The Realm of Ultrahigh-Pressure Metamorphism

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The discovery of diamond and coesite in crustal rocks is compelling evidence that continental material has experienced pressures that can only be achieved at mantle depths. At least 20 terranes of unequivocal continental crust containing diamond or coesite are now recognized around the globe; their study constitutes a new field in petrology called ultrahigh-pressure metamorphism. The idea that continents do not subduct has given way to the notion that Earth has been sufficiently cool since the Cryogenian (~850 Ma) to allow density changes to drive continental crust into the mantle during collision. Some of this crust is exhumed to the surface, some pools at the Moho, and the rest sinks into the mantle. In this issue, microscopic observations, phase-equilibrium modeling, geochronology, and geodynamic modeling track the journey of crustal rocks to the mantle and back to Earth’s surface.

Keywords: coesite, continental subduction, exhumation, diamond, eclogite, ultrahigh-pressure metamorphism

ULTRAHIGH-PRESSURE METAMORPHISM

The concept that buoyant continents resist subduction has slowly been eroded by the recognition of coesite and diamond in crustal rocks from mainly Phanerozoic mountain belts around the world (Fig. 1). Coesite, a high-pressure polymorph of SiO₂, was independently discovered in two different crustal rocks almost 30 years ago. Christian Chopin (1984) reported tiny grains of coesite as inclusions in pale pink garnet in an unusual quartzite from Dora-Maira, Italy, while David Smith (1984) identified coesite inclusions in clinopyroxene in an eclogite from Grytting, in the Western Gneiss Region of Norway. The identification of microdiamonds as abundant inclusions in garnet from eclogites, gneisses, and schists in the Kumdy Kol unit of the Kokchetav massif, Kazakhstan (Sobolev and Shatsky 1990), followed shortly after. These metamorphic diamonds are not the gem-quality diamonds brought to the surface by kimberlite pipes and coveted by society from time immemorial; rather, they are scraggly, little skeletal crystals, commonly less than 10 microns in diameter. Microdiamond and coesite in crustal rocks (Fig. 2) are relics of a journey that has taken surface material to mantle depths and back. Their discovery has fundamentally changed the way geologists view processes at convergent plate margins, from the Cryogenian to the present day.

Coesite is commonly found in eclogite—an attractive rock that is the poster child for high-pressure (HP) metamorphism because of its easily distinguished constituents, red garnet and green omphacite (Fig. 3). Basalt and gabbro transform into eclogite at high pressure when all the plagioclase has reacted with other ferromagnesian minerals to form omphacite, a dense Na-rich clinopyroxene, and garnet. The part of pressure-temperature (P-T) space that is inhabited by eclogite has long been known as the eclogite facies, but rocks of all compositions can occupy this space. The needle-in-a-haystack finds of diamond and coesite have extended known examples of eclogite facies metamorphism to even higher pressures and spawned a new field of metamorphic petrology called ultrahigh-pressure (UHP) metamorphism. Mineral assemblages with pressures above the quartz-to-coesite transition are ultrahigh-pressure metamorphic rocks by definition (e.g. Chopin 2003; Liou et al. 2009; Fig. 4). Coesite and diamond are the index minerals of UHP metamorphism, but many other minerals and microstructures point to pressures in excess of the quartz-to-coesite transition (see Schertl and O’Brien 2013 this issue). A look at P-T space (Fig. 4) shows that eclogite facies conditions are not attained in normal continental crust but are possible when the crustal thickness doubles. Even where the crust is over 80 km thick beneath the Tibetan Plateau, the thickest crust on Earth, the rocks are still in the quartz stability field. To produce coesite, rocks must travel to mantle depths. Terminology can be confusing because very high pressures are the norm deep in the Earth’s mantle and core (see Elements, June 2008); but in this issue, the term UHP metamorphism refers to continental rocks that have experienced mantle pressures.

We now recognize over 20 coesite and microdiamond terranes around the world (Fig. 1), which are made up of many individual localities. The majority of examples come from continental crust, but a few cases of oceanic crust are known as well. These so-called ultrahigh-pressure terranes are mainly situated in Phanerozoic continent—continent collision belts (Fig. 1)—in marked contrast to the kimberlite pipes in Precambrian cratons that host gem-quality diamonds (Harlow and Davies 2005). The most compelling evidence that rocks from the Earth’s surface have visited mantle depths comes from metamorphosed sediments. Diamond has been found in marble,
the metamorphic equivalent of limestone, while coesite and diamond are common in metasedimentary rocks with clastic depositional origins. A variety of rock types from the Triassic Dabie–Sulu UHP terrane in China still retain their premetamorphic, very negative δ18O values, which indicate exchange with heated, low-δ18O surface waters left over from Neoproterozoic glacialiations (Liou et al. 2012).

Another important indication that continental crust has visited mantle depths is the presence of lenses of garnet peridotite—mantle rock composed of olivine + garnet ± pyroxene—in the quartzofeldspathic UHP crust. In the majority of cases, garnet peridotites were transferred into the crust from the subcontinental lithospheric mantle wedge by tectonic processes during collision (Liou et al. 2009). The garnet peridotites demonstrate that continental crust not only reaches mantle depths but that it commonly returns with tectonically emplaced samples. Two well-known examples of garnet peridotite—Alpe Arami, Switzerland (Dobrzhinetskaya et al. 1996) and Ottrøy, Norway (Spengler et al. 2006)—may have come from depths in excess of 300 km before they encountered their crustal hosts. Exhumed UHP terranes thus provide direct observations of the deeper levels of orogenic belts, subduction zones, and Earth’s mantle.

**WHAT DO UHP TERRANES LOOK LIKE?**

Field observations from the best-exposed continental UHP terranes show that the majority of the rocks are rather ordinary, gray, banded amphibolite facies gneisses. The gray gneisses are composed of common rock-forming minerals, mainly quartz, feldspar, garnet, amphibole, biotite, and white mica. In many cases they are orthogneisses (derived from an igneous parent), but they can also be paragneisses (Fig. 5a), in which case they may be interlayered with marbles and quartzites. Thin, centimeter-scale leucocratic layers formed by post-UHP partial melting are typical of the gneisses. A clue to their potential UHP heritage is the presence of easily recognizable layers and lenses of eclogite within the quartzofeldspathic gneisses. The protoliths of eclogite were original mafic components of the crust—common features such as lava flows, dikes, sills, plutons, and xenoliths—that resided in the crust prior to UHP metamorphism. During deformation, the stiffer mafic rocks were typically pulled apart to form lenses and pods, while the softer quartzofeldspathic rocks flowed around them. The example in Figure 5b shows a coesite-bearing eclogite with isoclinally folded layers of light-colored kyanite eclogite, garnet-rich eclogite, and dark green, pyroxene-rich eclogite; the compositional variation reflects the sequence’s origin as a layered gabbroic pluton. Historically, the host gneisses have been ignored in favor of the eclogites, but the discovery of diamond and coesite in zircon from such gneisses shows that large volumes of crust have seen UHP conditions. Nowhere is this better displayed than in a 5 km
Coarse-grained eclogite with round to elliptical, glasy, pink garnet in a matrix of light green omphacite, North-East Greenland. Strong minerals such as garnet, omphacite, and zircon commonly form containers for inclusions of diamond and coesite. The coin is 2.5 cm in diameter.

deep drill hole through the Sulu UHP terrane, China, where over 90% of the core is felsic gneiss and every lithology contains coesite (F. Liu et al. 2007). Such blocks of eclogite-bearing UHP continental crust are referred to as coherent eclogite terranes to emphasize that all crustal components share the same UHP history and to distinguish them from HP eclogite and blueschist blocks in accretionary mélanges.

The deformation state of coherent continental UHP terranes is varied. The common situation is an isoclinally folded package of high-strain rocks with subparallel, composite deformation fabrics cutting all rock types. In some cases, the eclogites retain an HP fabric at an angle to the lower-grade fabrics in the enveloping gneiss. On the other hand, remarkable pockets of low strain can remain even in highly deformed UHP terranes. Coronitic granodiorites associated with the coesite-bearing pyrope quartzite in the Brossasco-Cisasc unit of the Dora-Maira massif, western Alps, retain their igneous texture. Original plagioclase in the metagranitoid is statically replaced by a jadeitic pyroxene with ~13% Ca-Eskola molecule, a subtle sign of UHP metamorphism (Bruno et al. 2002). In a spectacular example from Yangkou beach, China (Fig. 5c), undeformed gabbro transforms to coesite-bearing eclogite (Fig. 2a) over a distance of a few meters (Zhang and Liou 1997). Low-strain regions are small but widespread in many UHP terranes, and are windows into the original character of the continental crust.

Continental UHP terranes come in assorted sizes. The largest in areal extent are the Dabie–Sulu belt, China, which is a part of the exhumed Yangtze craton (>30,000 km²), and the UHP area of the Western Gneiss Region, Norway (>5000 km²), a deeply subducted part of Baltica. Both are associated with significantly larger regions of coherent HP eclogite terranes derived from the same continental crust. A more complete estimate of size includes the thickness of the UHP terrane, but this can be difficult to determine. The Dabie–Sulu terrane must be a minimum of 10 km thick, based on exposed structural relief and the 5 km deep drill hole, while the exposed UHP Western Gneiss Region may be over 15 km thick (Kylander-Clark et al. 2012). The smaller UHP terranes are on the order of 1–50 km² and 1–3 km thick, and include the well-documented Dora-Maira and Lago di Cignana terranes in the western Alps. In most cases, size is probably underestimated because not all the diamond- or coesite-bearing rocks have been found. A current challenge is to identify individual UHP structural slices.

For example, two separate UHP units are now recognized in the Kokchetav massif, Kazakhstan (Scherli and Sobolev 2013): the diamond-bearing Kumdy Kol terrane and the coesite-bearing Kulet terrane; on the other hand, Lanari et al. (2013) proposed that the Himalayan UHP localities all belong to one terrane. Identifying individual UHP units based on structural geology and shared metamorphic history, in addition to index minerals, will lead to a better understanding of the overall tectonic evolution of UHP terranes.

**WHAT CAME UP MUST HAVE GONE DOWN**

The finds of coesite and diamond in rocks that today reside at the surface are direct evidence that crust was transported to mantle depths and returned as recognizable slices. Continental subduction during plate collision is the main mechanism for forming UHP terranes. The simple idea is that subduction acts like a cool conveyor belt, where the leading edge of the subducting plate starts out as oceanic crust and converts to eclogite at depth. Eclogite, being denser than the upper mantle, sinks and pulls the attached continent down to mantle depths as well. In subduction zones with geotherms around 5–8°C/km, the crust remains cool enough to prevent melting at increasing depths. The preponderance of Phanerozoic-age continental UHP terranes (Fig. 1) also supports a subduction zone origin on a cooler Earth with well-established plate tectonics. Other mechanisms that could lead to the formation of felsic UHP terranes include subduction erosion of the overriding continental plate and...
transport of the quartzofeldspathic crustal slices to mantle depths, or delamination of overthickened, dense crustal roots, which then sink into the mantle.

Exhumation brings UHP rocks from great depths back to Earth’s surface. Exhumation mechanisms are less well understood than the processes that form UHP terranes, but ultimately they depend on body forces and the positive buoyancy of the subducted continental crust in comparison to the mantle. A variety of factors—such as size, exhumation rate, the percentage of crust actually converted to UHP assemblages, and the volume of eclogite together with garnet peridotite hitchhikers—will influence the exhumation process. Subduction zones lend themselves to exhumation because their geometry creates a complex pathway for return flow in a cool channel. Geodynamic models of continental subduction provide insight into possible mechanisms that promote exhumation (Gerya 2011).

A convenient way to describe the round-trip from Earth’s surface to the mantle and back is as a path through pressure–temperature space over time \((P–T–t)\), or a \(P–T–t\) loop. The path is built by connecting points where the mineralogy and mineral compositions allow for a unique history, i.e., the exhumation of an “assemblage” (Larue et al. 2006). Time is added to the loop by the judicious application of geochronological methods to the available minerals in the rock (McClelland and Lapen 2013 this issue). U–Pb dating of multiple growth domains in zircon is a common approach. Not surprisingly, transport around the loop takes place at typical plate tectonic speeds, on the order of 1–10 cm/y. Subduction rates are approximately equal to exhumation rates for the smaller UHP terranes, which tend to take \(~10\) My to make the entire trip. Large UHP terranes may take \(~10–20\) My to develop; they commonly return to the surface in two stages after stalling at the lower crust on their return (Zheng et al. 2009; Kylander-Clark et al. 2012).

\(P–T\) paths for HP and UHP terranes have a characteristic hairpin shape (Fig. 4), with long, steep sections that show profound increases and then decreases in pressure at relatively constant temperature. On the basis of temperature, the \(P–T\) paths can be divided into cold loops (to \(600^\circ\mathrm{C}\)), tepid loops (to \(800^\circ\mathrm{C}\)), and hot loops (to \(1000^\circ\mathrm{C}\)). Cold loops are the hallmark of blueschist and eclogite terranes with oceanic affinities. Oceanic UHP terranes are rare, not because they fail to form but because they are too dense to be exhumed. The majority of continental UHP terranes follow a medium-\(T\) path to maximum temperatures of \(~800^\circ\mathrm{C}\) (Hacker 2006). Hot UHP loops are relatively uncommon, but the three best-studied diamond-bearing terranes—the Bohemian, Kokchetav, and Rhodope massifs—fall into this category. Rocks that follow hot loops tend to melt, which decreases the chance of preserving coesite and diamond and may explain the paucity of UHP minerals in HP granulate terranes. The influence of fluids and melts during the formation and exhumation of UHP terranes is further examined by Hermann et al. (2013 this issue).

**GLOSSARY**

**Buoyancy** – the upward force exerted on the crust by the mantle; the term also refers to the difference in density between the mantle and the oceanic or continental crust because density determines the amount of displacement (floating or sinking) of the crust with respect to the mantle.

**Coeサイト** – a high-pressure polymorph of \(\text{SiO}_2\). Coesite is more dense than quartz and is stable at depths greater than 90 km \((P > 2.6 \text{ GPa})\) at \(600^\circ\mathrm{C}\). Coesite is the main index mineral of UHP metamorphism, but it can also form by shock from a meteorite impact.

**Delamination** – a process whereby rocks at the base of the crust become dense, perhaps by overthickening or gravitational instability, and sink into the mantle. These so-called mantle drips have been imaged seismically and produced in geodynamic models.

**Diamond** – a dense, high-pressure polymorph of carbon, in which each carbon atom is bonded to four other carbon atoms in a rigid tetrahedron, resulting in tetrahedral symmetry. Diamond is also an index mineral of UHP metamorphism.

**Eclogite** – a metamorphosed mafic rock that contains garnet and omphacite, but not plagioclase. Other common minerals in eclogite are kyanite, quartz/

**Exhumation** – the movement of a buried rock towards Earth’s surface. Exhumation is distinct from uplift, which is simply the increase in elevation of the surface.

**Garnet peridotite** – an ultramafic metamorphic rock composed of garnet + olivine ± pyroxene, sometimes called orogenic peridotite because such rocks are found in collisional orogens. Garnet peridotites are commonly derived from the sublithospheric mantle, but they can also represent minor ultramafic cumulates associated with crustal mafic intrusions.

**High-pressure (HP) metamorphism** – metamorphism at pressures above the calcite to aragonite transition. Na pyroxenes are also stable in this field. HP rocks occupy the blueschist, eclogite, and HP granulate facies.

**Metamorphic facies** – the collection of mineral assemblages from rocks of all bulk compositions that crystallize at the same pressure and temperature conditions. The greenschist, blueschist, amphibolite, granulate, and eclogite facies boundaries are established based on the mineral assemblages in metamorphosed mafic rocks.

**Omphacite** – a dense, Na-rich clinopyroxene, with a minimum of 20% jadeite component. Jadeite is the pure Na pyroxene \((\text{NaAlSi}_2\text{O}_6)\) end-member.

**Pseudomorph** – the result of the replacement of one mineral by another, where the new mineral assumes the form of the original.

**Relamination** – a process whereby continental rocks that have reached mantle depths—or their melt products—are returned to the base of the crust.

**Stishovite** – the second high-pressure polymorph of \(\text{SiO}_2\), formed by the conversion of coesite at mantle depths in excess of 200 km \((~7 \text{ GPa})\) at \(600^\circ\mathrm{C}\) or 300 km \((~10 \text{ GPa})\) at \(1400^\circ\mathrm{C}\). Natural stishovite has only been observed in meteorite impact structures.

**Terrane** – a crustal block with a distinct stratigraphy, structure, and geologic history. Exotic terranes are fault-bounded blocks that have a foreign origin compared to the surrounding rocks. Most UHP terranes are of known provenance and belong to a craton, although exotic UHP terranes that originated as continental arcs are also known. A terrane can be thought of as any physical landmass, and the term sometimes refers to topography, as in “rough terrain.”

**Ultrahigh-pressure (UHP) metamorphism** – metamorphism of crustal rocks that occurs at pressures in the coesite stability field. UHP metamorphism is identified by the presence of coesite or diamond, or by the equivalent pressure–temperature conditions calculated from thermodynamic models of mineral compositions.
The Himalayan orogen provides a conceptual framework for understanding the cycle of UHP metamorphism during continent–continent collision. The Himalayas started to form after India collided with Eurasia around 55 million years ago. The Indian subcontinent was at the leading edge of the Tethyan oceanic crust and was subducted beneath Eurasia. Two coesite-bearing localities in the western Himalayas, Kaghan Valley and Tso Morari, expose rocks belonging to the Indian margin. UHP metamorphism at Kaghan Valley is dated at 46 Ma by U–Pb spot analysis of the coesite-bearing domains of zircon (Kaneko et al. 2003), and the rocks were exhumed to the middle crust by 44 Ma (Parrish et al. 2006). The Himalayan UHP examples followed a typical tepid P–T path, with exhumation rates approximately the same as subduction rates. Even though the India–Eurasia collision is ongoing, UHP rocks have already been exposed in the exhumed core of the orogen, in a position structurally below the suture with Asia and at the top of the subducting Indian plate. The prevailing paradigm for UHP metamorphism based on the Himalayan example holds that continental subduction occurs at the leading edge of the down-going crust early in collision and that the subducted rocks follow a tepid P–T path consistent with metamorphism in a subduction channel environment. UHP terranes are assumed to be coherent crustal slices that are returned to the surface in the upper parts of subduction zones, near the base of the overriding plate. This early paradigm is already being outpaced by new results from UHP research. We are learning that some UHP terranes form late in the collision process, that some are hot, some take a long time to form, some exhum slow, and a few are derived from the overriding plate (Hacker et al. 2013 this issue).

**DENSITY AND THE LIMITS OF UHP METAMORPHISM**

The density contrast between metamorphosed continental crust and mantle strongly influences the maximum depth to which the crust can be subducted. Continental crust starts out with a density between 2.7 and 3.0 g/cm³ and floats on subcontinental lithospheric mantle, whose density is about 3.3 g/cm³. The density of oceanic crust is ~3.0 g/cm³ and changes to 3.5–3.6 g/cm³ as basalt converts to eclogite during subduction, allowing subducted oceanic crust to easily sink into the mantle. The density of continental crust at mantle depths cannot be directly observed but can be predicted from thermodynamic models. Calculated mineral assemblages and modes for a variety of quartzofeldspathic lithologies show that crustal rocks approach the density of the mantle at >4 GPa (Massonne et al. 2007), or ~120 km depth. For example, an average sedimentary rock at 3.5 GPa and 900 °C will consist of approximately 30% coesite, 7% garnet, 26% phengite (white mica), 26% omphacite, 10% epidote, and 1% titanite and will have a density of 3.2 g/cm³. More aluminous compositions, such as the diamond-bearing gneiss from Fjortoft (Fig. 5A), contain kyanite and 30–40% garnet, and these minerals push the density of the paragneiss to over 3.4 g/cm³, greater than mantle density. The extraction of partial melts during UHP metamorphism will lead to even higher densities in the residual rock.

If the density of continental crust exceeds that of the mantle, then there is no limiting depth for recycling quartzofeldspathic material into the mantle. The fact that UHP terranes are exhumed is perhaps more remarkable. The actual “point of no return” will depend on the specific crustal composition. How deep has continental crust been subducted and still returned to the surface? Metamorphic diamond forms at a minimum of 4 GPa at 800 °C, or the equivalent of ~130 km depth, and we know of at least nine terranes where diamonds occur in crustal rocks (Fig. 1). The reaction dolomite [CaMg(CO₃)₂] → magnesite (MgCO₃) + aragonite (CaCO₃) takes place at higher pressures than the graphite → diamond transition and has been identified in impure marbles from Dabie–Sulu, China (Proyer et al. 2013). Coesite exsolved from supersilicic titanite in marbles from Kumdy Kol, Kokchetav massif, records pressures of 6 GPa at 1000 °C, or depths of 200 km (Ogasawara et al. 2002). The stunning interpretation of quartz + kyanite...
pseudomorphs after stishovite, the SiO$_2$ polymorph stable above 9 GPa, in metasedimentary rocks from the Altyrn Tagh, China, suggests that crust has been exhumed from depths exceeding 350 km (L. Liu et al. 2007). Garnet peridotites that accompany deeply subducted crust back to the surface can record extreme pressures, but this is not unexpected in mantle rocks.

**THE FATE OF UHP CRUST AT MANTLE DEPTHS**

Continental UHP terranes can be exhumed, consumed, or partially exhumed to the base of the crust. Subduction zones provide an obvious return pathway for exhumation in the form of a two-way channel; they can also form a conveyor belt for consumption by the mantle. Crustal roots that become thick and dense can delaminate from the base of the crust, founder, and sink into the mantle. As the crust reaches greater depths and temperatures, partial melting will begin. Felsic melts will separate from the denser residue, rise, and perhaps pond at the base of the crust. Such relamination of continental material to the base of the crust could be an important process of crustal growth and lead to a more felsic composition for the lower crust than currently accepted (Hacker et al. 2011).

In this issue of *Elements*, we use field geology, microscopic observations, phase-equilibrium modeling, geochronology, and geodynamic modeling to track the journey of continental crust to the mantle and back. Continental UHP terranes impact our understanding of crustal growth and recycling, mantle geochemistry, melting in subduction zones, plate tectonics through time, and collisional processes in general. The burgeoning new field of UHP metamorphism offers exciting avenues for future research and a deeper understanding of Earth’s crust.

**ACKNOWLEDGMENTS**

I thank all the contributors to this issue of *Elements* for their dedication, hard work, and patience, and John Valley and Pierrette Tremblay for their cheerful, able guidance through the editorial process. Helpful reviews from Mike Brown and Zeb Page improved this manuscript. NSF grants EAR-0208236 and EAR-1049433 have funded my research on UHP metamorphism.

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