parts. See text for further explanation. UHPM = ultrahigh-pressure metamorphism.

stable depths but is thermally isolated from the wedge asthenosphere, thus reaching a peak pressure of 3 GPa and a peak temperature of 400 °C before being exhumed as part of the first crustal block. This numerical model demonstrates that the *P–T–t* paths of UHP rocks in the same metamorphic complex may be dramatically different. Consequently, a proper understanding of the geodynamic scenarios that form different UHP complexes requires parallel, mutually informed, and systematic modeling and geologic investigations.

UHP TERRANES: GEOLOGICAL OBSERVATIONS AND ALTERNATIVE MODELS

The reigning paradigm (Figs. 1, 2) does seem to provide a reasonable explanation for some UHP terranes—for example, the small UHP terranes exposed in the Kaghan Valley, Pakistan, and at Tso Morari, India. Both of these Himalayan localities consist of chiefly quartzofeldspathic rocks from the leading edge of the Indian plate, are in the footwall of the India–Asia suture, and yet are now being thrust over the downgoing Indian footwall (Massonne and O'Brien 2003), which is still subducting northward. UHP metamorphism at Kaghan and Tso Morari occurred at ~46 Ma, not long after continental collision began at ~55–50 Ma. The UHP rocks were exhumed rapidly to crustal levels at ~44 Ma (Parrish et al. 2006).

Channel Flow

An alternative explanation for exhumation of the Himalayan UHP terranes is by ductile return flow in a subduction channel (Fig. 3), as suggested by the numerical models of Warren et al. (2008) and Beaumont et al. (2009). Whether these localities are better explained by exhumation of relatively coherent slabs (Figs. 1, 2) or ductile return flow (Fig. 3) hinges on the internal deformation of the UHP terrane; field study of the Tso Morari and Kaghan UHP terranes could resolve this question. Ductile return flow in a subduction channel is a plausible explanation for many of the smaller UHP terranes.

"Eduction"

Another major challenge to the fast-subduction and fast-exhumation aspect of the Chemenda model has arisen with the burgeoning data sets suggesting slow subduction and exhumation of at least two UHP terranes: the Dabie–Sulu of eastern China and the Western Gneiss Region of Norway. Not only did these two UHP terranes apparently undergo *slow* subduction and exhumation over tens of millions of years, they are also *large*—tens of kilometers thick and tens of thousands of square kilometers in area (including related HP eclogites). Kylander-Clark et al. (2012) have drawn attention to the possibility that UHP terranes might be divided into two main types: big terranes formed and exhumed slowly and small terranes formed and exhumed quickly.

The Western Gneiss Region (WGR) consists chiefly of orthogneisses of the Baltica craton. The UHP–HP portion of the WGR is inferred to have formed by Silurian subduction of the western edge of the Baltica craton beneath Laurentia, prior to the final stages of the Baltica–Laurentia collision. The preservation of a tectonostratigraphy, the general coherence of peak pressures, and the preservation of pre-UHP structures indicate that this giant UHP terrane was exhumed without strong deformation except in its highest *P–T* portions (Hacker et al. 2010). An extensive database of dates obtained via a range of methods and isotopic systems indicates that subduction was underway by 425 Ma and ended around 400 Ma, and that exhumation of the deepest rocks to crustal levels was complete no sooner than ~390 Ma (Kylander-Clark 2008). In other words, the entire cycle was much slower than the rapid subduction–exhumation cycle proven for Tso Morari and Kaghan and inherent to the Chemenda-type model.

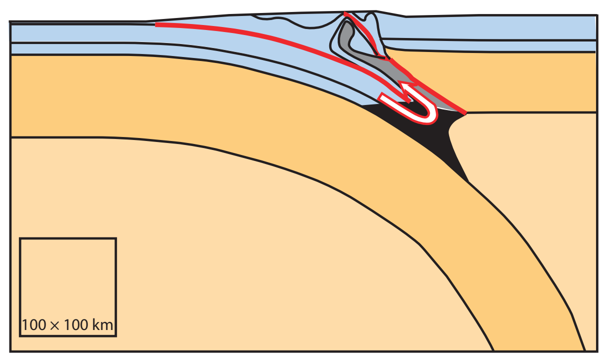

Figure 3 A numerical model of the formation and exhumation of UHP rocks in a subduction channel about 7 My after the beginning of continental subduction. Thickening of the subduction channel leads to instability, and a slice of UHP continental crust detaches from the downgoing slab and rises as a strongly deformed plume to crustal levels in ~1 My. After Beaumont et al. (2009). Colors as in previous figures.

How the Western Gneiss Region was subducted and exhumed slowly and with relatively little internal deformation remains a mystery because slow isothermal processes demand large conductive length scales. The inability to identify a contractional structure carrying the WGR eastward over the Baltica foreland led Andersen et al. (1991) to propose one of the first alternatives to the Chemenda model: wholesale extraction of the Baltica craton from beneath Laurentia by reversal of relative motion between the two plates (Fig. 4). Andersen and coauthors applied the term *eduction* to this process. Numerical models show that eduction is feasible once the subducted slab has failed by necking (Duretz et al. 2012). Other workers in the WGR have long maintained that contractional structures placed the UHP–HP rocks over lower-pressure rocks (Tucker et al. 2004), which would invalidate a pure eduction model. Assessing whether such a basal thrust exists in the Scandinavian Caledonides will allow differentiation between these exhumation hypotheses.

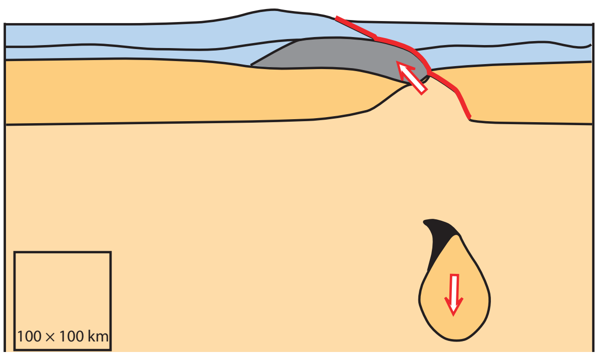

Figure 4 A conceptual model of the exhumation of a subducted continental margin by reversal of relative plate motion. The model entails slab breakoff, followed by rebound of the continental margin by slip along a large-scale extensional structure and no underlying thrust fault. After Andersen et al. (1991). Colors as in previous figures.

The Dabie–Sulu terrane is dominated by crustal rock inferred from its isotopic signatures and tectonostratigraphy to represent the northern margin of the South China Block (Liou et al. 2012). It is thought to have formed by northward Permo-Triassic subduction beneath the North China Block. Like the WGR, an extensive database of dates indicates that subduction was underway by 245 Ma and that exhumation of the deepest rocks to crustal levels was complete no sooner than ~220 Ma (Hacker et al. 2000). The specific exhumation mechanism of this giant UHP terrane is obscured by significant Jurassic–Cretaceous igneous and structural reworking (Ratschbacher et al. 2000). An along-strike gradient in peak pressures and a differential orientation of retrograde stretching lineations suggest rotation of the UHP–HP terrane during exhumation from mantle depths, but crustal-slice models have been suggested as well. The degree of internal deformation was sufficient to form kilometer-scale folds but not so severe as to destroy a presubduction tectonostratigraphy or delicate, local igneous textures (Schmid et al. 2003). Limited exposures and strong deformation within the foreland south of the orogen preclude assessing whether the UHP–HP rocks were extruded over the foreland or whether the entire lower plate was extracted by eduction.

Trans-mantle Diapirs

An enigmatic and intriguing small UHP terrane is exposed in a series of eclogite-bearing gneiss domes in the D'Entrecasteaux Islands of Papua New Guinea (PNG) (Baldwin et al. 2008). The enigmatic nature of this terrane stems from the fact that the UHP eclogite formed at ~8 Ma, and yet the most recent subduction event in the region was the subduction of the Australia–New Guinea continental margin at 35–30 Ma. Possible solutions to this conundrum include subduction of the protolith shortly before 8 Ma along an unknown subduction zone that is not currently active, or subduction of the protolith at ~30 Ma and transformation to eclogite at ~8 Ma (Little et al. 2011). Zircon U–Pb data indicate that the gneiss was derived chiefly from Cretaceous or younger rock (Zirakparvar et al. 2013), but whether that material was seafloor sediment or Australian-margin sedimentary rock is unclear. The PNG terrane might also be the best-known example of UHP rocks formed by subduction beneath an oceanic hanging wall, perhaps similar to the modern-day subduction of the Australian plate beneath the Banda arc. The PNG terrane is unusual in one other respect: it is composed of ~30–40% plutonic rocks that formed during exhumation-related melting at 3.5–2.5 Ma (Gordon et al. 2012). The combination of a >20 My gap between the last-known subduction event and the eclogite date, and the presence of extensive exhumation-related 3.5–2.5 Ma plutonic rocks has led to the suggestion that the PNG terrane may have been exhumed through the mantle as a diapir (Fig. 5) (Little et al. 2011).

The idea that UHP terranes might be exhumed as aggregates of diapirs (Fig. 5) that rose through the mantle was originally suggested for the UHP rocks of the Alps (Gerya and Stöckhert 2006). The idea may seem outrageous at first blush, but Currie et al. (2007) and Yin et al. (2007) have shown that subducted crustal rocks may rise diapirically through the mantle wedge without melting or being assimilated into the wedge. Sediment subduction is ongoing beneath arcs around the world (Clift and Vannucchi 2004; Scholl and von Huene 2007), and while these authors suggested that most of this crustal material is recycled in the mantle, it is equally likely that much of this material may relaminate the base of the upper plate, perhaps after undergoing significant changes in chemical and physical properties (Hacker et al. 2011). If the D'Entrecasteaux Islands terrane was derived from seafloor sediment, it could perhaps represent the first recognized occurrence of large-scale continental relamination, now exhumed.

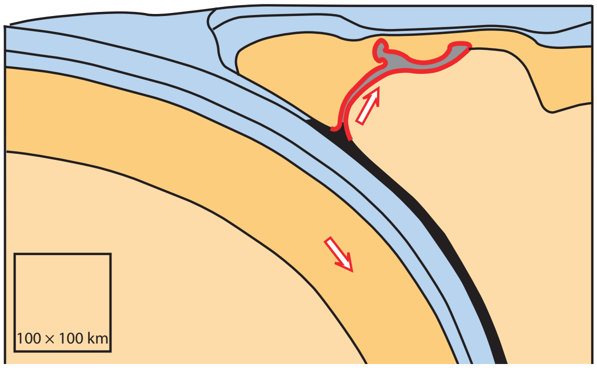

Figure 5 A conceptual model of the formation and exhumation of a UHP terrane by the rise of diapirs through the overlying mantle. After Little et al. (2011). Colors as in previous figures.

UHP Metamorphism in the Overriding Plate

Not all UHP terranes need be derived from the subducting slab. Most active subduction zones are erosional (Scholl and von Huene 2007), meaning that pieces of the overriding plate are being plucked from the hanging wall and subducted to unknown depth. Xenoliths of Asian crust erupted in the southern Pamir from near-UHP mantle depths may be direct evidence of tectonic erosion of Asia by the downgoing Indian plate (Hacker et al. 2005). Wholesale subduction and UHP metamorphism of the overriding plate is also possible. Intracontinental subduction is a plausible explanation for the UHP terrane in North-East Greenland (Gilotti and McClelland 2011), where Laurentian crust in the overriding plate of the Caledonides experienced UHP metamorphism late in the collision and far from the suture with Baltica, in a setting not unlike the Tibetan Plateau today. Deep subduction of material from the overriding plate demonstrates that HP and UHP rocks alone are not conclusive evidence for the polarity of subduction.

FUTURE WORK

The diversity of *observations* from UHP terranes has led to the realization that there must have been a variety of 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.

For the future, we see the following tasks as exciting and relevant: (1) Understanding why there are so many Phanerozoic UHP terranes, but few older. (2) Producing geodynamic models that replicate as closely as possible the geologic data from well-studied UHP terranes (for example, the very long timescales for subduction and exhumation of the giant UHP terranes). (3) Acquiring field and laboratory data that test the predictions of the latest geodynamic models. (4) Imaging actively exhuming UHP terranes (e.g. PNG). (5) Identifying more UHP material that originated in the overriding plate. (6) Assessing the fluxes of continental material returned to the mantle, exhumed to Earth's surface, and relaminated to the base of continents.

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