UHP METAMORPHISM: OCCURRENCE, PROTOLITHS, P-T-TIME PATH, AND EXHUMATION

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Summary

This abstract describes an overview of UHP metamorphism, global distribution, protoliths, assemblages of UHP rocks, P-T-time paths and an exhumation model. Through such review we conclude that thin UHP slab is bounded by pair faults, consists of protoliths of continental affinity, has been recrystallized at extremely low-geothermal gradient regimes, and subsequently returned to crustal level by wedge extrusion and doming. We have suggested several petrochemical and tectonic problems remained to be investigated for UHP terranes in order to understand the processes of continent subduction-collision.

Introduction

Ultrahigh-pressure metamorphism (UHP) refers to the metamorphism of crustal rocks (both continental & oceanic) at P high enough to crystallize the index minerals coesite and/or diamond. Prior to the initial discoveries of coesite in supracrustal rocks (Chopin 1984; Smith 1984), coesite and diamond were thought to occur only in meteorite-impact craters and mantle xenoliths. The discovery of upper-crustal rocks metamorphosed to UHP requires a revision in our understanding of crustal-scale processes in continental collision zones. The process by which buoyant continental crust is subducted to depths exceeding 100 km is at least generally understood in the context of subduction, but how such rocks are later returned to the surface is not yet clear. The existence of UHP belts challenges many beliefs about subduction, exhumation, continental collision + growth, and the nature of crust-mantle interactions. Understanding UHP tectonics is viewed as a significant new undertaking of considerable import as underscored by the plethora of recent task groups, workshops, conference sessions, and special issues and books devoted to the subject. In this review, we describe the world distribution, general characteristics, and protoliths of UHP terranes and general model for their formation and exhumation.

Occurrences

Thus far, more than a dozen UHP terranes have been documented in Eurasian continental collision orogens (e.g., Ernst & Liou 2000). All formed at P >3 GPa during aborted subduction to depths as great as 135 km and share the following structural and lithological characteristics. (i) Records of UHP metamorphism occur as coesite inclusions in garnet, zircon, and omphacite, and as microdiamond in garnet and zircon, mainly in eclogites and garnet peridotites included as pods and slabs within quartzofeldspathic gneisses. Zircon separates from gneisses and other metasediments also contain inclusions of coesite ± microdiamonds. In rare cases, peridotites also contain clinoenstatite (Bozhilov et al. 1999) and evidence of former majorite documenting mantle crystallization depths of >150 km (Van Roermund et al. 2000). (ii) The host rocks are of continental and subcontinental geochemical and petrological affinities. (iii) The exhumed UHP metamorphic rocks occur in a supracrustal setting as multi-kilometer thick subhorizontal slabs bounded above by normal faults and below by reverse faults (Maruyama et al. 1996). And (iv) coeval calc-alkalic volcanic and plutonic rocks are virtually absent, whereas post-collisional or late-stage granitic plutons are common in some belts. In these UHP terranes, supracrustal protoliths experienced subduction-zone metamorphism at mantle depths, followed by a retrograde amphibolite-granulite facies overprint during exhumation, and finally younger deformation and thermal recrystallization accompanying granitic intrusion.

Traces of UHP minerals are preserved in strong containers such as zircon or garnet. The special conditions necessary for such preservation are being increasingly recognized both in many country rock gneisses of well established UHP terranes and in newly discovered areas. The latest reported areas include: (i) coesite in Himalayan eclogite from the Upper Kaghan Valley, Pakistan (O'Brien et al. 1999), (ii) coesite and microdiamond inclusions in zircons from jadeite-bearing quartzite from Sulawesi, Indonesia (Parkinson 1999), and (iii) microdiamond inclusions in garnet, kyanite, and zircon from gneisses of the Erzgebirge, Germany (Massonne 1999).

Protoliths and UHP Rocks

One of the characteristic features of UHP terranes is the widespread occurrence of supracrustal protoliths of continental affinity associated with minor amount of recognizable mafic and ultramafic rocks. Large masses of oceanic crustal rocks have not been reported, except in the Zermatt-Sass zone of the Western Alps and in southern Sulawesei, central Indonesia. Garnet peridotites of some UHP terranes may represent tectonic slices of upper mantle introduced during collision; others may be mafic-ultramafic rocks, which were emplaced into crust prior to UHP metamorphism. Both mafic and ultramafic rocks contain ubiquitous UHP assemblages and will only be briefly described. However, other abundant rocks deserve detailed description as they have been considered to be country rocks that do not carry UHP record.

Eclogites: The end-products of UHP metamorphism of gabbro, basalt flow and tuff, and diabase sill and dike are eclogitic rocks forming blocks, lenses, boudins or layers of various dimensions in gneiss (I), marble (II) and ultramafic rocks (III). In addition to garnet, omphacite, coesite/quartz and rutile, some UHP eclogites contain kyanite, and/or hydrous and carbonate minerals. Inclusions of coesite and coesite pseudomorphs have been found in zircon, garnet, omphacite, kyanite, zoisite, epidote and dolomite. Moreover, UHP eclogites contain excess Si and/or K in omphacites, Na and Ti in garnets, and high Si content ($\geq$ 3.5 per unit formula.) in phengite. Some of these excess components were precipitated as exsolution lamellae in these minerals during their subsequent decompression.

Garnet Peridotites: Recognized UHP garnet peridotites often experience a prolonged, complex evolution during their subduction and exhumation. At least three distinct stages may be distinguished: i) primary formation, ii) peak UHP metamorphism, iii) retrograde stage including granulite-facies recrystallization, amphibolite-facies retrogression, and greenschist-facies overprinting. Garnet peridotites may originally have been mantle fragments, which were introduced into subducting slabs or may have derived from mafic - ultramafic complexes that were emplaced into the crust prior to subduction. The mantle-derived peridotites could have several initial settings: i) the mantle wedge above a subduction zone, ii) the footwall mantle of the subducted slab, and (iii) ancient mantle fragments that probably had a resident history in the crust prior to UHP metamorphism. Garnets from mantle-derived peridotites contain high pyrope contents (> 50 mole%) and high Cr_2O_3 contents (up to > 4 wt%). All orthopyroxenes of UHP garnet peridotites have low Al_2O_3 contents less than 1 wt%, (the lowest Al_2O_3 content is less than 0.08 wt%).

Felsic Gneisses: Felsic gneisses are the predominant rock types in most UHP terranes; they do not preserve a clear UHP metamorphic record. This lack of evidence for UHP metamorphism led to an early hypothesis that eclogites and their country rocks were metamorphosed under different P-T regimes, and were subsequently juxtaposed by faulting. According to this hypothesis, the extent of UHP metamorphism was no larger than eclogite boudins now exposed, which measure no more than a few m in length and thickness. Mineralogical indicators of UHP metamorphism have now been found in a number of country rocks including gneiss, whiteschist, quartzite, and marble. Tiny coesite inclusions have been reported (1) in zircons from felsic gneiss, (2) in dolomite and garnet from siliceous marble and dolomite-bearing eclogite, and (3) in garnet and jadeite from jadeite-bearing quartzite. Detailed study of compositions of garnet and mica in felsic gneiss and UHP schist from Dabie and pyrope-bearing whiteschist of the Dora Maira Massif shows that they were metamorphosed under P-T conditions similar to the intercalated coesite eclogites and garnet peridotites. Available field and petrochemical data demonstrate that the country rocks of UHP eclogites and garnet peridotites also record UHP metamorphism.

Pelitic Rocks + Quartzites: Characteristic assemblages of these lithologies occur in many terranes but are best described in the Dora Maira Massif. These assemblages include Phe (Si = 3.55) + Tlc + Ky + pyrope + Coe/Qtz ± Jd in quartzites and magnesian pelitic rocks, and almandine-rich Grt + Ky + Phe (Si = 3.5) + Coe/Qtz ± Jd + Rt and occurrence of paragonite, biotite, chlorite, chloritoid and staurolite in normal Fe-rich pelites. Coesite occurs as inclusion in both garnet and kyanite. Stable occurrences of Ky + Tlc + Pyr + Coe indicate P > 2.7 GPa at 700-800^{o}C, and Ky + Tlc + Phe + Coe at P > 3.6 GPa. In the Dabie UHP terrane of China, coesite-bearing jadeite quartzites occur locally as intercalated layers with marble and mafic eclogite. Mineral parageneses and coronitic textures reveal a multistage metamorphic evolution and complex exhumation history. The primary peak metamorphic assemblage consists of Jd + Grt + Coe + Rt ± Ap. Minor coesite and coesite pseudomorphs occur as inclusions in jadeite and garnet.

Whiteschist: Whiteschist is characterized by the occurrence of Tlc + Ky ± Grt ± Phe, by its unusually high MgO and Al_2O_3 contents, and by its white-color, foliated and porphyroblastic appearance. Chopin (1984) discovered coesite as inclusions in pyrope, as the first example in metamorphic rocks derived from continental crust and named this rock "pyrope quartzite", later "pyrope-phengite quartzite". In the literature, both names, whiteschist and pyrope quartzite, have been used; many prefer whiteschist in order to emphasize both its peculiar chemical composition and its mineral assemblage. Whiteschists from the Dora Maira Massif occur within felsic gneiss as layers that range from a few cm to several m thick, and from a few m to several tens of m long. These whiteschists have been considered to be Mg-rich sediments deposited in an evaporitic environment. However, recent geochemical studies indicate that they were metasomatic transformation products of granitic rocks along active ductile shear zones in the presence of a hydrous fluid mineral.

Whiteschists from the Kokchetav Massif contain similar assemblages. Garnets show large compositional variations, and are characterized by the occurrence of abundant inclusions and prograde compositional zoning. Some cores contain abundant inclusions of quartz and are recrystallized at 380^{o}C (inner core) to 580^{o}C (outer core) at P <1 GPa. Mantles of the garnet contain inclusions of coesite pseudomorphs and coesite with peak P-T conditions at about 3.6 GPa at 780-800^{o}C. Post-peak garnet rims recrystallized at around P~2.8 GPa and T~800^{o}C, are compositionally homogeneous and lack silica inclusions (Parkinson, 2000).

Marble and Calc-silicate Rocks: Diamondiferous dolomitic marbles from the Kokchetav Massif contain variable amounts of diopside, dolomite, garnet, and phlogopite. Some dolomites display exsolved calcite lamellae whereas diopside shows K-feldspar lamellae. Microdiamond occurs mainly in garnet and rarely in diopside and phlogopite pseudomorphs after garnet, whereas dolomite contains graphitized diamond inclusions. At the estimated P-T peak conditions for diamond-bearing dolomitic marble, about 960^{o}C and > 4.0 GPa, the stable coexistence of dolomite and diopside (+ diamond) requires an aqueous fluid composition with X_{CO2} > 0.05.

Marbles interlayered with coesite-bearing eclogites occur in several other UHP terranes. Most carbonate rocks are marble; some siliceous carbonates contain minor grossular garnet, diopsidic pyroxene, and clinohumite or olivine in different compositional layers. Siliceous dolomitic marbles from the Sulu region of China contain the assemblage Mg-calcite + Dol ± Ol ± Di ± clinohumite. In the Dabie Mountains, the UHP assemblage consists of aragonite/calcite + Dol + grossular-rich Grt ± Cs ± Omp + Phe ± Rt. Dolomite is common and appears to coexist with coesite; this implies that dolomite is stable up to 3.5-5.5 GPa, consistent with experimental results. Other samples contain relict coesite and aragonite. Calculation of P-T condition for coexisting Grt + Rt + Coe + Zo yield minimum P of 2.8 GPa at 650^{o}C.

P-T –Time Path

P-T time paths of many UHP belts have been constructed through detailed investigations of inclusion assemblages in UHP minerals, compositions of zoned minerals, appropriate mineral reaction equilibria, and relationships of micro-structure + texture. They are clockwise paths covering a wide P-T range; most show a pattern with first P-T increasing until the peak metamorphic condition, followed by isothermal decompression. The final retrograde path is along the intermediate-P type facies series ranging from the GS, AM and GR facies. Infiltration of H_2O-rich fluids along cracks or faults into the UHP unit nearly completely obliterated the UHP mineralogy under amphibolite and greenschist facies conditions. Mainly by this reason, a debate whether or not the eclogites in the UHP terranes are exotic blocks (foreign) or *in situ* has been continued. Occurrence of thin veins of amphibole in eclogite outcrops in many UHP terranes clearly indicates the infiltration of H_2O-rich fluids into eclogite bodies. Such occurrences support the *in situ* origin. The final P-T conditions are identical to those of overlying and underlying low-P units bounded by the faults, roughly at about 0.6 GPa.

Mineral parageneses of UHP eclogites have been commonly used to delineate P-T-time paths; at least three distinct stages of metamorphic recrystallization occur: pre-eclogite stage, peak coesite eclogite-facies stage and retrograde stage. Eclogites in gneisses from the Dabie terrane were selected as examples of metamorphic evolution and deduced P-T paths. The pre-eclogite stage is mainly defined by relict mineral inclusions in garnet and prograde mineral zoning, with the assumption that the identified inclusions are representative of mineral parageneses stable at various stages during prolonged prograde garnet growth. Observed inclusions of epidote amphibolite-facies metamorphism occurred at ~ 500^{o}C, based on Fe-Mg partitioning between garnet and hornblende. Similarly, a well-documented record of the pre-eclogite stage was preserved in the Yangkou UHP slab of eastern China; the initial metamorphism of the gabbroic protolith took place at 540 ± 50^{o}C and about 1 GPa. Preservation of metastable low-P assemblages in garnet suggests that the UHP metamorphism may have been of short duration, insufficient to upgrade completely the low-grade assemblage to the coesite eclogite-facies. For most localities such as the Weihai eclogite of eastern China, however, only an exhumation P-T path from peak to retrograde stage has been deduced.

Peak stage assemblages were identified by the coexistence of garnet, omphacite and coesite, together with minor kyanite, phengite and some hydrous and carbonate minerals. Peak temperatures were estimated based on Fe-Mg partitioning between coexisting garnet and clinopyroxene, and range from 650 to 850^{o}C at 3 GPa. Most published P estimates for coesite eclogite give a minimum P, based on the presence of coesite. However, the garnet-omphacite-phengite barometer yields P-estimates of 3-4 GPa for some Dabie eclogites.

The early decompression stage is identified by continuous growth of coarse-grained amphibole, which contains abundant inclusions of eclogitic minerals except for the absence of inclusions of coesite and coesite pseudomorphs. This stage occurred at P less than the coesite-quartz transition. The retrograde stage is characterized by hydration and granulite/amphibolite-facies overprinting. Coexisting Grt- Cpx pairs of granulite-facies recrystallization yield a P-T estimate of ~760^{o}C, 0.9 GPa for the Weihai eclogite. Amphibolite-facies overprints producing the plagioclase + hornblende assemblage occurred at 500-600^{o}C, <1 GPa.

Exhumation

Maruyama et al. (1996) proposed an extrusion model for exhumation of UHP terranes based on the observed thermal structures in many UHP terranes. The mode of occurrence as a thin, subhorizontal tectonic slab bounded by a paired faults, internal thermal structure, vergence of nappe movement, chronologic age depending on distance from the root zone, and the presence of a foreland basin all indicate that the UHP unit was exhumed from mantle depth to middle- or shallow crustal levels by subhorizontal tectonic extrusion. The thermal structures documented recently in the Kokchetav massif (Maruyama & Parkinson, 2000) are consistent with the other UHP terranes. These thermal structures may reflect that more ductile, higher T, hence buoyant quartzofeldspathic materials could be extruded faster than the surrounding lower grade rocks. Once the UHP unit was emplaced at middle to shallow crustal depths, the cooling of the UHP unit, and mechanical change from ductile to brittle behavior resulted in no density difference between the extruding UHP unit and its adjacent units; lack of buoyancy would prohibit further tectonic denudation.

The tectonic juxtaposition of a dehydrated UHP unit above hydrous low-grade rocks would allow infiltration of fluid into the UHP unit. Such tectonic overlapping onto a weakly metamorphosed unit transports sufficient fluids from underlying to the overlying UHP unit and would effectively obliterate the UHP mineralogy. Accordingly, most UHP minerals are selectively replaced by low-P hydrous assemblages. The extent of such retrogression complicates the debate on the exotic versus coherent origin of coesite-bearing rocks enveloped in gneiss. During or after the tectonic juxtaposition at shallow crustal level and synchronous retrograde metamorphism, these units begin to dome upward.

The most essential driving force to extrude the deep-seated accretionary wedge may be wedging. The subducted hanging wall of a quartzofeldspathic wedge may be extruded to shallower crustal depths only if the subduction angle becomes shallower with time, because overlying peridotite and underlying eclogite would behave as brittle media, whereas the wedge-shaped felsic unit is deformed easily as a ductile agent. Presumably the more ductile central core of the wedge would move selectively upwards faster to form the observed thermobaric structures in the UHP belts.

The major driving force for domal uplifts during the second-stage exhumation process is not well understood. Underthrusting beneath the UHP belt from the newly developed oceanward trench may elevate the UHP rocks. For example, the Miocene underthrusting of the Indian continent from further southward beneath the Lesser Himalayas may have elevated the Higher Himalayas.

Conclusions and Suggestions

In our previous review (Liou et al. 1998), we have pointed out that many petrogenetic grids for mafic and ulramafic rocks and experimentally determined P-T fields for UHP phases have not been reversed. Synthesis does not necessarily equate with stability. A reasonable demonstration of chemical equilibrium can only be accomplished in cases where it can be proven that the synthetic products are homogeneous and that the occurrence is independent of P-T path. Another major problem concerns rates of transformation: degrees to which UHP equilibrium assemblages have been attained are very much a function of reaction kinetics, and as yet this topic has not been fully addressed in laboratory studies.

Experimental investigations of the pelitic system have revealed possible occurrences of several OH-bearing phases in UHP rocks (e.g. Schreyer, 1988). These include MgMgAl-pumpellyite, Mg-carpholite, phase Pi, OH-Topaz and K-cymrite; their stability fields together with Phase A and lawsonite and other OH-bearing phases occur at 500 - 750^{o}C near 4-10 GPa, but only along extremely cold geotherms considerably less than 5^{o}C/km. These P-T fields lie within a "forbidden zone" inasmuch as the 5^{o}C/km geotherm has been regarded as the lowest one realized on the Earth (Schreyer 1988). New computations regarding the temperature distribution within subduction zones indicate that some of UHP rocks have been subducted along subduction-zone gradients as low as 3°C/km (Liou et al., 2000). These low geotherms are restricted to the inner parts of rapidly buried continental or oceanic crust in long-lasting subduction zones. The finding of UHP metamorphic conditions in the forbidden zone is significant, as the cold subducting slab could have transported significant fluids to mantle depths through the OH-bearing phases mentioned above.

In many UHP terranes, since such conditions are essentially transient and will inevitably be followed by a period of thermal relaxation, all these low-T phases have little chance to survive the T-increase on return to the surface through erosional and tectonic processes. However, one possibility for their preservation evidently is as minute inclusions in high-strength, impervious containers like garnet, zircon, or diamond. Zircon and garnet are the best containers of primary UHP minerals in metamorphic rocks. Systematic characterization of crystalline inclusions employing various analytical instrumentation including the laser micro-Raman spectrometer and microsynchrotron beam analysis may lead to discovery of UHP minerals as relict inclusions in garnet, zircon, and other strong, unreactive minerals. Recent examples include finding of microdiamond inclusion in coesite within zircon from jadeite-bearing quartzite in Indonesia (Parkinson, personal com., 1999)

Moreover, while our knowledge of UHP tectonics has vastly improved since the first early reports of coesite and coesite pseudomorphs, many petrotectonic questions remain to be answered: (1) How common is the process by which low-density continental crust is carried to great depths (> 100 km)? Is the number of UHP orogens limited by the subduction process (creation), by the exhumation process (preservation), or by younger geologic events? (2) Is it possible that all collisional orogens include exhumed UHP terranes now retrogressed beyond recognition? (2) Are UHP rocks formed and exhumed in both ocean–continent or in continent –continent convergence zones? (3) What mechanisms are responsible for exhuming UHP rocks? Are these processes related to buoyancy, unusual plate configurations, and/or something else? (4) Is the active Himalayan collision between the Indian and Eurasian continents a correct analogue for UHP orogens? Is the subduction of Australia beneath Timor a proper analogue? (5) What exhumation rates and/or other special conditions are required to preserve UHP mineralogy? (6) What factors influence the kinetics of prograde and retrograde reactions in UHP rocks? (7) What exactly are the protoliths of UHP rocks, and can these be traced into or correlated with lithologies on unsubducted parts of the same tectonic plate? (8) How are mantle-derived peridotites introduced into a UHP supracrustal collage? (9) What kinds of crust-mantle interaction take place when continental material is subducted to great depths, and how do such processes affect global geochemical recycling?

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