The Geological Society of America
Special Paper 433
2007

Petrotectonics of ultrahigh-pressure crustal and upper-mantle rocks—Implications for Phanerozoic collisional orogens

W.G. Ernst
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115, USA

B.R. Hacker
Department of Geological Sciences, University of California, Santa Barbara, California 93106-9630, USA

J.G. Liou
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115, USA

ABSTRACT

Ultrahigh-pressure (UHP) metamorphic terranes in contractional orogens reflect descent of continental crust bonded to a dense, dominantly oceanic plate to depths of 90–140 km. All recognized well-documented UHP complexes formed during Phanerozoic time. Rocks are intensely retrogressed to low-pressure assemblages, with rare relict UHP phases retained in tough, refractory host minerals. Resurrected UHP slabs consist chiefly of quartzofeldspathic rocks and serpentinites; dense mafic + ultramafic lithologies comprise <10% of exhumed masses. Associated garnet-bearing ultramafic lenses are of four general origins: type A peridotite + eclogite pods reflect premetamorphic residence in the mantle wedge; type B masses were mantle-derived ultramafic-mafic magmas that rose into the crust prior to subduction; type C tectonic lenses were present in the oceanic lithosphere prior to underflow; and type D garnet peridotites achieved their deep-seated mantle mineralogy long before—and independent of—the subduction event that produced the UHP-phase assemblages in garnet peridotite types A, B, and C. Geochronology constrains the timing of protolith, peak, and retrograde recrystallization of gneissic, ultramafic, and eclogitic rocks. Round-trip pressure-temperature (*P-T*) paths were completed in <5–10 m.y., where ascent rates approximated subduction velocities. Exhumation from profound depth involves near-adiabatic decompression through *P-T* fields of much lower-pressure metamorphic facies. Many complexes consist of thin, allochthonous sheets, but those in eastern China and western Norway are about 10 km thick. Ductilely deformed nappes generated in subduction zones allow heat to be conducted away as sheet-like UHP complexes rise, cooling across both upper and lower surfaces. Thicker UHP massifs also must be quenched. Ascent along the subduction channel is driven mainly by buoyancy of low-density crustal material relative to the surrounding mantle. Rapid exhumation prevents establishment of a more normal geothermal regime in the subduction zone. Lack of H_2O impedes back reaction, whereas its presence accelerates transformation

Ernst, W.G., Hacker, B.R., and Liou, J.G., 2007, Petrotectonics of ultrahigh-pressure crustal and upper-mantle rocks—Implications for Phanerozoic collisional orogens, *in* Sears, J.W., Harms, T.A., and Evenchick, C.A., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 27–49, doi: 10.1130/2007.2433(02). For permission to copy, contact editing@geosociety.org.

to low-P phase assemblages. Late-stage domal uplifts characterize some collisional terranes; erosion, combined with underplating, contraction, tectonic aneurysms, and/or lithospheric plate shallowing, may further elevate mid-crustal UHP terranes toward the surface.

Keywords: ultrahigh-pressure metamorphism, subduction-zone metamorphism, continental collision, exhumation of UHP rocks.

INTRODUCTION

Most compressional mountain belts form at or near the active edges of continents and/or fringing island arcs. Virtually all result from the underflow of oceanic lithosphere and the consequent transport and descent of spreading centers, oceanic plateaus, island arcs, far-traveled microcontinental terranes, and/or continental crustal salients beneath the continental lithosphere. The downgoing slab is subjected to relatively high-pressure (HP), low-temperature subduction-zone metamorphism, which produces lawsonite and jadeitic pyroxene-bearing assemblages, and mafic blueschists. Long-continued subduction results in the construction of a massive calc-alkaline volcanic-plutonic arc on the crust of the stable, hanging-wall plate, but consumption of a small intervening ocean basin prior to collision does not generate a substantial arc. Most mountain chains are a reflection of their specific geography and unique plate-tectonic history; each orogen tends to exhibit major structural and petrologic contrasts along its length. Some sialic collisional belts contain mineralogic relics reflecting ultrahigh-pressure (UHP) stages of prograde recrystallization. Ultrahigh-pressure conditions are defined as those in which the high-pressure polymorphs of silica and carbon (i.e., coesite and diamond) are stable. Other dense phases and mineral assemblages, including Si- and K-bearing pyroxene, Mg-rich garnet, and eclogite-facies rocks are stable under such remarkable pressure-temperature (*P-T*) conditions.

Two main end members have been defined, but it is clear that all gradations exist between continent collisional (Alpine-type) and circum-Pacific (Pacific-type) compressional mountain belts. Similar to Pacific HP metamorphic belts, UHP Alpine orogens mark convergent plate junctions (e.g., Hacker et al., 2003a; Ernst, 2005). The former are characterized by the underflow of thousands of kilometers of oceanic lithosphere, whereas the latter involve the consumption of an intervening ocean basin followed by the suturing of an outboard island arc, microcontinent, or promontory of sialic crust against the nonsubducted continental margin. During collision, crustal sections may reach depths approaching 90–140 km, as indicated by the metamorphic crystallization of UHP indicator minerals, phases, and assemblages that are only stable at pressures exceeding ~2.5 GPa. On resurrection, many collisional UHP terranes consist of an imbricate stack of tabular sheets (Ernst et al., 1997). The Dabie-Sulu belt of east-central China, the Western Alps, the Kokchetav Massif of northern Kazakhstan, the western Himalayan syntaxis of northern Pakistan, and the Western Gneiss Region of Norway constitute the best-documented examples of exhumed UHP rocks. In all these complexes, scattered UHP phases are partially preserved in strong, tough, refractory zircon, pyroxene, and garnet—minerals characterized by great tensile strength and low rates of intracrystalline diffusion. Armoring of the UHP inclusions subjects them to high confining pressure, provides spatial separation from the recrystallizing matrix minerals and rate-enhancing intergranular fluids, and thus protects them from back reaction during decompression.

This review tries to assess the nature of the orogenic process from a general petrotectonic viewpoint, concentrating on the architectures and rock assemblages of Phanerozoic UHP complexes. Although Precambrian analogues may have resulted from the operation of comparable lithospheric plate motions, where systematic lithotectonic contrasts were related to the higher geothermal gradients that attended a younger, hotter Earth, the ancient rock record is less clear; for this reason, unambiguously ancient UHP complexes have not yet been well documented; accordingly, we concentrate on Phanerozoic collisional mountain belts in this synthesis.

Exhumation of deeply subducted UHP complexes involves near-adiabatic decompression through the *P-T* fields of much lower-pressure metamorphic facies. Thus, back reaction, especially where kinetically enhanced by the presence of an aqueous fluid, causes recrystallization and obliteration of the earlier UHP phases. Although volumetrically dominant in exhumed UHP complexes, quartzofeldspathic and pelitic rocks generally retain very few relics of the maximum physical conditions, whereas eclogites and some anhydrous peridotites, because they are relatively impervious to the diffusion of H_2O, have more fully preserved effects of the deep-seated processes (Ernst et al., 1998; Liou et al., 1998). The index minerals coesite and diamond are largely lacking in mafic and ultramafic rock types; hence we attempted to quantify the *P-T* conditions of putative UHP rocks by employing thermobarometric computations as well as phase-equilibrium experiments on rocks and minerals.

PRESSURE-TEMPERATURE CONDITIONS OF ULTRAHIGH-PRESSURE METAMORPHIC COMPLEXES

HP and UHP terranes are typified by the presence of mafic (and/or ultramafic) eclogite-facies rocks. However, *P-T* determinations on eclogites are inherently difficult because most contain only two silicate phases, garnet and clinopyroxene. Measuring the Fe-Mg exchange between these two minerals enables calculation of temperature, but additional phases such as phengite or kyanite are required for barometry. Even for simple Fe-Mg exchange reactions, two problems render temperature calculation via this method tenuous: (1) diffusional reequilibration during retrogression ensures that recovery of the peak temperature is unlikely—especially at the highest temperatures; and (2) the *P-T* position of an Fe-Mg exchange reaction cannot be calculated accurately unless the Fe^{3+}/Fe^{2+} ratios of the iron-bearing phases, particularly clinopyroxene, are known. The former problem is well known (Pattison et al., 2003), but the magnitude of the latter problem perhaps is not widely appreciated. Krogh Ravna and Paquin (2003) summarized the results of half a dozen studies that compared ferrous/ferric ratios calculated by charge balance with ratios measured by Mössbauer, micro-XANES (X-ray absorbtion near edge structure), or titration. They found that Fe-Mg garnet-clinopyroxene temperatures calculated without knowledge of mineral Fe^{3+}/Fe^{2+} typically had uncertainties of ±100 °C. Proyer et al. (2004) used the Mössbauer milliprobe to demonstrate that the problem can be even worse, with apparent temperatures as much as 300 °C too high. Unfortunately, only a handful of Fe^{3+}/Fe^{2+} measurements on UHP eclogites have been made, so this method has not found general application.

A better solution to both of these difficulties with eclogite thermobarometry is to use net-transfer reactions rather than exchange equilibria, although garnet activities for Ca-rich solid solutions also can be problematic. The retrograde diffusional reequilibration problem is solved or at least reduced because the increase in diffusive length scale from grain scale in net-transfer reactions to grain-boundary scale in exchange reactions vastly increases the ability to capture peak temperature, and the problem with ferrous/ferric ratios is solved by using equilibria that involve Mg rather than Fe. In eclogites, the two principal equilibria of choice are (Nakamura and Banno, 1997; Ravna and Terry, 2004):

$$\begin{gathered} Mg_3Al_2Si_3O_{12} + Ca_3Al_2Si_3O_{12} + KMgAlSi_4O_{10}(OH)_2 \\ = CaMgSi_2O_6 + KAl_2AlSi_3O_{10}(OH)_2 \\ \text{(pyrope + grossular + celadonite} \\ \text{= diopside + muscovite);} \end{gathered} \tag{1}$$

and

$$\begin{gathered} Mg_3Al_2Si_3O_{12} + Ca_3Al_2Si_3O_{12} + SiO_2 \\ = Al_2SiO_5 + CaMgSi_2O_6 \\ \text{(pyrope + grossular + coe/qtz} \\ \text{= kyanite + diopside).} \end{gathered} \tag{2}$$

Unfortunately, kyanite-phengite eclogites make up only a small portion of the total eclogite population, gravely restricting the applicability of this method. This limitation is offset, however, by the great advantage of the robust pressures and temperatures determined by this method.

We applied this method to calculate accurate eclogite *P-T* conditions from microprobe mineral analyses presented in the literature. The positions of net-transfer equilibria were calculated using two approaches: (1) using Thermocalc v. 3.1 (Powell et al., 1998) with the May 2001 updated database of Powell and Holland (1988); and (2) employing the spreadsheet of Ravna and Terry (2004), which depends on the same data set, but involves the Ganguly et al. (1996) garnet activity model rather than the Newton and Haselton (1981) model used by Thermocalc. Only data from the latter model (Hacker, 2006) are shown in Figure 1; *P-T* data for the former are similar but are slightly more dispersed. In samples for which a range of mineral compositions was reported, we calculated *P-T* conditions using the most jadeite-rich omphacite, the most Si-rich white mica, and garnet with the highest $a_{prp}a_{gr}^2$ (prp = pyrope; gr= grossular), following the logic outlined by Carswell et al. (2000). Where possible, we supplemented these data with other robust temperature determinations (e.g., oxygen isotope temperature measurements from Dora Maira by Sharp et al., 1993).

Several important conclusions can be obtained from this diagram. As determined by this technique, the temperature range of UHP kyanite-phengite eclogites is 550–1000 °C, although most values are 600–750 °C; the maximum pressure is slightly in excess of 4 GPa for collisional terranes. This *P-T* field is smaller than that determined for kyanite- or phengite-free eclogites for which Fe^{3+}/Fe^{2+} had to be assumed. None falls on the high-pressure side of the "forbidden zone," defined as the array of geotherms less than 5 °C/km (Liou et al., 2000; but see Schmid et al., 2003). Within uncertainty, most of the determinations fall along the granite, tonalite, and metasediment solidi. This may indicate that: (1) UHP rocks that experienced hypersolidus temperatures recrystallized continuously in the presence of melt, and then froze in mineral compositions during cooling; (2) UHP rocks that have been subjected to hypersolidus temperatures are rarely exposed at Earth's surface; or (3) few UHP rocks are produced at hypersolidus temperatures. In contrast, as described farther on, some garnet peridotites have computed conditions of crystallization that fall within the high-pressure realm of the "forbidden zone."

GENERATION AND EXHUMATION OF UHP METAMORPHIC COMPLEXES

Ductilely deformed nappes and thrust sheets formed in subduction channels (e.g., Koons et al., 2003; Hacker et al., 2004; Terry and Robinson, 2004) make up the architecture of most recovered HP-UHP complexes; others may represent coherent, non-nappe sections of continental lithosphere (Young et al., 2007). Ascent to shallow crustal levels reflects one or more of several processes: tectonic extrusion (Maruyama et al., 1994, 1996; Searle et al., 2003; Mihalynuk et al., 2004); corner flow blocked by a hanging-wall backstop (Cowan and Silling, 1978; Cloos and Shreve, 1988a, 1988b; Cloos, 1993); underplating combined with extensional or erosional collapse (Platt, 1986, 1987, 1993; Ring and Brandon, 1994, 1999); and/or buoyant ascent (Ernst, 1970, 1988; England and Holland, 1979; Hacker, 1996; Hacker et al., 2000, 2004). Old, thermally relaxed, sinking oceanic lithosphere appears to roll back oceanward more

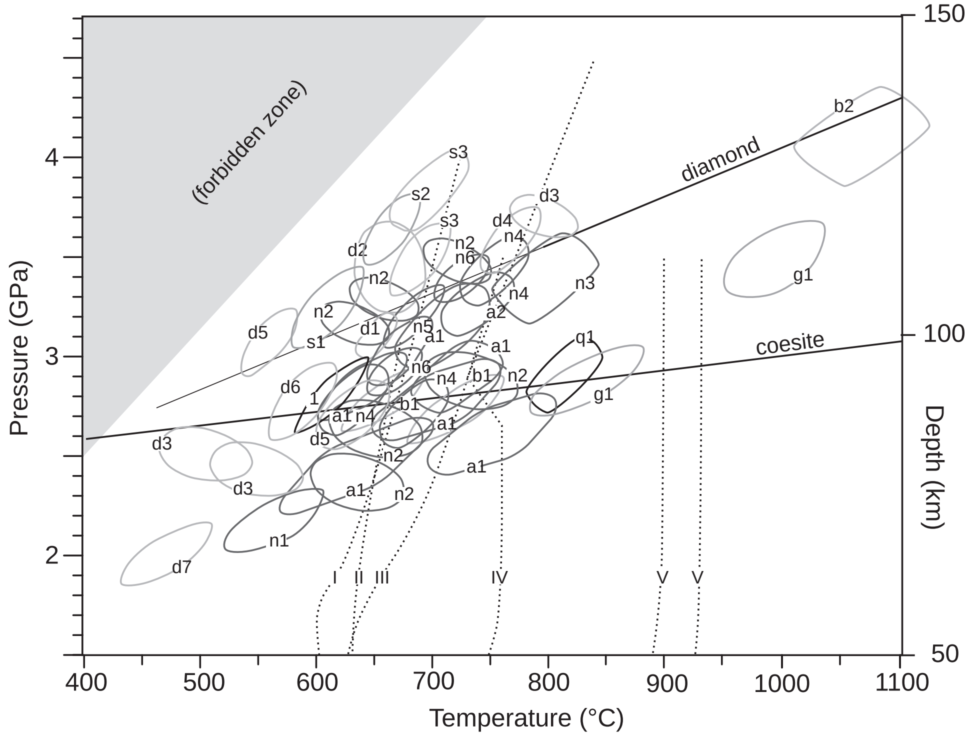

Figure 1. Robust pressure and temperature (*P-T*) conditions of kyanite–phengite eclogites in high-pressure–ultrahigh-pressure terranes (Hacker, 2006) determined using the intersection between garnet–clinopyroxene–muscovite–kyanite–quartz/coesite net-transfer equilibria and the solution models of Krogh Ravna and Terry (2004). The solution models of Thermocalc result in a similar, but slightly more dispersed set of pressures and temperatures. *P-T* data derived from mineral compositions of: a1—Nowlan (1998), Dora Maira; a2—Kienast et al. (1991), Dora Maira; a3—Coggon and Holland (2002), Dora Maira; b1—Massonne and O'Brien (2003), Münchberg; b2—Massonne and O'Brien (2003), Saidenbach; d1—Okay (1993), Dabie; d2—Proyer et al. (2004), Dabie; d3—Krogh Ravna and Terry (2004), Dabie; d4—Zhang et al. (1995b), Dabie; d5—Okay (1995), Dabie; d6—Zhang and Liou (1994), Hong'an; d7—Eide and Liou (2000), Hong'an; g1—Gilotti and Krogh Ravna (2002), Greenland; n1—Engvik et al. (2000), Norway; n2—Krogh Ravna and Terry (2004), Norway; n3—Terry et al. (2000a), Norway; n4—Wain (1998), Norway; n5—Wain (1998), combined with an Fe^{3+} measurement by C. McCammon of a D. Root sample from Norway; n6—Young et al. (2007), Norway; q1—Song et al. (2003), Qaidam; s1—Zhang et al. (1995a), Sulu; s2—Mattinson et al. (2004), Sulu; s3—Hirajima and Nakamura (2003), Sulu; m1—Caby (1994), Mali. Solidi: I—tonalite (Stern et al., 1975), II—sediment (Nichols et al., 1994), III—granite (Stern et al., 1975), IV—gabbro dehydration (Vielzeuf and Schmidt, 2001), V—mica dehydration (Patiño Douce and McCarthy, 1998).

rapidly than the nonsubducted plate moves forward (Molnar and Atwater, 1978; Seno, 1985; Busby-Spera et al., 1990; Hamilton, 1995), so compression and extrusion of subducted sialic slabs in such convergent plate junctions cannot be responsible for the exhumation unless the oceanic lithosphere tears away. Constriction by a backstop requires buoyancy or tectonic contraction to produce the return flow of subducted sections. Extension and erosion help to unroof HP-UHP terranes once they reach crustal levels, but these processes do not produce the major pressure discontinuities (up to >2 GPa) that mark the major fault boundaries between deeply subducted and nonsubducted crust (Ernst, 1970; Ernst et al., 1970; Suppe, 1972).

Buoyancy coupled with erosional decapitation provides a plausible mechanism for the exhumation of low-density crustal slices propelled upward from great depth by body forces. Geologic relationships, laboratory scale models (Chemenda et al., 1995, 1996, 2000), and numerical simulations (Beaumont et al., 1996, 1999; Pysklywec et al., 2002), illustrated schematically in Figure 2, document this process (see also volumes edited by: Parkinson et al., 2002; Carswell and Compagnoni, 2003; and Malpas et al., 2004). The strengths and integrity of the subducted lithospheric materials, extents of deep-seated devolatilization, and rates of recrystallization strongly influence the characteristics of the resultant UHP metamorphic belts (Ernst et al., 1998). The petrotectonic features of Phanerozoic UHP complexes thus reflect their plate-tectonic settings and *P-T* histories (Table 1).

Attending circum-Pacific subduction of a largely sedimentary mélange, devolatilization and increased ductility cause

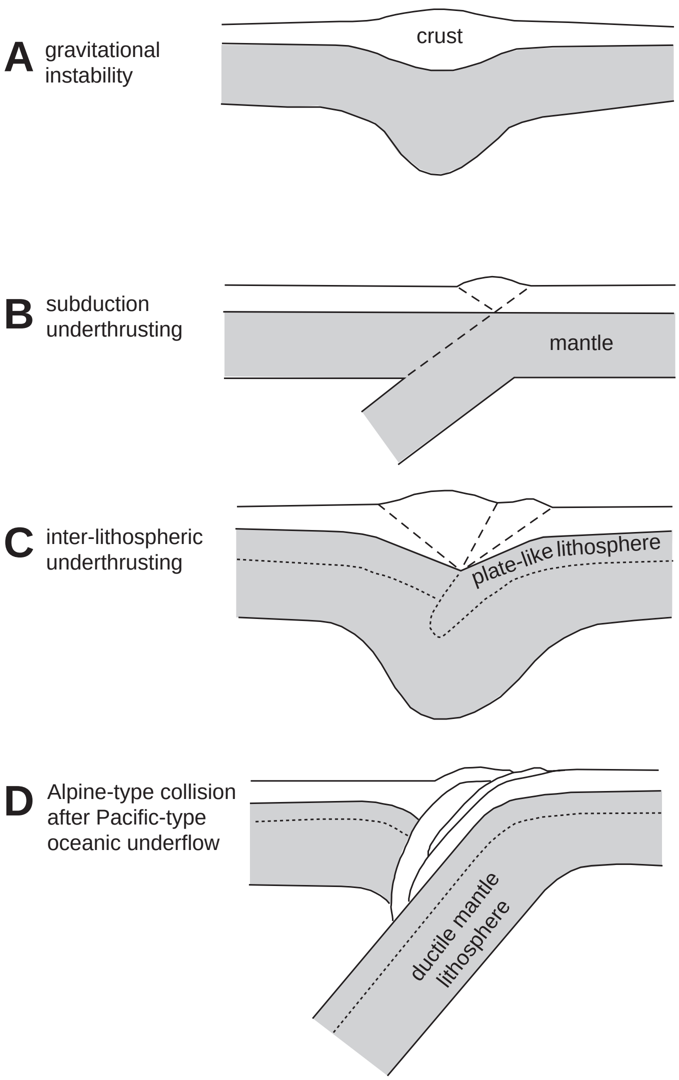

Figure 2. Simplified structural evolution of contractional orogens chiefly based on scale-model experiments (Chemenda et al., 1995, 1996, 2000) and numerical modeling (Beaumont et al., 1996, 1999; Pysklywec et al., 2002). Crust is white; mantle lithosphere is gray. Delamination of mantle lithosphere due to (A) gravitational instability and (B) subduction underthrusting. (C) Modeled deformation of South Island, New Zealand, involving upper-mantle detachment. (D) Himalayan-type nappe imbrication resulting from Pacific-type lithospheric underflow and continental collision; individual décollements are much thinner than that illustrated.

decoupling of subducted HP materials from the downgoing oceanic plate at ~20–50 km, followed by piecemeal ascent. In contrast, for a continental salient well bonded to the lithosphere, disengagement of a coherent crustal slice from the descending oceanic plate may be delayed to a depth of 90–140 km. The insertion of increasing amounts of low-density material into the subduction zone gradually reduces the overall negative buoyancy of the lithosphere. Attainment of neutral buoyancy at moderate upper mantle depths, where the plate is in extension (Isacks et al., 1968), may result in rupture and accelerated sinking of the dense oceanic lithosphere. Slab breakoff (Sacks and Secor, 1990; von Blanckenburg and Davies, 1995) increases the net buoyancy of the updip, relatively low-density sialic UHP complex and allows sheets to disengage from the oceanic plate and move back up the subduction channel (van den Beukel, 1992; Davies and von Blanckenburg, 1998). During collision, decoupling and exhumation also may be enhanced as the continental crust warms in the upper mantle and passes through the brittle-ductile transition (Stöckhert and Renner, 1998).

The two-way migration of terranes along subduction channels is well known (Ernst, 1970; Suppe, 1972; Willett et al., 1993). Similar to the subduction of circum-Pacific metaclastic mélanges, low-density sialic crustal sections descend at plate-tectonic rates, and at great depth, generate the distinctive HP-UHP prograde mineralogy of Alpine continental collisional complexes (Peacock, 1995; Ernst and Peacock, 1996). Return of these decoupled sections up the subduction channel during exhumation obviates the need to remove 50–100 km of the overlying hanging wall (the mantle wedge acts as a stress guide) by erosion, extensional collapse, or tectonism.

Densities (g/cm^3) of unaltered oceanic crust, 3.0, continental material, 2.7, and anhydrous mantle, 3.2, increase with elevated pressure, reflecting the transformation of open framework silicates to more compact layer-, chain-, and orthosilicates. Stable UHP mineralogic assemblages and computed rock densities appropriate for burial depths of ~100 km and 700 °C are roughly as follows: metabasaltic eclogite, 3.55; eclogitic granitic gneiss, 3.05; and garnet peridotite, 3.35 (Ernst et al., 1997; Hacker et al., 2003a). Even when transformed completely to a UHP assemblage, K-feldspar + jadeite + coesite-bearing granitic gneiss remains ~0.30 g/cm^3 less dense than garnet lherzolite, whereas metabasaltic eclogite is ~0.20 g/cm^3 denser than upper mantle lithologies. Evidently, subducted packets of UHP metamorphosed sialic crust are buoyant enough to overcome the traction of the oceanic plate carrying them downward because quartzofeldspathic nappes are now exposed at the Earth's surface.

Continental crustal rocks contain muscovite and biotite, minerals stable to 800–1100 °C at subduction depths >140 km (Stern et al., 1975; Nichols et al., 1994; Patiño Douce and McCarthy, 1998), as the main hydrous phases; therefore, such rocks do not devolatilize completely during normal subduction (Ernst et al., 1998). In the absence of a rate-enhancing aqueous fluid, such lithologies are unlikely to transform rapidly, or totally, to UHP mineral assemblages (Hacker, 1996; Austrheim, 1998). In contrast, the main H_2O-bearing phase in mafic rocks is hornblende, which is a pressure-limited mineral that devolatilizes at moderate temperatures where depths exceed ~70–80 km. In the presence of this evolving aqueous fluid, metabasaltic eclogites are far more likely to recrystallize to the stable prograde HP-UHP assemblage than are sialic units. Consequently, at upper-mantle depths, continental crust converted completely or incipiently to UHP-phase assemblages remains buoyant relative to the surrounding mantle and should rise to mid-crustal

TABLE 1. SUMMARY DATA FOR ULTRAHIGH-PRESSURE (UHP) METAMORPHIC COMPLEXES†

Terrane characteristic	Dabie-Sulu belt, coesite-eclogite unit	Kokchetav Massif, UHP unit	Dora Maira Massif, L. Venasca nappe	Western Gneiss region	Western Himalayan syntaxis, Kaghan V.
Protolith formation age	Chiefly 800–650 Ma	2.3–2.2 Ga	Ca. 300 Ma	1.8–0.4 Ga	>170 Ma
Temperature of metamorphism	650–750 °C	900 ± 75 °C	725 ± 50 °C	600–800 °C	750–780 °C
Depth of metamorphism	90–125 km	~140 km	90–110 km	90–130 km	~100 km
Time of metamorphism	236–226 Ma	535 ± 3 Ma	35 Ma	410–405 Ma	44 Ma
Crustal annealing	230–195 Ma	529 Ma	32 Ma	Ca. 402 Ma	40–42 Ma
Rise time to mid-crust	6 m.y.	6 m.y.	3 m.y.	3–8 m.y.	2–4 m.y.
Exhumation rate§	≥10 mm/yr	15–30 mm/yr	~20 mm/yr	8–20 mm/yr	>15 mm/yr
Coesite inclusions	Relatively abundant	Rare, locally abundant	Relatively abundant	Rare	Rare
Diamond inclusions	Very rare	Relatively abundant	Absent	2 localities	Absent
Areal extent	>400 × 50 km	~120 × 10 km	35 km^2	165 × 50 km	30 × 70? km
Thickness of individual UHP units	5–15 km	1–3 km	1–2 km	>10 km?	1 km

†After Coleman and Wang (1995), Harley and Carswell (1995), Ernst and Peacock (1996), Amato et al. (1999), Hacker et al. (2000, 2003b, 2006), Maruyama and Parkinson (2000), Terry et al. (2000a, 2000b), Hermann et al. (2001), Katayama et al. (2001), Rubatto and Hermann (2001), Massone and O'Brien (2003), Parrish et al. (2003), Rubatto et al. (2003), Treloar et al. (2003), Baldwin et al. (2004), Root et al. (2004, 2005), and Leech et al. (2005).

§Average exhumation rates were estimated by dividing depth of UHP metamorphism by time of ascent to 10–15 km crustal depth.

levels; in contrast, eclogitized oceanic crust becomes negatively buoyant compared to both near-surface oceanic basalt and garnet lherzolite and continues to sink. This relationship explains why exhumed HP-UHP terranes worldwide consist of ~90% low-density felsic material and contain only small proportions of dense mafic and anhydrous ultramafic rock types.

Times of UHP recrystallization in well-studied complexes ranges from about 535 Ma in northern Kazakhstan (Sobolev and Shatsky, 1990; Hermann et al., 2001; Katayama et al., 2001; Hacker et al., 2003b) to ~44 Ma in the western Himalayas (Kaneko et al., 2003; Treloar et al., 2003; Schlup et al., 2003), and 35 Ma in the Western Alps (Tilton et al., 1991; Gebauer et al., 1997; Rubatto and Hermann, 2001). Late Proterozoic UHP complexes eventually may be discovered, but Earth's ancient geothermal gradient may have been too high to allow the generation of UHP mineral parageneses during Archean and Early Proterozoic time.

RATE OF ASCENT OF UHP CONTINENTAL COMPLEXES

Considerable effort has been expended to measure the exhumation rates of UHP terranes by radiometric investigations and, to a lesser extent, by diffusion modeling. In general, the most comprehensive studies infer relatively rapid exhumation, approaching plate-tectonic rates. This poses a challenge for geochronologists for several reasons: (1) uncertainties in the decay constants for some radiometric clocks (i.e., ^{40}K and ^{176}Lu) increase the difficulty of obtaining sufficiently accurate ages for pre-Cenozoic rocks; (2) accurate Lu/Hf and Sm/Nd mineral-isochron ages require unzoned, unaltered phases that formed at a single, known *P-T* stage; and (3) U/Pb ages must have high temporal precision and come from discrete crystal volumes formed at a specific pressure. Advances are being made along all of these fronts, but none of these problems has yet been solved; accurate decay constants (e.g., Begemann et al., 2001) and the ability to analyze subcrystal volumes that can be tied to specific pressures are required. However, the best-documented cases show that exhumation to mid-crustal levels is rapid, with minimum average exhumation rates of tens of millimeters per year (Table 1).

UHP complexes with relatively few geochronological data paint a fairly simple picture. The exhumation rate of the Dora Maira Massif is constrained by U/Pb (chiefly sensitive high-resolution ion microprobe [SHRIMP]), Lu/Hf, and fission-track ages to ~20 mm/yr (see review by Rubatto et al., 2003). The Kokchetav Massif, investigated by Sm/Nd, U/Pb SHRIMP, and $^{40}Ar/^{39}Ar$ techniques, rose at 15–30 mm/yr (Hermann et al., 2001; Katayama et al., 2001; Hacker et al., 2003b). Sm/Nd and Rb/Sr ages indicate that the Lago di Cignana eclogites of the Lepontine Alps were exhumed at 26 mm/yr (Amato et al., 1999). Pliocene U/Pb ages for UHP rocks in Papua New Guinea indicate exhumation rates of 10–20 mm/yr (Baldwin et al., 2004). The Tso Morari complex of the NW Indian Himalaya was exhumed at 10–15 mm/yr (Massonne and O'Brien, 2003; Leech et al., 2005). The Kaghan Valley eclogites in Pakistan were exhumed within 2–4 m.y. (Treloar et al., 2003), evidently at an average rate approaching 20 mm/yr. Geochronological data from the giant UHP terranes in China and Norway are vastly more abundant, and, as a result, more complex, but exhumation rates in the Dabie-Sulu UHP terrane of China certainly exceeded 10 mm/yr (Hacker et al., 2000, 2006), as did those in the Western Gneiss Region of Norway (Carswell et al., 2003a, 2003b; Root et al., 2004, 2005). Such speedy unloading exceeds present-day regional exhumation and erosion rates (Blythe, 1998), implying that modern erosion rates are mischaracterized or that erosion alone did not expose the known UHP complexes.

CONDUCTIVE COOLING OF UHP CONTINENTAL COMPLEXES

Diffusion modeling studies demonstrate that Himalayan UHP rocks were subjected to temperatures >600 °C for only short times during decompression (O'Brien and Sachan, 2001; Massonne and O'Brien, 2003). These complexes evidently were quenched during exhumation. Poor thermal conductivities of rocks account for high-pressure prograde conditions attending underflow, but this property of Earth materials also dictates that deeply buried units retain heat on rapid exhumation. During decompression, UHP complexes exhibit pervasive mineralogic overprinting and assemblages characteristic of heating (typically granulite-facies), maintenance of constant temperature (amphibolite facies), or only modest cooling (greenschist facies). As an example, Figure 3 illustrates prograde and nearly isothermal retrograde *P-T*-time (*t*) trajectories calculated for the Paleogene subduction complex of the western Himalayan syntaxis. On decompression, the presence of a rate-enhancing aqueous fluid would have resulted in virtually complete obliteration of all pre-existing UHP-phase assemblages. Lack of catalytic, grain-boundary H_2O in a complex subjected to rapid ascent substantially decreases the rate of retrogression (Rubie, 1986, 1990; Ernst et al., 1998; Mosenfelder et al., 2005), but even so, heat must be effectively withdrawn from the rocks at some early stage during exhumation while the complex is relatively hot, or mineralogic evidence of former HP-UHP conditions would be lost. The preservation of UHP relics in a rising subduction complex is favored by juxtaposition against cooler rocks, such as by extensional faulting against a colder hanging wall and/or by thrusting against a colder footwall (Hacker and Peacock, 1995). Nevertheless, only in optimally favorable kinetic circumstances are any relict UHP phases and/or mineral assemblages preserved.

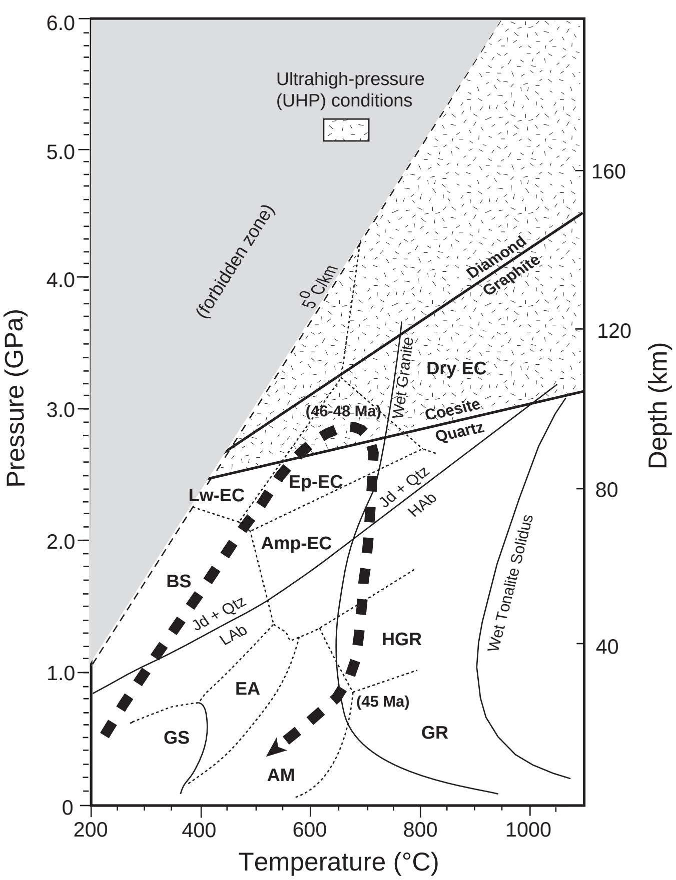

Figure 3. Pressure-temperature history of subduction and nearly isothermal exhumation to mid-crustal levels of ultrahigh-pressure imbricate thrust sheets cropping out in the Kaghan Valley, western Himalayan syntaxis, after O'Brien et al. (2001), Parrish et al. (2003), and Kaneko et al. (2003). For location, geologic map, and cross section, see Figure 4.

To first order, the thermal history of a UHP body during decompression is determined by its minimum dimension (i.e., thickness), its rate of ascent, and the temperature of the medium through which it ascends (e.g., Root et al., 2005). Relatively thin ascending slices will exchange heat more effectively than will thicker units. If a thin UHP body ascends slowly through a typical (cool) subduction thermal gradient, the *P-T* path during ascent can simply be the reverse of that during compression. However, if a thin UHP body ascends slowly through a zone of much hotter rocks—say, through interior portions of the mantle wedge—it may become hot enough that the evidence of UHP metamorphism is obliterated. Most well-characterized UHP terranes show neither of these types of behavior but, instead, near-isothermal decompression down to ~1 GPa. If a UHP body is thick, the heating or cooling of the body interior will be reduced proportional to the square of its thickness. If the rate of ascent is more rapid, the heating or cooling of the body interior will be reduced, following the square root of the ascent rate. In general terms, for a UHP complex to ascend without significant heating or cooling, its minimum dimension (radius or half-thickness) must exceed the characteristic diffusion distance

$$u = \sqrt{[\kappa \Delta z/(dz/dt)]},$$

where κ is thermal diffusivity, Δz is the vertical ascent distance, and dz/dt is the vertical ascent rate. For example, a UHP body with a minimum dimension of 15 km must ascend at >10 km/m.y., and a UHP body with a minimum dimension of 2 km must ascend at >500 km/m.y. The rapid ascent rates required mean that thin UHP sheets cannot have ascended near-isothermally from 100 km depth in their present shape, but must have cooled, approximating in reverse the subduction-zone prograde *P-T* trajectory (Chopin, 1984; Rubie, 1984; Ernst, 1988; Ernst and Peacock, 1996). The manner in which thick, decompressing slabs are quenched remains problematic. Of course, for UHP phases to be preserved in even fragmentary form, the ascending complex—thick or thin—must be quenched prior to complete back reaction. Examples of thin and thick UHP sheets are presented in Figures 4–6.

Well-studied exposures in the western syntaxis of the Himalayas (O'Brien et al., 2001; Parrish et al., 2003; Kaneko et al.,

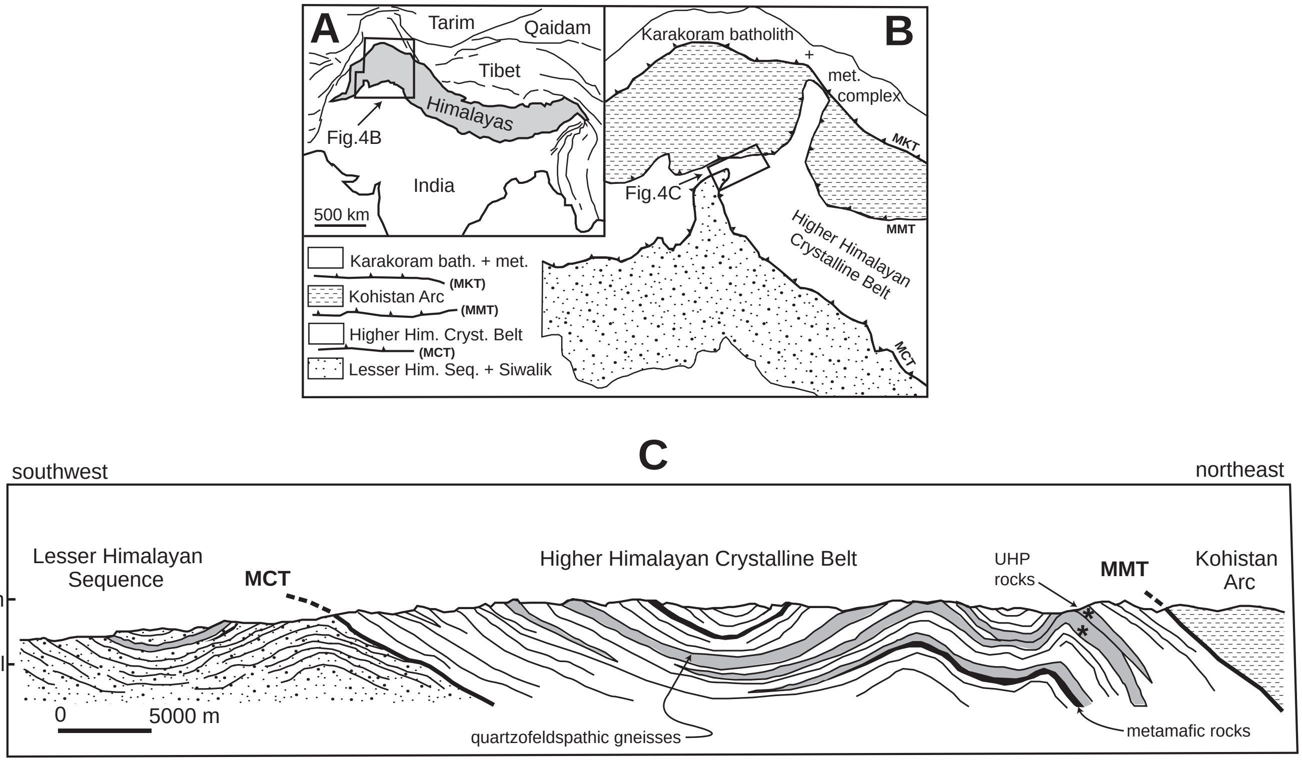

Figure 4. General geologic map and cross section through the Kaghan Valley, western Himalayan syntaxis, Pakistan, from Kaneko et al. (2003). Index maps are shown in A and B. A geologic map and cross section are presented in C. Note in C that the coesite-bearing UHP thrust sheets, indicated by stars, individually are less than about a kilometer thick. MKT—Main Karakorum thrust; MMT—main mantle thrust; MCT—main central thrust.

2003) and the Central and Western Alps (Henry, 1990; Michard et al., 1995) include nappes and imbricate slices of UHP continental crust less than 1–2 km thick. Similar aspect-ratio coesite-bearing thrust sheets have also been documented from the northern Western Gneiss Region of coastal Norway (Terry et al., 2000a, 2000b; Terry and Robinson, 2004), and the Kokchetav Massif of northern Kazakhstan (Kaneko et al., 2000; Maruyama and Parkinson, 2000; see also Dobretsov et al., 2006). In contrast, UHP sections at least 5 km thick have been proven by drilling in the Sulu belt of east-central China (Liu et al., 2004, 2007; Z. Zhang et al., 2006). Moreover, other intensively mapped portions of UHP terranes of comparable thickness include the Hong'an-Dabie terrane of eastern China (Hacker et al., 2000, 2004), and major tracts of the southern Western Gneiss Region (Root et al., 2005). Geologic maps and cross sections of Figures 4–6 illustrate the imbricate nature common to all these UHP complexes; the most striking contrast involves the differing thicknesses of the various UHP nappes.

Schematic relations shown in Figure 7 apply to the underflow and later exhumation of HP-UHP sheets. Descent of the low-density crust occurs only if shear forces caused by underflow (F_s) exceed the combined effects of buoyancy (F_b) and frictional resistance along the hanging wall of the subduction channel (F_r). Here, $F_s > F_b \cos \theta + F_r$. Decoupling and ascent of a slice of the low-density crust take place where buoyancy is greater than the combined effects of shearing along its footwall and resistance to movement along its upper, hanging-wall surface. In this case, $F_b \cos \theta > F_s + F_r$. The mantle wedge guides exhumation, and the rising nappe is emplaced oceanward (outboard) from the site of metamorphism. Where the angle of subduction decreases, the effect of buoyancy lessens during both underflow and exhumation. For HP-UHP complexes to be returned to shallow depths and partly preserved, the rising slab must overcome frictional resistance to sliding, so it must be thick enough for buoyancy-driven ascent, yet thin enough that heat is efficiently removed by conduction across the bounding faults—upper normal and lower reverse. Such kinematic structural relationships have been mapped in many resurrected, relatively thin-aspect-ratio subduction terranes, i.e., the Himalayas (Burchfiel et al., 1989; Searle, 1996; Searle et al., 2001; Kaneko et al., 2003); the Franciscan Complex (Ernst, 1970; Suppe, 1972; Platt, 1986; Jayko et al., 1987); the Western Alps (Henry, 1990; Compagnoni et al., 1995; Michard et al., 1995); the Sanbagawa belt (Kawachi, 1968; Ernst et al., 1970; Banno and Sakai, 1989); and the Kokchetav Massif (Kaneko et al., 2000; Ishikawa et al., 2000; Ota et al., 2000; Maruyama and Parkinson, 2000). Nappes have also been described from the Western Gneiss Region of Norway (Harley and Carswell, 1995; Krogh and Carswell, 1995; Terry et al., 2000a, 2000b); and the Dabie-Sulu belt (Liou et al., 1996; Hacker et al., 1995, 1996, 2000; Webb et al., 1999).

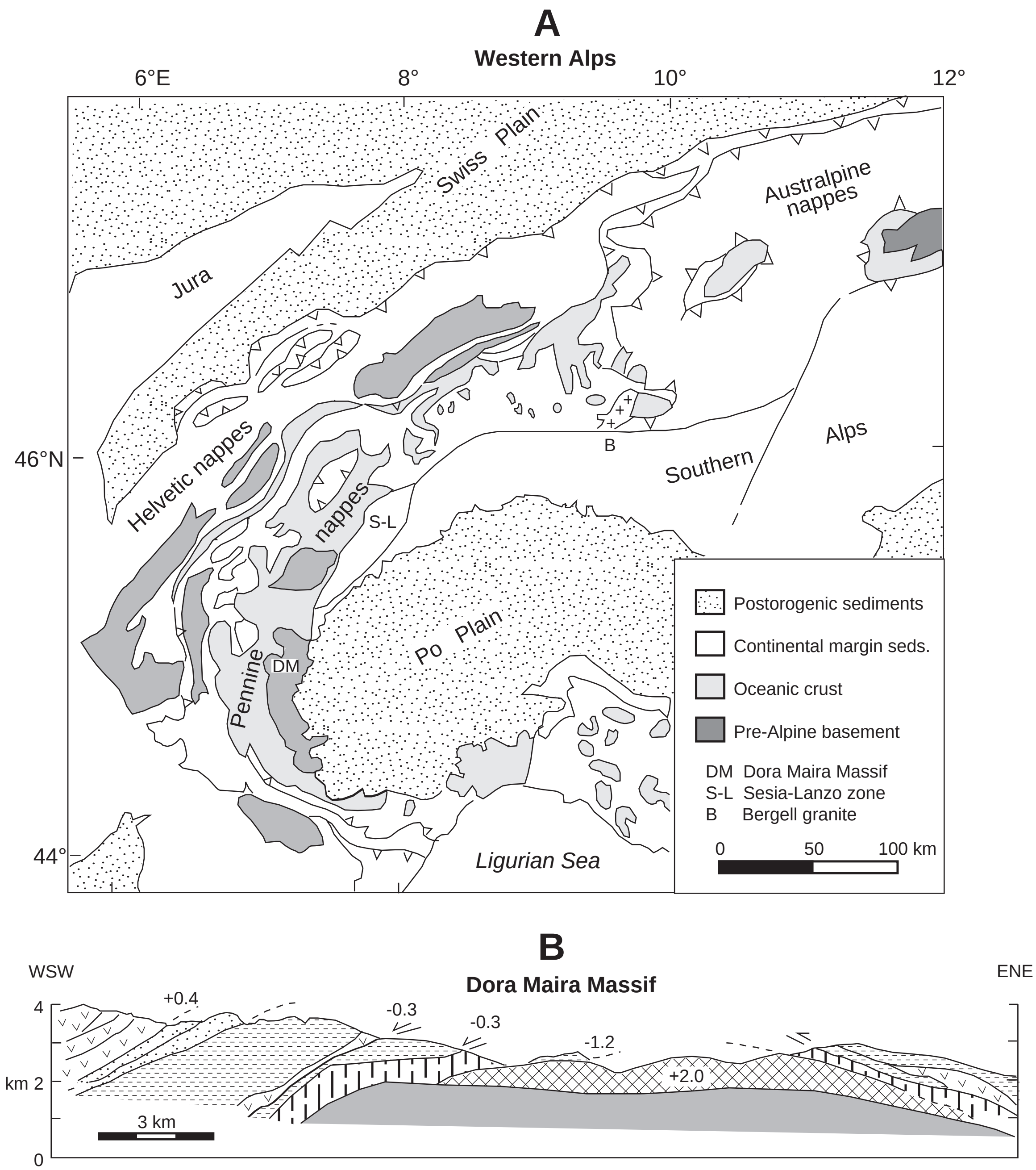

Figure 5. Geologic sketch map (A) of the western and central Alps, and diagrammatic cross section (B) through the southern Dora Maira Massif (DM; after Henry, 1990; Michard et al., 1995). In B, the transect across the Dora Maira Massif, numbers indicate the upward change in recorded pressure in GPa relative to the adjacent underlying unit. The lower Venasca ultrahigh-pressure (UHP) nappe is shown in the gridiron pattern.

Recrystallized, retrogressed UHP complexes, although less dense than anhydrous mantle, become neutrally buoyant at approximately middle levels of the sialic crust (Walsh and Hacker, 2004). In some cases, further exhumation of such slabs may be the product of contractional tectonism (Maruyama et al., 1994, 1996) or low-density crustal underplating—in either case combined with isostatically compensated regional exhumation and erosional decapitation (Platt, 1986, 1987, 1993). In addition, a drop in overall density of the subducting lithosphere after plate breakoff results in a shallowing of the downgoing, increasingly buoyant slab, and may be partly responsible for the late doming recognized in many exhumed convergent plate junction regimes (Ernst et al., 1997; O'Brien, 2001; O'Brien et al., 2001). Yet another unloading mechanism involves the antithetic faulting typical of some con-

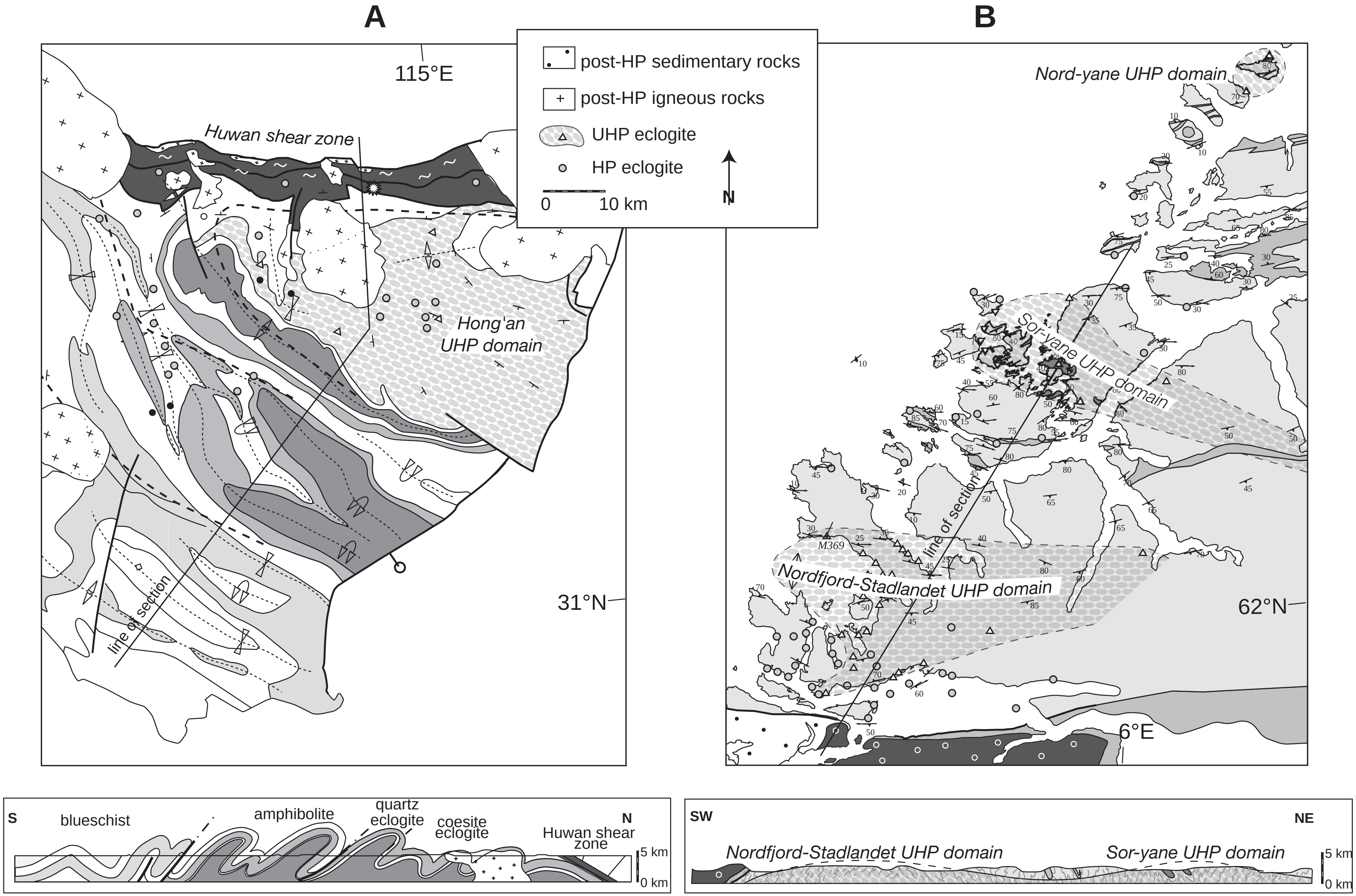

Figure 6. High-pressure–ultrahigh-pressure (HP-UHP) domains in the (A) Hong'an area of China and (B) Western Gneiss Region of Norway, after Hacker et al. (2000) and Root et al. (2005), respectively. Gray shades are used to distinguish different units. Cross sections provide a measure of the relatively great thickness of these HP-UHP complexes.

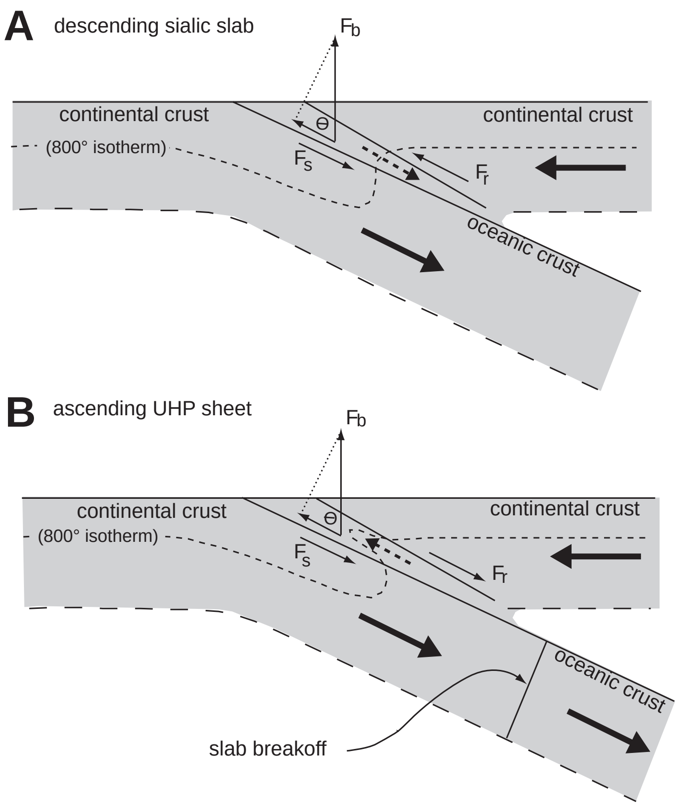

Figure 7. Schematic convergent lithospheric plate-boundary diagram for active subduction, after Ernst and Peacock (1996). (A) Deep burial and thermal structure of a subducted sheet of continental crust. (B) Later decompression cooling of a rising slice of the sialic material. Relative motions of plates and slices are indicated by arrows (the subducting plate actually is sinking and rolling backward; Hamilton, 1995). During ascent of the HP-UHP terrane (thickness exaggerated for clarity), cooling of the upper margin of the sheet takes place where it is juxtaposed against the lower-temperature hanging wall (the mantle wedge); cooling along the lower margin of the sheet takes place where it is juxtaposed against the lower-temperature, subduction-refrigerated lithosphere. Exhumation of low-density slices requires erosive denudation and/or gravitational collapse and a sialic root at depth. The resolutions of forces acting on the sialic slab in stages A and B are discussed in the text. Lithosphere is shaded (crust-mantle boundary not indicated); asthenosphere is unshaded. Degrees in Celsius.

tractional orogens, in which double vergence is produced during terminal stages of the ascent of low-density crust (e.g., Dal Piaz et al., 1972; Ring and Brandon, 1994, 1999).

Exhumation of domal or diapiric bodies of granitic crust appears to be occurring along convergent plate junctions where curvilinear arcs intersect at large angles. At such lithospheric boundary cusps, overthickened continental crust gradually warms and loses strength. Basal portions may partially melt, but in any case, the crust softens, becomes even more buoyant, and rises more-or-less like a salt dome. Such uplifts, shown diagrammatically in Figure 8, have been termed tectonic aneurysms (Zeitler et al., 2001; Koons et al., 2002; Chamberlain et al., 2002). Some appear to be the sites of exhumed UHP terranes (Ernst, 2006).

TECTONIC SIGNIFICANCE OF GARNET PERIDOTITES IN UHP CONTINENTAL COMPLEXES

Studies of volumetrically minor mafic eclogite boudins and layers in subducted continental crust have provided important quantitative constraints regarding the UHP conditions that attended metamorphism of the enclosing, largely quartzofeldspathic complex. The occurrences of spatially associated garnet-bearing peridotite bodies are less well understood. Such ultramafic rocks occur as tectonic massifs, pods, and lenses in many ancient collisional mountain belts. HP-UHP examples include the Caledonian, Variscan, and Alpine orogens of Europe, the Kokchetav Massif of Kazakhstan, and the Triassic Dabie-Sulu terrane in east-central China (for reviews, see Medaris, 1999; Brueckner and Medaris, 2000; O'Brien, 2000). These garnet peridotites are of contrasting origins. Some have been interpreted as mantle-derived bodies tectonically emplaced into sialic crustal sequences (Ernst, 1978; Carswell and Gibb, 1980), whereas, others are regarded as products of prograde HP metamorphism of spinel peridotite, or their serpentinized equivalents, previously emplaced in the crust (e.g., Evans and Trommsdorff, 1978; England and Holland, 1979). Medaris (1999) subdivided garnet peridotites from Eurasian HP-UHP terranes into four general types: (1) serpentinites or ultramafic igneous complexes emplaced in the crust prior to subduction, followed by underflow and UHP metamorphism; (2) mantle wedge spinel and/or garnet peridotites inserted into a downgoing lithospheric plate; (3) low-pressure, high-temperature spinel peridotites that may reflect the upwelling of asthenospheric material; and (4) HP garnet peridotites tectonically extracted from the deepest portions of the continental crust–capped lithosphere.

Quantitative compositional and structural data for the subcontinental lithospheric mantle provide crucial information for the erection of realistic large-scale models describing Earth's geochemical and tectonic evolution (Griffin et al., 1999). Our knowledge of mantle compositions and heterogeneities has been obtained mainly through the study of xenoliths and xenocrysts from kimberlites and volcanic rocks of deep origin. However, detailed, integrated petrochemical, mineralogic, and geochronologic studies of orogenic garnet peridotites provide important constraints on mantle processes, and the chemical-mineralogic compositions and evolution of the mantle wedge overlying a subduction zone. The discovery of phases of very deep origin, such as majoritic garnet, HP clinoenstatite, and olivine containing elevated concentrations of $FeTiO_3$ rods in garnet peridotites from several UHP terranes (e.g., Dobrzhinetskaya et al., 1996; Bozhilov et al., 1999; van Roermund et al., 2000, 2001; Massonne and Bautsch, 2002) has provides important information about mantle dynamics. How these deep-seated (>200 km) mantle rocks were transported to shallow depths, and by what means they were incorporated in subducted continental slabs of contractional mountain belts remain unclear. Some of these garnet peridotites and the enclosing continental crust have been postulated to have undergone subduction-zone UHP metamor-

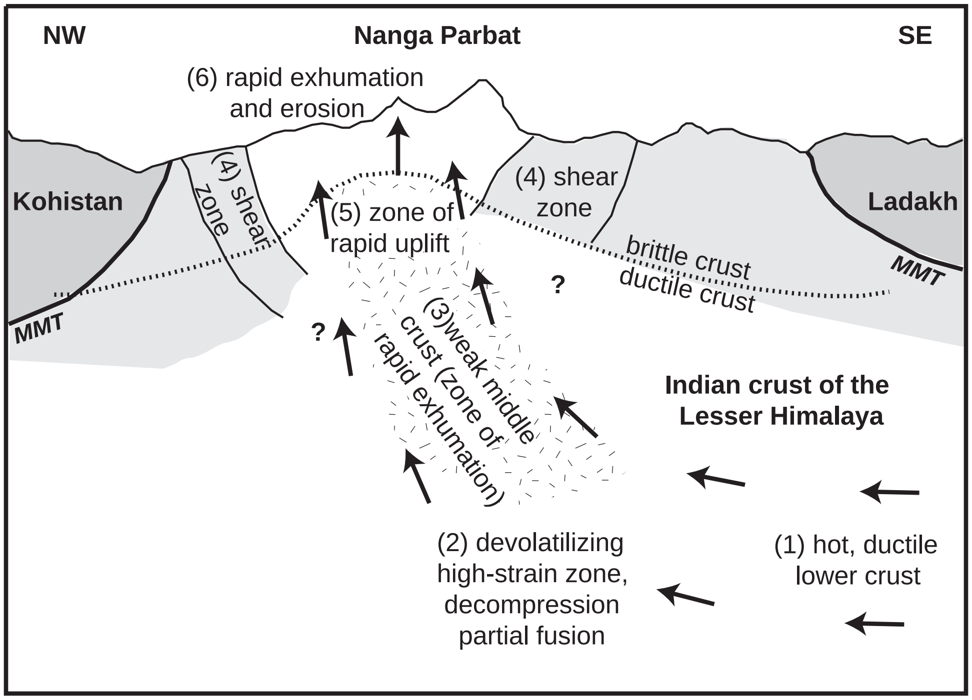

Figure 8. Diagrammatic cross section of the Neogene tectonic aneurysm at the western Himalayan syntaxis, simplified from Zeitler et al. (2001). Erosion-induced rapid unloading of high mountains overlying deep-seated, thickened crust causes upward flow of thermally softened, buoyant crust. Numbered features are as follows: (1) hot, ductile, devolatilizing metamorphosed crust enters flow regime, and (2) passes through high-strain zone, incipiently melting and degassing further. (3) Crust enters region of rapid exhumation as unloading and further melting take place, with granitoids (4) possibly inserted into massif along NW and SE shear zones. (5) Strain focusing leads to accelerated upward advective transport of the lower, ductile crust, carrying along its thermal structure. (6) High topography surmounting the weak diapiric zone is partly removed by vigorous erosion, exposing back-reacted, decompressed migmatites. Also involved laterally is a strong meteoric circulation system (not illustrated). MMT—main mantle thrust.

phism characterized by extremely low thermal gradients, on the order of ≤5 °C/km (e.g., Liou et al., 2000; Zhang et al., 2004). High-pressure experiments reveal that numerous hydrous phases may be stable in such HP environments, the so-called forbidden zone (Liou et al., 1998). Thus, unusually cold subduction zones might well represent the sites of major recycling of H_2O back into the mantle. These findings have advanced our quantitative understanding of the thermal structure of subduction zones and of the return of volatiles to the mantle.

Most Eurasian HP-UHP garnet peridotites are rich in Mg and Cr and represent depleted-upper-mantle materials, but several are more Fe-rich and originated as igneous mafic-ultramafic complexes (Medaris, 1999). These peridotites are polymetamorphic, with UHP garnet-bearing assemblages extensively replaced by a succession of retrograde mineral assemblages generated during exhumation and cooling. Some peridotites also contain evidence for a pre-UHP stage, evidenced by spinel and/or Ti-clinohumite inclusions in garnet. Equilibration conditions of peak-UHP stages have been calculated from garnet-bearing peridotites by employing the olivine-garnet Fe-Mg exchange thermometer and the Al-in-orthopyroxene barometer (but see section dealing with *P-T* conditions of UHP metamorphism). Garnet peridotites occur as meter- to kilometer-sized blocks and lenses in gneisses; the quartzofeldspathic host rocks also have been subjected to UHP metamorphism and exhibit massive, granoblastic or porphyroblastic textures. Most garnet peridotites are deformed and are partially to almost fully serpentinized. Relict garnet-bearing assemblages on the surface are more completely preserved in the central parts of such ultramafic boudins; some occupy up to 30 vol% of the entire body. Garnet peridotite samples from drill holes, however, tend to be relatively less intensely serpentinized. Exsolution microstructures in olivine, garnet, and diopside, and clinoenstatite polymorphs of orthopyroxene are common (Dobrzhinetskaya et al., 1996; Zhang and Liou, 1999, 2003; Zhang et al., 1999, 2003; Spengler et al., 2006). Geochronologic data for garnet peridotites are poorly constrained, but associated mafic eclogites have been dated by various methods, such as Sm-Nd mineral isochrons and SHRIMP zircon U-Pb dating (Katayama et al., 2003; Zhang et al., 2005a, 2005b; Z. Zhang et al., 2006; Zhao et al., 2007).

Numerous tectonic origins for garnet peridotites in UHP terranes have been proposed (e.g., Brueckner, 1998; Medaris, 1999; Zhang and Liou, 1999). Similar to, but slightly different from the classification of Medaris, we infer contrasting origins for HP-UHP garnet peridotites based on their modes of occurrence, petrochemical characteristics, and tectonic histories; the range of properties for some of these bodies is summarized in Table 2. The four general types of ultramafic rock, now recrystallized to garnet peridotite, are as follows: type-A, hanging-wall (mantle wedge) fragments; type-B, crustal mafic-ultramafic igneous complexes; type-C, tectonic blocks from the footwall mantle lithosphere; and type-D, ancient mantle complexes tectonically emplaced in the crust prior to subduction. Inasmuch as many of the Eurasian garnet peridotites listed in Table 2 are incompletely characterized tectonically, geochemically, and/or are undated (particularly by Re-Os isotopic systematics), our assignment of tectonic type must be considered tentative. Moreover, several types of garnet peridotite may occur in certain HP-UHP terranes. For example, in the Western Gneiss of Norway, type-B garnet peridotites with Caledonian HP assemblages occur in addition to type-D Proterozoic UHP assemblages (Jamtveit, 1987). Global locations of some of these garnet peridotites in UHP metamorphic belts are indicated in Figure 9.

Type-A Garnet Peridotites

These ultramafic rocks originated in the mantle wedge above a subduction zone. Type-A uppermost mantle peridotites are either residual mantle fragments, or they are peridotite and pyroxenite bodies differentiated from mantle-sourced magma; they possess isotopic and geochemical signatures of the hanging-wall mantle. For example, garnet peridotites from eastern China are in fault contact with enclosing country-rock granitic gneisses, they are massive and relatively homogeneous without layering, they exhibit either near-equigranular or porphyroblastic textures, and they contain lenses of bimineralic coesite-bearing eclogite. Most such garnet peridotites belong to the Mg-Cr type of Medaris and Carswell (1990) and contain more MgO and Cr_2O_3 and less fertile elements such as TiO_2, Al_2O_3, CaO, and FeO than primitive mantle as defined by Ringwood (1975). Type-A garnet lherzolites and pyroxenites preserve mantle $\delta^{18}O$ value ranges for garnet, olivine, and clinopyroxene of +4.8‰–+5.6‰, +4.7‰, and +4.5‰–5.6‰, respectively (Zhang et al., 1998, 2000, 2004). They tend to have low $^{87}Sr/^{86}Sr$ (0.7038–0.7044) and $^{143}Nd/^{144}Nd$ (0.5123–0.5124) values. However, some exhibit unusually high isotopic ratios and plot outside the range of mantle values; these anomalous isotopic compositions may be due to later metasomatism and/or contamination by crustal materials. It should be noted that low-pressure, high-temperature garnet peridotites reported by Medaris (1999), such as those from the Bohemia Massif, are included here (see also Carswell and O'Brien, 1993; O'Brien and Rötzler, 2003). Some of these high-temperature bodies were evolved from spinel peridotites, contain abundant inclusions of spinel in garnet, and equilibrated at ~1000–1300 °C.

Type-B Garnet Peridotites

Such bodies were derived from ultramafic portions of presubduction crustal mafic-ultramafic complexes. The protoliths were produced by differentiation from mafic magma prior to UHP metamorphism (e.g., Z. Zhang et al., 2006); the continental crustal section was then subjected to underflow and HP-UHP metamorphism. Typically, garnet peridotites are interlayered with eclogites of various compositions. Garnet peridotites from the Dabieshan are characterized by: (1) well-developed compositional banding and/or layering; (2) the occurrence of low-pressure mineral inclusions in garnets (e.g., Okay, 1994); (3) the preservation of relatively light isotopic bulk-rock oxygen compositions ($\delta^{18}O < 5‰$); and (4) an old, presubduction age of intrusion (~500–300 Ma) into the sialic crust, as well as a Triassic (~230–220 Ma) UHP metamorphic age (Chavagnac and Jahn, 1996; Jahn et al., 2003). Type-B mafic-ultramafic igneous complexes exhibit a large range in major-element concentrations, and most contain lower MgO and higher SiO_2, CaO, TiO_2, Al_2O_3, and FeO values than type-A peridotites. Some type-B garnet peridotites contain well-preserved prograde low-pressure mineral assemblages as inclusions in UHP phases. For example, inclusions of sapphirine, corundum, clinochlore, and amphibole occur in garnet porphyroblasts from the Maowu area of the Dabieshan (Okay, 1993). In the Lotru garnet peridotite from the South Carpathians, garnet and orthopyroxene formed as reaction products at the boundary of partly serpentinized olivine and pseudomorphs after plagioclase, now consisting of amphibole, zoisite, and chlorite (Medaris et al., 2003).

Type-C Garnet Peridotites

These tectonic entities were derived from the underlying mantle of subducted oceanic or continental lithosphere. Protoliths of the footwall mantle of a sinking slab in some cases were serpentinized prior to HP-UHP metamorphism. The ultramafic rocks may represent part of an ophiolitic sequence that was emplaced in the downgoing plate prior to deep underflow. Thus, some Alpine garnet peridotites of the Western Alps are associated with eclogites that recrystallized from rodingitized gabbros, and retain geochemical evidence of earlier seawater alteration. Petrochemically, such garnet peridotites are difficult to distinguish from type-A hanging-wall mantle-derived analogues. Accordingly, only a few garnet peridotites from the Lepontine Alps (e.g., Cima de Gagnone and Monte Duria bodies) have been assigned to this group (Evans and Trommsdorff, 1978).

Type-D Garnet Peridotites

These deep-seated mantle fragments were emplaced tectonically at crustal levels prior to subduction. Relict high-pressure, high-temperature peridotitic lenses are present in the Western Gneiss region of coastal Norway; the ultramafic lithologies represent fragments of ancient depleted mantle, the

TABLE 2. CHARACTERISTICS OF GARNET PERIDOTITES IN UHP METAMORPHIC BELTS WORLDWIDE

Terrane	Type	Modes of occurrence	Rock types*	Mineral assemblage	Peak-stage *T-P* (°C, GPa)	Metamorphic age (Ma)	References
Sulu, Eastern China							
Rongcheng	A	Blocks in gneiss	LZ, DN	Grt+Ol+Opx+Cpx	820–920; 4–6	Triassic	Zhang et al. (1994); Hiramatsu et al. (1995); Jahn (1998); Hacker et al. (1997)
Yangkou		Layers and blocks in gneiss	PD, CP	Ol+Cpx+Opx+Grt+Amp	750 ± 50; >4	Triassic	Zhang et al. (2005a, 2005b)
Rizhao	A	Layers and blocks in gneiss	HZ, CP	Grt+Cpx+Ilm+Chl±Ol	>820; >4	Triassic	Zhang et al. (1994, 2000); Zhang and Liou (2003)
Donghai	A	Blocks in gneiss	LZ, HZ, WR, WB	Grt+Ol+Opx+Cpx±Phl±Mgs	780–980; 4–6.7	SHRIMP U-Pb: 230 ± 5	Zhang et al. (1994, 1995a, 1998, 2000, 2005b)
Dabie, Eastern China							
Bixiling	B	Layered mafic-ultramafic	LZ, WR, WB	Grt+Ol+Opx+Cpx±Chu±Mgs	820–950; 4.7–6.7	Triassic	Zhang et al. (1995b, 2000); Chavanac and Jahn (1996)
Maowu	B	Layered ultramafic	HZ, CP, OP	Ol+Opx+Grt+Cpx+Rt± Mz	750 ± 50; 4–6	Ca. 220–230	Okay (1994); Liou and Zhang (1998); Zhang et al. (1998, 1999); Jahn et al. (2003)
Raobazhai		Fault block	DN, HZ	Ol+Opx+Cpx+Spn±Grt	>1100; 1.8–2.2	Triassic	Tsai et al. (2000)
Western China							
Altyn	A	Blocks in gneiss	LZ, WR, CP	Grt+Ol±Opx+Cpx±Mgs	890–970; 3.8–5.1	Caledonian	Liu et al. (2002); Zhang et al. (2004)
N Qaidam	A	Block, lens, layers in gneiss	LZ, DN, CP	Grt+Ol+Opx+Cpx	780–850; >2.7–4.5	Caledonian	Yang et al. (2000, 2002); Song et al. (2004, 2005); Zhang et al. (2004)
Indonesia							
Sulawesi	C	Fault slice and xenolith in granite	LZ	Ol+Grt+Opx+Cpx	1025–1200; 2.6–4.8	Cretaceous	Kardarusman and Parkinson (2000)
SW Japan							
Sanbagawa	A	Lens, boudins, or layers	DN, CP, WR, WB	Grt+Ol+Cpx+Cr-Sp±Opx	700–810; 2.9–2.38	Cretaceous	Enami et al. (2004); Mizukami et al. (2004)
Northern Kazakhstan							
Kokchetav	A (?)	Block in gneiss	PD	Ol+Grt+Ti-Chu Mg-Ilm±Cpx±Phl	790–880; 4–6	U-Pb SHRIMP 554–494 (528)	Muko et al. (2002); Katayama et al. (2003)
Western Gneiss Region							
Kalskaret	D	Large body in gneiss	PD	Grt+Ol+Opx+Cpx	890–950; 4.2–4.4	Proterozoic-Archean	Medaris (1984, 1999); Jamtveit et al. (1991); Beyer et al. (2004)
Lien	D	Large body in gneiss	PD	Opx+Grt+Ol+Cpx	850–900; 3.6–3.9	Proterozoic-Archean	Medaris (1980, 1984, 1999)
Rodhaugen	D	Large body in gneiss	PD	Opx+Grt+Ol+Cpx	740–859; 2.3–3.6	Proterozoic-Archean	Medaris (1980, 1999); Carswell (1981)
Sandvika	B, D	Large body in gneiss	PD	Opx+Grt+Ol+Cpx	930–950; 4.4–5.0	Proterozoic-Archean	Medaris (1984, 1999); Jamtveit (1984, 1987)
Raudhaugene, Otroy, Flemsey, Fjortoft	D	Large body in gneiss		Opx+Grt+Ol+Cpx	740–890; 2.3–4.3	Proterozoic-Archean	Carswell (1986); van Roermund et al. (2000, 2001, 2002); Beyer et al. (2004); Spengler et al. (2006)

(*continued*)

TABLE 2. CHARACTERISTICS OF GARNET PERIDOTITES IN UHP METAMORPHIC BELTS WORLDWIDE (*continued*)

Terrane	Type	Modes of occurrence	Rock types*	Mineral assemblage	Peak-stage *T-P* (°C, GPa)	Metamorphic age (Ma)	References
Bohemian Massif							
Moldanubian	A, B, C	Lenses in gneiss and granulite	PD, CP	Ol+Grt+Cpx+Opx	815–1330; 2.4–5.6	Variscan (ca. 370–330)	Medaris (1999); Medaris et al. (1990, 2005); Brueckner et al. (1996); Altherr and Kalt (1996); O'Brien and Rötzler (2003)
Erzgebirge	A	Elongate body in gneiss and granulite	PD	Ol+Grt+Opx+Cpx	800–900; 2.9–3.2	Variscan	Schmadicke and Evans (1997)
S. Carpathians	A, B	Lenses in gneiss	PD	Opx+Grt+Ol+Cpx	1150–1300; 2.5–3.2	Variscan (310–360)	Medaris (1999); Medaris et al. (2003)
Ronda	A	Large massif	LZ	Grt+Ol+Opx+Cpx+Dia	1080–1240; 2.1–2.8	Alpine (21–25)	Reisberg et al. (1989); Medaris (1999)
Western Alps							
Lepontine Alps	C	Macroboudins	PD	Grt+Ol+Opx+Cpx	775–820; 3.4–3.7	Alpine	Evans and Trommsdorff (1978)
Alpe Arami	A	Large lense	LZ	Grt+Ol+Opx+Cpx+Chu	840–1130; 3.4–5.2	Alpine	Evans and Trommsdorff (1978); Ernst (1978); Dobrzhinetskaya et al. (1996); Brenker and Brey (1997)
Dominican Republic	C	Boulders		Ol+Grt+Cpx+Spl±Crn	1570–1540; >3.4	Late Cretaceous	Abbott et al. (2005)
British Columbia	C	Detrital Grt, Cpx and Ol in conglomerate	PD		800–950; 3–6	>192–183	MacKenzie et al. (2005)

Note: Mineral abbreviations are after Kretz (1983).

*Rock type abbreviations: CP—clinopyroxenite, DN—dunite, HZ—harzburgite, LZ—lherzolite, OP—orthopyroxenite, PD—peridotite, WB—websterite, WR—wehrlite.

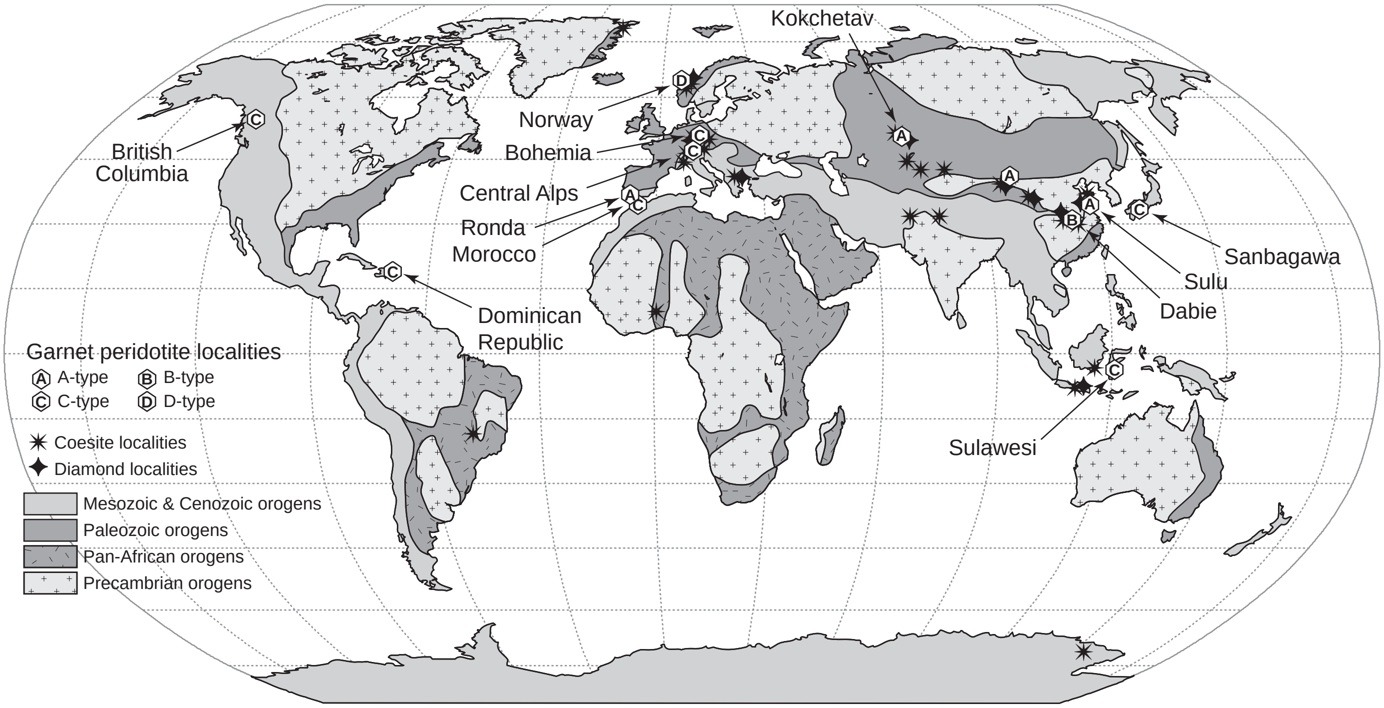

Figure 9. Sketch map by Tsujimori et al. (2006) showing the global distribution of largely continental-crustal ultrahigh-pressure (UHP) metamorphic belts that contain lenses and blocks chiefly of type-A, type-B, type-C, and type-D garnet peridotites (see Table 2 and the text for classification and descriptions). A few type-B ultramafic bodies occur in the Western Gneiss Region of Norway, and type-A and type-B ultramafic bodies are present in the Bohemian Massif.

origins of which are unrelated to the later Caledonian UHP metamorphism (Carswell and van Roermund, 2005). Several garnet peridotite bodies are especially noteworthy because they exhibit evidence of the former stability of megacrystic mineral assemblages that include now-exsolved high-pressure enstatite and majoritic garnet (van Roermund et al., 2000, 2001, 2002; Spengler et al., 2006). Early assemblages in these peridotites possess Sm-Nd Proterozoic ages (Brueckner and Medaris, 1998), close to the igneous crystallization ages of the host granitic gneisses. However, recent in situ Re-Os analysis of sulfides in the garnet peridotites yield a range of Proterozoic and Archean model ages. A Late Archean (3.1–2.7 Ga) protolith age also is supported by whole-rock Re-Os data for dunites from several such bodies (Beyer et al., 2004). The Archean ages bear testament to a process of partial fusion in the mantle that predated formation of the Proterozoic upper crust in the Western Gneiss Region. Apparently, some mantle blocks previously identified as Proterozoic subcontinental lithospheric mantle may represent metasomatized and refertilized Archean mantle.

Contrasting Physical Conditions of Crystallization of Mafic and Ultramafic UHP Rocks?

A comparison of the eclogite thermobarometry described in the text and presented in Figure 1 with computed garnet peridotite conditions of equilibration suggests that although some of the latter rock types (type-D and perhaps some type-A ultramafic bodies) evidently recrystallized under subduction-zone geothermal gradients less than 5 °C/km, none of the eclogites and associated sialic crustal entities can be proven to have formed at so-called forbidden-zone *P-T* conditions. The reasons for this disparity remain unclear. Possible explanations include: (1) systematic errors were made in the thermobarometric evaluations of peridotites or eclogites, or both lithologies; (2) eclogites and enclosing crustal units re-equilibrated during exhumation-decompression, yielding post-maximum pressures, whereas anhydrous peridotites did not; (3) peridotites characterized by "forbidden-zone" *P-T* conditions of formation are exotic and formed in a mantle environment unrelated to that of the eclogites. Additional geochemical, geochronologic, and phase-equilibrium investigations are needed to address this problem; what is clear is that at least some zones of continental collision produced subducted HP-UHP assemblages that have been recovered from upper-mantle depths characterized by low prograde geothermal gradients.

CONCLUSIONS FOR PHANEROZOIC CONTRACTIONAL OROGENS

Continental collision involves the essential and substantial consumption of oceanic lithosphere and the transport of a salient of sialic crust, island arc, or microcontinental fragment to the convergent plate junction. Insertion of continental crust and underflow to great depths result in the incipient-to-complete transformation of pre-existing low-pressure quartzofeldspathic and mafic-ultramafic lithologies to UHP-phase assemblages. During prograde metamorphism, evolution of H_2O due to the breakdown of hornblende and serpentine kinetically favors the conversion of mafic and ultramafic rock types to stable eclogitic-garnet peridotitic assemblages, whereas, reflecting the higher-pressure stabilities of biotite and muscovite, micaceous granitic gneisses may persist due to the lack of a free aqueous fluid. The spatial association of volumetrically minor amounts of garnet peridotite and mafic eclogite reflects active participation of both mantle and oceanic crust in the UHP subduction-zone deformation and recrystallization. However, worldwide, chiefly continental materials are regurgitated in exhumed UHP complexes, mirroring the low densities of sialic crust relative to mafic and ultramafic lithologies. Such quartzofeldspathic crustal assemblages are propelled upward by body forces, i.e., buoyancy. Characteristic decompression rates exceeding 10 mm/yr in general are comparable to rates of subduction. Many exposed ultrahigh-pressure complexes consist of ~1–2-km-thick allochthonous sheets, but the largest, in east-central China and western Norway, are ~10 km thick. For thin, ductilely deformed nappes, heat is efficiently conducted away as the UHP complexes rise, cooling the sheets across upper and lower fault-bounded surfaces. For such geometries, the rate of ascent need not be especially rapid. In contrast, the manner in which enormous, much thicker, rapidly decompressing UHP complexes like the Western Gneiss Region and the Dabie-Sulu belt are quenched, preserving relict UHP phases, remains enigmatic. In either case, however, surviving UHP bodies must be relatively dry during the ascent; the absence of a separate aqueous fluid accompanying exhumation would retard back reaction in the complex, allowing the scattered retention of early stage, UHP phases.

The significance of tectonic aneurysms is speculative, but it deserves consideration with regard to the mechanism of final exhumation of UHP terranes. Most recognized UHP collisional complexes bear extensive evidence of prior nappe emplacement, so exposure of the deep-seated terranes may reflect the operation in varying degrees of subduction-zone slab imbrication and/or buoyant massif ascent followed by late domal uplift aided by locally vigorous erosion. Due to relatively rapid decompression at moderately high temperatures, the critical requirement for preservation of UHP relict assemblages in at least fragmentary form is effective heat removal; this, in turn, requires that less rapidly decompressing complexes be characterized by large surface/volume ratios. Massif-type buoyant bodies must rise from great depths at near-adiabatic *P-T* conditions, i.e., extremely rapidly. For recognizable UHP terranes, transport to mid-crustal levels either in décollement-type structures or as giant slabs must occur first, allowing substantial cooling (quenching) of the UHP mineral assemblages. This event is followed by further exhumation combined with erosional collapse; possible late-stage processes include structural contraction, crustal underplating, shallowing of the dip of the subducting lithosphere, crustal back-folding or faulting, or domal ascent as tectonic aneurysms.

ACKNOWLEDGMENTS

This study was support by Stanford University and National Science Foundation grants EAR-9814889, 0003355, 0003568. and 0510325. Paddy O'Brien and Gordon Medaris provided constructive reviews of a first-draft manuscript. Appreciation is expressed to Hans-Peter Schertl for providing a copy of Elke Nowlan's dissertation. We thank these researchers and institutions for helpful feedback and support.

REFERENCES CITED

Abbott, R.N., Draper, G., and Keshav, S., 2005, UHP magma parageneses, garnet peridotite, and garnet clinopyroxenite: An example from the Dominican Republic: International Geology Review, v. 47, p. 233–247.

Altherr, R., and Kalt, A., 1996, Metamorphic evolution of ultrahigh-pressure garnet peridotites from the Variscan Vosges Mts., France: Chemical Geology, v. 134, p. 27–47, doi: 10.1016/S0009-2541(96)00088-5.

Amato, J.M., Johnson, C., Baumgartner, L., and Beard, B., 1999, Sm-Nd geochronology indicates rapid exhumation of Alpine eclogites: Earth and Planetary Science Letters, v. 171, p. 425–438, doi: 10.1016/S0012-821X(99)00161-2.

Austrheim, H., 1998, Influence of fluid and deformation on metamorphism of the deep crust and consequences for the geodynamics of collision zones, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 297–323.

Baldwin, S.L., Monteleone, B.D., Webb, L.E., Fitzgerald, P.G., Grove, M., and Hill, E.J., 2004, Pliocene eclogite exhumation at plate tectonic rates in eastern Papua New Guinea: Nature, v. 431, p. 263–267, doi: 10.1038/nature02846.

Banno, S., and Sakai, C., 1989, Geology and metamorphic evolution of the Sanbagawa belt, *in* Daly, J.S., Cliff, R.A., and Yardley, B.W.D., eds., Evolution of Metamorphic Belts; Proceedings of the 1987 Joint Meeting of the Metamorphic Studies Group and IGCP Project 235: Geological Society [London] Special Publication 43, p. 519–535.

Beaumont, C., Ellis, S., Hamilton, J., and Fullsack, P., 1996, Mechanical model for subduction-collision tectonics of Alpine-type compressional orogens: Geology, v. 24, p. 675–678, doi: 10.1130/0091-7613-(1996)024<0675:MMFSCT>2.3.CO;2.

Beaumont, C., Ellis, S., and Pfiffner, A., 1999, Dynamics of sediment subduction-accretion at convergent margins: Short-term modes, long-term deformation, and tectonic implications: Journal of Geophysical Research, v. 104, p. 17,573–17,602, doi: 10.1029/1999JB900136.

Begemann, F., Ludwig, K.R., Lugmair, G.W., Min, K., Nyquist, L.E., Patchett, P.J., Renne, P.R., Shih, C.-Y., Villa, I.M., and Walker, R.J., 2001, Call for an improved set of decay constants for geochronological use: Geochimica et Cosmochimica Acta, v. 65, p. 111–121, doi: 10.1016/S0016-7037(00)00512-3.

Beyer, E.B., Brueckner, H.K., Griffin, W.L., O'Reilly, S.Y., and Graham, S., 2004, Archean mantle fragments in Proterozoic crust, Western Gneiss Region, Norway: Geology, v. 32, p. 609–612, doi: 10.1130/G20366.1.

Blythe, A.E., 1998, Active tectonics and ultrahigh-pressure rocks, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 141–160.

Bozhilov, K.N., Green, H.W., and Dobrzhinetskaya, L., 1999, Clinoenstatite in the Alpe Arami peridotite: Additional evidence of very high pressure: Science, v. 284, p. 128–132, doi: 10.1126/science.284.5411.128.

Brenker, F.E., and Brey, G.P., 1997, Reconstruction of exhumation path of the Alpe Arami garnet-peridotite body from depths exceeding 160 km: Journal of Metamorphic Geology, v. 15, p. 581–592, doi: 10.1111/j.1525-1314.1997.00034.x.

Brueckner, H.K., 1998, Sinking intrusion model for the emplacement of garnet-bearing peridotites into continent collision orogens: Geology, v. 26, p. 631–634, doi: 10.1130/0091-7613(1998)026<0631:SIMFTE>2.3.CO;2.

Brueckner, H.K., and Medaris, L.G., Jr., 1998, A tale of two orogens: The contrasting *T-P-t* history and geochemical evolution of mantle in high- and ultrahigh-pressure metamorphic terranes of the Norwegian Caledonides and the Czech Variscides: Schweizerische Mineralogische und Petrographisches Mitteilungen, v. 78, p. 293–307.

Brueckner, H.K., and Medaris, L.G., Jr., 2000, A general model for the intrusion and evolution of "mantle" peridotites in high-pressure and ultrahigh-pressure metamorphic terranes: Journal of Metamorphic Geology, v. 18, p. 123–133, doi: 10.1046/j.1525-1314.2000.00250.x.

Brueckner, H.K., Blusztajn, J., and Bakun-Czubarow, N., 1996, Trace element and Sm-Nd "age" zoning in garnets from peridotites of the Caledonian and Variscan Mountains and tectonic implications: Journal of Metamorphic Geology, v. 14, p. 61–73, doi: 10.1111/j.1525-1314.1996.00061.x.

Burchfiel, B.C., Deng, Q., Molnar, P., Royden, L., Qang, Y., and Zhang, W., 1989, Intracrustal detachment within zones of continental deformation: Geology, v. 17, p. 748–752, doi: 10.1130/0091-7613(1989)017 <0448:IDWZOC>2.3.CO;2.

Busby-Spera, C.J., Mattinson, J.M., Riggs, N.R., and Schermer, E.R., 1990, The Triassic-Jurassic magmatic arc in the Mojave-Sonoran Deserts and the Sierran-Klamath region, *in* Harwood, D.S., and Miller, M.M., eds., Paleozoic and Early Mesozoic Paleogeographic Relations; Sierra Nevada, Klamath Mountains, and Related Terranes: Geological Society of America Special Paper 255, p. 93–114.

Caby, R., 1994, Precambrian coesite from northern Mali; first record and implications for plate tectonics in the trans-Saharan segment of the Pan-African belt: European Journal of Mineralogy, v. 6, p. 235–244.

Carswell, D.A., 1981, Clarification of the petrology and occurrence of garnet lherzolites, garnet websterites and eclogite in the vicinity of Rodhaugen, Almklovdalen, West Norway: Norsk Geologisk Tidsskrift, v. 61, p. 249–260.

Carswell, D.A., 1986, The metamorphic evolution of Mg-Cr type Norwegian garnet peridotites: Lithos, v. 19, p. 279–297, doi: 10.1016/0024-4937-(86)90028-9.

Carswell, D.A., and Compagnoni, R., eds., 2003, Ultrahigh Pressure Metamorphism: Notes in Mineralogy, Volume 5: Budapest, European Union, 508 p.

Carswell, D.A., and Gibb, F.G.F., 1980, The equilibration conditions and petrogenesis of European crustal garnet lherzolites: Lithos, v. 13, p. 19–29, doi: 10.1016/0024-4937(80)90058-4.

Carswell, D.A., and O'Brien, P.J., 1993, Thermobarometry and geotectonic significance of high pressure granulites: Examples from the Moldanubian zone of the Bohemian Massif in lower Austria: Journal of Petrology, v. 34, p. 427–459.

Carswell, D.A., and van Roermund, H.L.M., 2005, On multi-phase mineral inclusions associated with microdiamond formation in mantle-derived peridotite lens at Bardane on Fjørtoft, west Norway: European Journal of Mineralogy, v. 17, p. 31–42, doi: 10.1127/0935-1221/2005/0017-0031.

Carswell, D.A., Wilson, R.N., and Zhai, M., 2000, Metamorphic evolution, mineral chemistry and thermobarometry of schists and orthogneisses hosting ultra-high pressure eclogites in the Dabieshan of central China: Lithos, v. 52, p. 121–155, doi: 10.1016/S0024-4937(99)00088-2.

Carswell, D.A., Tucker, R.D., O'Brien, P.J., and Krogh, T.E., 2003a, Coesite micro-inclusions and the U-Pb age of zircons from the Hareidland eclogite in the Western Gneiss Region of Norway: Lithos, v. 67, p. 181–190, doi: 10.1016/S0024-4937(03)00014-8.

Carswell, D.A., Brueckner, H.K., Cuthbert, S.J., Mehta, K., and O'Brien, P.J., 2003b, The timing of stabilisation and the exhumation rate for ultra-high pressure rocks in the Western Gneiss Region of Norway: Journal of Metamorphic Geology, v. 21, p. 601–612, doi: 10.1046/j.1525-1314.2003.00467.x.

Chamberlain, C.P., Koons, P.O., Meltzer, A.S., Park, S.K., Craw, D., Zeitler, P.K., and Poage, M.A., 2002, Overview of hydrothermal activity associated with active orogenesis and metamorphism: Nanga Parbat, Pakistan Himalaya: American Journal of Science, v. 302, p. 726–748, doi: 10.2475/ajs.302.8.726.

Chavagnac, V., and Jahn, B.-M., 1996, Coesite-bearing eclogites from the Bixiling complex, Dabie Mountains, China: Sm-Nd ages, geochemical characteristics and tectonic implications: Chemical Geology, v. 133, p. 29–51, doi: 10.1016/S0009-2541(96)00068-X.

Chemenda, A.I., Mattauer, M., Malavieille, J., and Bokun, A.N., 1995, A mechanism for syn-collisional rock exhumation and associated normal faulting: Results from physical modeling: Earth and Planetary Science Letters, v. 132, p. 225–232, doi: 10.1016/0012-821X(95)00042-B.

Chemenda, A.I., Mattauer, M., and Bokun, A.N., 1996, Continental subduction and a new mechanism for exhumation of high-pressure metamorphic rocks: New modeling and field data from Oman: Earth and Planetary Science Letters, v. 143, p. 173–182, doi: 10.1016/0012-821X(96)00123-9.

Chemenda, A.I., Burg, J.P., and Mattauer, M., 2000, Evolutionary model of the Himalaya-Tibet system: Geopoem based on new modeling, geological and geophysical data: Earth and Planetary Science Letters, v. 174, p. 397–409, doi: 10.1016/S0012-821X(99)00277-0.

Chopin, C., 1984, Coesite and pure pyrope in high-grade blueschists of the western Alps: A first record and some consequences: Contributions to Mineralogy and Petrology, v. 86, p. 107–118, doi: 10.1007/BF00381838.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737, doi: 10.1130/0016-7606(1993)105<0715:LBACOS>2.3.CO;2.

Cloos, M., and Shreve, R.L., 1988a, Subduction-channel model of prism accretion, mélange formation and subduction erosion at convergent plate margins: 1. Background and description, *in* Ruff, L., and Kanamori, H., eds., Subduction Zones: Pure and Applied Geophysics, v. 128, p. 455–500.

Cloos, M., and Shreve, R.L., 1988b, Subduction-channel model of prism accretion, mélange formation and subduction erosion at convergent plate margins: 2. Implications and discussion, *in* Ruff, L., and Kanamori, H., eds., Subduction Zones: Pure and Applied Geophysics, v. 128, p. 501–545.

Coggon, R., and Holland, T.J.B., 2002, Mixing properties of phengitic micas and revised garnet-phengite thermobarometers: Journal of Metamorphic Geology, v. 20, p. 683–696, doi: 10.1046/j.1525-1314.2002.00395.x.

Coleman, R.G., and Wang, X., 1995, Overview of the geology and tectonics of UHPM, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: Cambridge, Cambridge University Press, p. 1–32.

Compagnoni, R., Hirajima, T., and Chopin, C., 1995, UHPM metamorphic rocks in the western Alps, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: Cambridge, Cambridge University Press, p. 206–243.

Cowan, D.S., and Silling, R.M., 1978, A dynamic, scaled model of accretion at trenches and its implications for the tectonic evolution of subduction complexes: Journal of Geophysical Research, v. 83, p. 5389–5396.

Dal Piaz, G.V., Hunziker, J.C., and Martinotti, G., 1972, La zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi nordoccidentali interne: Memoir Societa Geologia Italia, v. 11, p. 433–460.

Davies, J.H., and von Blanckenburg, F., 1998, Thermal controls on slab breakoff and the rise of high-pressure rocks during continental collisions, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 97–115.

Dobretsov, N.L., Buslov, M.M., Zhimulev, F.I., Travin, A.V., and Zayachkovsky, A.A., 2006, Vendian–Early Ordovician geodynamic evolution and model for exhumation of ultrahigh-pressure and high-pressure rocks from the Kokchetav subduction-collision zone: Russian Geology and Geophysics, v. 47, p. 424–440.

Dobrzhinetskaya, L., Green, H.W., and Wang, S., 1996, Alpe Arami: A peridotite massif from depths of more than 300 kilometers: Science, v. 271, p. 1841–1846, doi: 10.1126/science.271.5257.1841.

Eide, E., and Liou, J.G., 2000, High-pressure blueschists and eclogites in Hong'an: A framework: Lithos, v. 52, p. 1–22, doi: 10.1016/S0024-4937 (99)00081-X.

Enami, M., Mizukami, T., and Yokoyama, K., 2004, Metamorphic evolution of garnet-bearing ultramafic rocks from the Congen area, Sanbagawa belt, Japan: Journal of Metamorphic Geology, v. 22, p. 1–15, doi: 10.1111/j.1525-1314.2003.00492.x.

England, P.L., and Holland, T.J.B., 1979, Archimedes and the Tauern eclogites: The role of buoyancy in the preservation of exotic eclogitic blocks: Earth and Planetary Science Letters, v. 44, p. 287–294, doi: 10.1016/0012-821X (79)90177-8.

Engvik, A.K., Austrheim, H., and Andersen, T.B., 2000, Structural, mineralogical and petrophysical effects on deep crustal rocks of fluid-limited polymetamorphism, Western Gneiss Region, Norway: Geological Society [London] Journal, v. 157, p. 121–134.

Ernst, W.G., 1970, Tectonic contact between the Franciscan mélange and the Great Valley sequence, crustal expression of a late Mesozoic Benioff zone: Journal of Geophysical Research, v. 75, p. 886–901.

Ernst, W.G., 1978, Petrochemical study of lherzolitic rocks from the western Alps: Journal of Petrology, v. 28, p. 341–392.

Ernst, W.G., 1988, Tectonic histories of subduction zones inferred from retrograde blueschist *P-T* paths: Geology, v. 16, p. 1081–1084, doi: 10.1130/0091-7613(1988)016<1081:THOSZI>2.3.CO;2.

Ernst, W.G., 2005, Alpine and Pacific styles of Phanerozoic mountain building: Subduction-zone petrogenesis of continental crust: Terra Nova, v. 17, p. 165–188, doi: 10.1111/j.1365-3121.2005.00604.x.

Ernst, W.G., 2006, Preservation/exhumation of ultrahigh-pressure subduction complexes: Lithos, v. 92, p. 321–335, doi: 10.1016/j.lithos.2006.03.049.

Ernst, W.G., and Peacock, S., 1996, A thermotectonic model for preservation of ultrahigh-pressure mineralogic relics in metamorphosed continental crust, *in* Bebout, G.E., Scholl, D.W., Kirby, S.H., and Platt, J.P., eds., Subduction Top to Bottom: American Geophysical Union Geophysical Monograph 96, p. 171–178.

Ernst, W.G., Seki, Y., Onuki, H., and Gilbert, M.C., 1970, Comparative Study of Low-Grade Metamorphism in the California Coast Ranges and the Outer Metamorphic Belt of Japan: Geological Society of America Memoir 124, 276 p.

Ernst, W.G., Maruyama, S., and Wallis, S., 1997, Buoyancy-driven, rapid exhumation of ultrahigh-pressure metamorphosed continental crust: Proceedings of the National Academy of Sciences of the United States of America, v. 94, p. 9532–9537.

Ernst, W.G., Mosenfelder, J.L., Leech, M.L., and Liu, J., 1998, H_2O recycling during continental collision: Phase-equilibrium and kinetic considerations, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 275–295.

Evans, B.W., and Trommsdorff, V., 1978, Petrogenesis of garnet lherzolite, Cima di Gagnone, Lepontine Alps: Earth and Planetary Science Letters, v. 40, p. 333–348, doi: 10.1016/0012-821X(78)90158-9.

Ganguly, J., Cheng, W., and Tirone, M., 1996, Thermodynamics of aluminosilicate garnet solid solution: New experimental data, and optimized model, and thermometric applications: Contributions to Mineralogy and Petrology, v. 126, p. 137–151, doi: 10.1007/s004100050240.

Gebauer, D., Schertl, H.P., Briz, M., and Schreyer, W., 1997, 35 Ma old ultrahigh-pressure metamorphism and evidence for very rapid exhumation in the Dora Maira Massif, western Alps: Lithos, v. 41, p. 5–24, doi: 10.1016/S0024-4937(97)82002-6.

Gilotti, J.A., and Krogh Ravna, E., 2002, First evidence of ultrahigh-pressure metamorphism in the North-East Greenland Caledonides: Geology, v. 30, p. 551–554, doi: 10.1130/0091-7613(2002)030<0551:FEFUPM>2.0.CO;2.

Griffin, W.L., Fisher, N.I., Friedman, J., Ryan, C.G., and O'Reilly, S.Y., 1999, Cr-pyrope garnets in lithospheric mantle: I. Compositional systematics and relations to tectonic setting: Journal of Petrology, v. 40, p. 679–705, doi: 10.1093/petrology/40.5.679.

Hacker, B.R., 1996, Eclogite formation and the rheology, buoyancy, seismicity, and H_2O content of oceanic crust, *in* Bebout, G.E., Scholl, D.W., Kirby, S.H., and Platt, J.P., eds., Subduction Top to Bottom: American Geophysical Union Geophysical Monograph 96, p. 171–178.

Hacker, B.R., 2006, Pressures and temperatures of ultrahigh-pressure metamorphism: Implications for UHP tectonics and H_2O in subducting slabs: International Geology Review, v. 48, p. 1053–1066.

Hacker, B.R., and Peacock, S.M., 1995, Creation, preservation and exhumation of UHPM rocks, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: Cambridge, Cambridge University Press, p. 159–181.

Hacker, B.R., Ratschbacher, L., Webb, L., and Dong, S., 1995, What brought them up? Exhuming the Dabie Shan ultrahigh-pressure rocks: Geology, v. 23, p. 743–746, doi: 10.1130/0091-7613(1995)023<0743:WBTUEO>2.3.CO;2.

Hacker, B.R., Wang, X., Eide, E.A., and Ratschbacher, L., 1996, The Qinling-Dabie ultrahigh-pressure collisional orogen, *in* Harrison, T.M., and Yin, A., eds., The Tectonic Development of Asia: Cambridge, Cambridge University Press, p. 345–370.

Hacker, B.R., Sharp, T., Zhang, R.Y., Liou, J., and Hervig, R.L., 1997, Determining the origin of ultrahigh-pressure lherzolite?: Science, v. 278, p. 702–704, doi: 10.1126/science.278.5338.702.

Hacker, B.R., Ratschbacher, L., Webb, L., McWilliams, M.O., Ireland, T., Calvert, A., Dong, S., Wenk, H.-R., and Chateigner, D., 2000, Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic–Early Jurassic tectonic unroofing: Journal of Geophysical Research, v. 105, p. 13,339–13,364, doi: 10.1029/2000JB900039.

Hacker, B.R., Abers, G.A., and Peacock, S.M., 2003a, Subduction factory: 1. Theoretical mineralogy, density, seismic wave speeds, and H_2O content: Journal of Geophysical Research, v. 108, no. B1, doi: 10.1029/2001JB001127.

Hacker, B.R., Calvert, A.T., Zhang, R.Y., Ernst, W.G., and Liou, J.G., 2003b, Ultra-rapid exhumation of ultrahigh pressure diamond-bearing metasedimentary and meta-igneous rocks of the Kokchetav Massif: Lithos, v. 70, p. 61–75, doi: 10.1016/S0024-4937(03)00092-6.

Hacker, B.R., Ratschbacher, L., and Liou, J.G., 2004, Subduction, collision and exhumation in the ultrahigh-pressure Qinling-Dabie orogen, *in* Malpas, J., Fletcher, C.J.N., Ali, J.R., and Aitchison, J.C., eds., Aspects of the Tectonic Evolution of China: Geological Society [London] Special Publication 226, p. 157–175.

Hacker, B.R., Wallis, S.R., Grove, M., and Gehrels, G., 2006, High-temperature geochronology constraints on the tectonic history and architecture of the ultrahigh-pressure Dabie-Sulu orogen: Tectonics, v. 25, TC5006, doi: 10.1029/2005TC001937.

Hamilton, W., 1995, Subduction systems and magmatism, *in* Smellie, J.L., ed., Volcanism Associated with Extension at Consuming Plate Margins: Geological Society [London] Special Publication 81, p. 3–28.

Harley, S.L., and Carswell, D.A., 1995, Ultradeep crustal metamorphism: A prospective review: Journal of Geophysical Research, v. 100, p. 8367–8380, doi: 10.1029/94JB02421.

Henry, C., 1990, L'unité à coesite du massif Dora-Maira dans son cadre petrologique et structural (Alpes occidentales, Italie): Paris, Université de Paris VI, 453 p.

Hermann, J., Rubatto, D., Korsakov, A., and Shatsky, V.S., 2001, Multiple zircon growth during fast exhumation of diamondiferous, deeply subducted continental crust (Kokchetav Massif, Kazakhstan): Contributions to Mineralogy and Petrology, v. 141, p. 66–82.

Hirajima, T., and Nakamura, D., 2003, The Dabie Shan–Sulu orogen: EMU Notes in Mineralogy, v. 5, p. 105–144.

Hiramatsu, N., Banno, S., Hirajima, T., and Cong, B., 1995, Ultrahigh-pressure garnet lherzolite from Chijiadian, Rongcheng County, in the Su-Lu region of eastern China: The Island Arc, v. 4, p. 324–333, doi: 10.1111/j.1440-1738.1995.tb00153.x.

Isacks, B., Oliver, J., and Sykes, L.R., 1968, Seismology and the new global tectonics: Journal of Geophysical Research, v. 73, p. 5855–5899.

Ishikawa, M., Kaneko, Y., and Yamamoto, H., 2000, Subhorizontal boundary between ultrahigh-pressure and low-pressure metamorphic units in the Sulu-Tjube area of the Kokchetav Massif, Kazakhstan: The Island Arc, v. 9, p. 317–328, doi: 10.1046/j.1440-1738.2000.00281.x.

Jahn, B.-M., 1998, Geochemical and isotopic characteristics of UHP eclogites of the Dabie orogen: Implications for continental subduction and collisional tectonics, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 203–239.

Jahn, B.-M., Fan, Q., Yang, J.-J., and Henin, O., 2003, Petrogenesis of the Maowu pyroxenite-eclogite body from the UHP metamorphic terrane of Dabieshan: Chemical and isotopic constraints: Lithos, v. 70, p. 243–267, doi: 10.1016/S0024-4937(03)00101-4.

Jamtveit, B., 1984, High-*P* metamorphism and deformation of the Gurskebotn garnet peridotite, Sunnmore, western Norway: Norsk Geologisk Tidsskrift, v. 64, p. 97–110.

Jamtveit, B., 1987, Metamorphic evolution of the Eiksunddal eclogite complex, western Norway, and some tectonic implications: Contributions to Mineralogy and Petrology, v. 95, p. 82–99, doi: 10.1007/BF00518032.

Jamtveit, B., Caswell, D.A., and Mearns, E.W., 1991, Chronology of the high-pressure metamorphism of Norwegian garnet peridotites/pyroxenes: Journal of Metamorphic Geology, v. 9, p. 125–139.

Jayko, A.S., Blake, M.C., and Harms, T., 1987, Attenuation of the Coast Range ophiolite by extensional faulting, and nature of the Coast Range "thrust," California: Tectonics, v. 6, p. 475–488.

Kadarusman, A., and Parkinson, C.D., 2000, Petrology and *P-T* evolution of garnet peridotites from central Sulawesi, Indonesia: Journal of Metamorphic Geology, v. 18, p. 193–210, doi: 10.1046/j.1525-1314.2000.00238.x.

Kaneko, Y., Maruyama, S., Terabayashi, M., Yamamoto, H., Ishikawa, M., Anma, R., Parkinson, C.D., Ota, T., Nakajima, Y., Katayama, I., Yamamoto, J., and Yamauchi, K., 2000, Geology of the Kokchetav ultrahigh-pressure–high-pressure metamorphic belt, north-eastern Kazakhstan: The Island Arc, v. 9, p. 264–283, doi: 10.1046/j.1440-1738.2000.00278.x.

Kaneko, Y., Katayama, I., Yamamoto, H., Misawa, K., Ishikawa, M., Rehman, H.U., Kausar, A.B., and Shirashi, K., 2003, Timing of Himalayan ultrahigh-pressure metamorphism: Sinking rate and subduction angle of the

Indian continental crust beneath Asia: Journal of Metamorphic Geology, v. 21, p. 589–599, doi: 10.1046/j.1525-1314.2003.00466.x.

Katayama, I., Maruyama, S., Parkinson, C.D., Terada, K., and Sano, Y., 2001, Ion micro-probe U-Pb zircon geochronology of peak and retrograde stages of ultrahigh-pressure metamorphic rocks from the Kokchetav Massif, northern Kazakhstan: Earth and Planetary Science Letters, v. 188, p. 185–198, doi: 10.1016/S0012-821X(01)00319-3.

Katayama, I., Mukou, A., Iizuka, T., Maruyama, S., Terada, K., Tsutsumi, T., Sano, S., Zhang, R.Y., and Liou, J.G., 2003, Dating of zircon from Ti-clinohumite–bearing garnet peridotite: Implication for timing of mantle metasomatism: Geology, v. 31, p. 713–716, doi: 10.1130/G19525.1.

Kawachi, Y., 1968, Large-scale overturned structure in the Sanbagawa metamorphic zone in central Shikoku, Japan: Geological Society of Japan Journal, v. 74, p. 607–616.

Kienast, J.R., Lombardo, B., Biino, G., and Pinardon, J.L., 1991, Petrology of very-high-pressure eclogitic rocks from the Brossasco-Isasca Complex, Dora-Maira Massif, Italian western Alps: Journal of Metamorphic Geology, v. 9, p. 19–34.

Koons, P.O., Zeitler, P.K., Chamberlain, C.P., Craw, D., and Meltzer, A.S., 2002, Mechanical links between erosion and metamorphism in Nanga Parbat, Pakistan Himalaya: American Journal of Science, v. 302, p. 749–773, doi: 10.2475/ajs.302.9.749.

Koons, P.O., Upton, P., and Terry, M.P., 2003, Three-dimensional mechanics of UHPM terrains and resultant *P–T-t* paths, *in* Carswell, D.A., and Compagnoni, R., eds., Ultrahigh Pressure Metamorphism: European Union Notes in Mineralogy, Volume 5: Budapest, European Union, p. 415–441.

Kretz, R., 1983, Symbols for rock-forming minerals: The American Mineralogist, v. 68, p. 277–279.

Krogh, E.J., and Carswell, D.A., 1995, HP and UHP eclogites and garnet peridotites in the Scandinavian Caledonides, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: Cambridge, Cambridge University Press, p. 244–298.

Krogh Ravna, E., and Paquin, J., 2003, Thermobarometric methodologies applicable to eclogites and garnet ultrabasites, *in* Carswell, D.A., and Compagnoni, R., eds., Ultrahigh Pressure Metamorphism: European Union Notes in Mineralogy, Volume 5: Budapest, European Union, p. 229–259.

Krogh Ravna, E.J., and Terry, M.P., 2004, Geothermobarometry of phengite-kyanite-quartz/coesite eclogites: Journal of Metamorphic Geology, v. 22, p. 579–592, doi: 10.1111/j.1525-1314.2004.00534.x.

Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L., and Manickavasagam, R.M., 2005, The onset of India-Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya: Earth and Planetary Science Letters, v. 234, p. 83–97, doi: 10.1016/j.epsl.2005.02.038.

Liou, J.G., and Zhang, R.Y., 1998, Petrogenesis of ultrahigh-*P* garnet-bearing ultramafic body from Maowu, the Dabie Mountains, central China: The Island Arc, v. 7, p. 115–134, doi: 10.1046/j.1440-1738.1998.00188.x.

Liou, J.G., Zhang, R.Y., Wang, X., Eide, E.A., Ernst, W.G., and Maruyama, S., 1996, Metamorphism and tectonics of high-pressure and ultrahigh-pressure belts in the Dabie–Sulu region, China, *in* Yin, A., and Harrison, T.M., eds., The Tectonic Evolution of Asia: Cambridge, Cambridge University Press, p. 300–344.

Liou, J.G., Zhang, R.Y., Ernst, W.G., Rumble, D., III, and Maruyama, S., 1998, High pressure minerals from deeply subducted metamorphic rocks: Reviews in Mineralogy, v. 37, p. 33–96.

Liou, J.G., Hacker, B.R., and Zhang, R.Y., 2000, Into the forbidden zone: Science, v. 287, p. 1215–1216, doi: 10.1126/science.287.5456.1215.

Liu, F.L., Xu, Z.Q., Liou, J.G., and Song, B., 2004, SHRIMP U-Pb ages of ultrahigh-pressure and retrograde metamorphism of gneiss, south-western Sulu terrane, eastern China: Journal of Metamorphic Geology, v. 22, p. 315–326, doi: 10.1111/j.1525-1314.2004.00516.x.

Liu, F.L., Xu, Z.Q., Liou, J.G., Dong, H.L., and Xue, H.M., 2007, Ultrahigh-pressure mineral assemblages in zircons from the surface to 5158 m depth in cores of the main drill hole, Chinese Continental Scientific Drilling Project, SW Sulu belt, China: International Geology Review, v. 49, p. 454–478.

Liu, L., Sun, Y., Xiao, P., Che, Z., Luo, J., Chen, D., Wang, Y., Zhang, A., Chen, L., and Wang, Y., 2002, Discovery of ultrahigh-pressure magnesite-bearing garnet lherzolite (>3.8 GPa) in the Altyn Tagh, northwest China: Chinese Science Bulletin, v. 47, p. 881–886, doi: 10.1360/02tb9197.

MacKenzie, J.M., Canil, D., Johnston, S.T., English, J., Mihalynuk, M.G., and Grant, B., 2005, First evidence for ultrahigh-pressure garnet peridotite in the North American Cordillera: Geology, v. 33, p. 105–108, doi: 10.1130/G20958.1.

Malpas, J., Fletcher, C.J.N., Ali, J.R., and Aitchison, J.C., eds., 2004, Aspects of the Tectonic Evolution of China: Geological Society [London] Special Publication 226, 362 p.

Maruyama, S., and Parkinson, C.D., 2000, Overview of the geology, petrology and tectonic framework of the HP-UHP metamorphic belt of the Kokchetav Massif, Kazakhstan: The Island Arc, v. 9, p. 439–455, doi: 10.1046/j.1440-1738.2000.00288.x.

Maruyama, S., Liou, J.G., and Zhang, R., 1994, Tectonic evolution of the ultrahigh-pressure (UHP) and high-pressure (HP) metamorphic belts from central China: The Island Arc, v. 3, p. 112–121, doi: 10.1111/j.1440-1738.1994.tb00099.x.

Maruyama, S., Liou, J.G., and Terabayashi, M., 1996, Blueschists and eclogites of the world and their exhumation: International Geology Review, v. 38, p. 485–594.

Massonne, H.J., and Bautsch, H.J., 2002, An unusual garnet pyroxenite from the Granulitgebirge, Germany: Origin in the transition zone (>400 km depths) or in a shallower upper mantle region?: International Geology Review, v. 14, p. 779–796.

Massonne, H.J., and O'Brien, P.J., 2003, The Bohemian Massif and the NW Himalaya, *in* Carswell, D.A., and Compagnoni, R., eds., Ultrahigh Pressure Metamorphism: European Union Notes in Mineralogy, Volume 5: Budapest, European Union, p. 145–187.

Mattinson, C.G., Zhang, R.Y., Tsujimori, T., and Liou, J.G., 2004, Epidote-rich talc-kyanite-phengite eclogites, Sulu terrane, eastern China: The American Mineralogist, v. 89, p. 1772–1783.

Medaris, L.G., Jr., 1980, Petrogenesis of the Lien peridotite and associated eclogites, Almklovdalen western Norway: Lithos, v. 13, p. 339–353, doi: 10.1016/0024-4937(80)90053-5.

Medaris, L.G., Jr., 1984, A geothermobarometric investigation of garnet peridotites in the Western Gneiss Region of Norway: Contributions to Mineralogy and Petrology, v. 87, p. 72–86, doi: 10.1007/BF00371404.

Medaris, L.G., Jr., 1999, Garnet peridotite in Eurasian HP and UHP terranes: A diversity of origins and thermal histories: International Geology Review, v. 41, p. 799–815.

Medaris, L.G., and Carswell, D.A., 1990, Petrogenesis of Mg-Cr garnet-peridotites in European metamorphic belts, *in* Carswell, D.A., ed., Eclogite Facies Rocks: Glasgow, Blackie and Sons, p. 260–290.

Medaris, L.G., Wang, H.F., Misar, Z., and Jelinek, E., 1990, Thermobarometry, diffusion modeling and cooling rates of crustal garnet peridotites: Two examples from the Moldanubian zone of the Bohemian Massif: Lithos, v. 25, p. 189–202, doi: 10.1016/0024-4937(90)90014-R.

Medaris, L.G., Ducea, M., Ghent, E., and Iancu, V., 2003, Conditions and timing of high-pressure Variscan metamorphism in the South Carpathians, Romania: Lithos, v. 70, p. 141–161, doi: 10.1016/S0024-4937(03)00096-3.

Medaris, L.G., Wang, H., Jelinek, E., Mihaljevic, M., and Jakes, P., 2005, Characteristics and origins of diverse Variscan peridotites in the Gföhl Nappe, Bohemian Massif, Czech Republic: Lithos, v. 82, p. 1–23, doi: 10.1016/j.lithos.2004.12.004.

Michard, A., Henry, C., and Chopin, C., 1995, Structures in UHPM rocks: A case study from the Alps, *in* Coleman, R.G., and Wang, X., eds., Ultrahigh Pressure Metamorphism: Cambridge, Cambridge University Press, p. 132–158.

Mihalynuk, M.G., Erdmer, P., Ghent, E.D., Cordey, F., Archibald, D.A., Friedman, R.M., and Johannson, G.G., 2004, Coherent French Range blueschist: Subduction to exhumation in <2.5 m.y.?: Geological Society of America Bulletin, v. 116, p. 910–922, doi: 10.1130/B25393.1.

Mizukami, T., Wallis, S.R., and Yamamoto, J., 2004, Natural examples of olivine lattice preferred orientation patterns with a flow-normal *a*-axis maximum: Nature, v. 427, p. 432–436, doi: 10.1038/nature02179.

Molnar, P., and Atwater, T., 1978, Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere: Earth and Planetary Science Letters, v. 41, p. 330–340, doi: 10.1016/0012-821X(78)90187-5.

Mosenfelder, J.L., Schertl, H.P., Smyth, J.R., and Liou, J.G., 2005, Factors in the preservation of coesite: The importance of fluid infiltration: The American Mineralogist, v. 90, p. 779–789, doi: 10.2138/am.2005.1687.

Muko, A., Okamoto, K., Yoshioka, N., Zhang, R.Y., Parkinson, C.D., Ogasawara, Y., and Liou, J.G., 2002, Petrogenesis of Ti-clinohumite–bearing garnetiferous ultramafic rocks from Kumdy-kol, *in* Parkinson, C.D., Katayama, I., Liou, J.G., and Maruyama, S., eds., 2002, The Diamond-Bearing

Kokchetav Massif, Kazakhstan: Tokyo, Universal Academy Press, Frontiers Science Series, no. 38, p. 343–360.

Nakamura, D., and Banno, S., 1997, Thermodynamic modeling of sodic pyroxene solid-solution and its application in a garnet–omphacite–kyanite–coesite geothermobarometer for UHP metamorphic rocks: Contributions to Mineralogy and Petrology, v. 130, p. 93–102, doi: 10.1007/s004100050352.

Newton, R.C., and Haselton, H.T., 1981, Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer, *in* Newton, R.C., ed., Thermodynamics of Minerals and Melts: New York, Springer-Verlag, p. 131–147.

Nichols, G.T., Wyllie, P.J., and Stern, C.R., 1994, Subduction zone melting of pelagic sediments constrained by melting experiments: Nature, v. 371, p. 785–788, doi: 10.1038/371785a0.

Nowlan, E.U., 1998, Druck-Temperatur-Entwicklung und Geochemie von Eklogiten des Dora-Maira-Massivs, Westalpen [Ph.D. thesis]: Bochum, Bochum University, 359 p.

O'Brien, P.J., 2000, The fundamental Variscan problem: High-temperature metamorphism at different depths and high-pressure metamorphism at different temperatures, *in* Franke, W., Haak, V., Onken, O., and Tanner, D., eds., Orogenic Processes: Quantification and Modelling in the Variscan Belt: Geological Society [London] Special Publication 179, p. 369–386.

O'Brien, P.J., 2001, Subduction followed by collision: Alpine and Himalayan examples, *in* Rubie, D.C., and van der Hilst, R., eds., Processes and Consequences of Deep Subduction: Physics of the Earth and Planetary Interiors, v. 127, p. 277–291.

O'Brien, P.J., and Rötzler, J., 2003, High-pressure granulites: Formation, recovery of peak conditions, and implications for tectonics: Journal of Metamorphic Geology, v. 21, p. 3–20, doi: 10.1046/j.1525-1314.2003.00420.x.

O'Brien, P.J., and Sachan, H.K., 2000, Diffusion modelling in garnet from Tso Morari eclogite and implications for exhumation models: Earth Science Frontiers, v. 7, p. 25–27, China University of Geosciences, Beijing.

O'Brien, P.J., Zotov, N., Law, R., Khan, M.A., and Jan, M.Q., 2001, Coesite in Himalayan eclogite and implications for models of India-Asia collision: Geology, v. 29, p. 435–438, doi: 10.1130/0091-7613(2001)029<0435:CIHEAI>2.0.CO;2.

Okay, A.I., 1993, Petrology of a diamond and coesite-bearing metamorphic terrain: Dabie Shan, China: European Journal of Mineralogy, v. 5, p. 659–675.

Okay, A.I., 1994, Sapphirine and Ti-clinohumite in ultra-high-pressure garnet-pyroxenite and eclogite from Dabie Shan, China: Contributions to Mineralogy and Petrology, v. 116, p. 145–155, doi: 10.1007/BF00310696.

Okay, A.I., 1995, Paragonite eclogites from Dabie Shan, China: Re-equilibration during exhumation?: Journal of Metamorphic Geology, v. 13, p. 449–460.

Ota, T., Terabayashi, M., Parkinson, C.D., and Masago, H., 2000, Thermobarometric structure of the Kokchetav ultrahigh-pressure–high-pressure massif deduced from a north-south transect in the Kulet and Saldat-kol regions, northern Kazakhstan: The Island Arc, v. 9, p. 328–357, doi: 10.1046/j.1440-1738.2000.00282.x.

Parkinson, C.D., Katayama, I., Liou, J.G., and Maruyama, S., eds., 2002, The Diamond-Bearing Kokchetav Massif, Kazakhstan: Tokyo, Universal Academy Press, Frontiers Science Series, no. 38, 527 p.

Parrish, R.R., Gough, S., Searle, M., and Waters, D., 2003, Exceptionally rapid exhumation of the Kaghan UHP terrane, Pakistan from U-Th-Pb measurements on accessory minerals: Geological Society of America Abstracts with Programs, v. 34, no. 7, p. 556–557.

Patiño Douce, A.E., and McCarthy, T.C., 1998, Melting of crustal rocks during continental collision and subduction, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 27–55.

Pattison, D.R.M., Chacko, T., Farquhar, J., and McFarlane, C.R.M., 2003, Temperatures of granulite-facies metamorphism; constraints from experimental phase equilibria and thermobarometry corrected for retrograde exchange: Journal of Petrology, v. 44, p. 867–900, doi: 10.1093/petrology/44.5.867.

Peacock, S.M., 1995, Ultrahigh-pressure metamorphic rocks and the thermal evolution of continent collision belts: The Island Arc, v. 4, p. 376–383, doi: 10.1111/j.1440-1738.1995.tb00157.x.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037–1053, doi: 10.1130/0016-7606(1986)97<1037:DOOWAT>2.0.CO;2.

Platt, J.P., 1987, The uplift of high-pressure, low-temperature metamorphic rocks: Philosophical Transactions of the Royal Society of London, v. 321, p. 87–103.

Platt, J.P., 1993, Exhumation of high-pressure rocks: A review of concepts and processes: Terra Nova, v. 5, p. 119–133.

Powell, R., and Holland, T.J.B., 1988, An internally consistent dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program: Journal of Metamorphic Geology, v. 6, p. 173–204.

Powell, R., Holland, T., and Worley, B., 1998, Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC: Journal of Metamorphic Geology, v. 16, p. 577–588, doi: 10.1111/j.1525-1314.1998.00157.x.

Proyer, A., Dachs, E., and McCammon, C., 2004, Pitfalls in geothermobarometry of eclogites: Fe^{3+} and changes in the mineral chemistry of omphacite at ultrahigh pressures: Contributions to Mineralogy and Petrology, v. 147, p. 305–318, doi: 10.1007/s00410-004-0554-6.

Pysklywec, R.N., Beaumont, C., and Fullsack, P., 2002, Lithospheric deformation during the early stages of continental collision: Numerical experiments and comparison with South Island, New Zealand: Journal of Geophysical Research, v. 107, no. B7, doi: 10.1029/2001JB000252

Reisberg, L., Zindler, A., and Jagoutz, E., 1989, Further Sr and Nd isotopic results from peridotites of the Ronda ultramafic complex: Earth and Planetary Science Letters, v. 96, p. 161–180, doi: 10.1016/0012-821X(89)90130-1.

Ring, U., and Brandon, M.T., 1994, Kinematic data for the Coast Range fault and implications for the exhumation of the Franciscan subduction complex: Geology, v. 22, p. 735–738, doi: 10.1130/0091-7613(1994)022<0735:KDFTCR>2.3.CO;2.

Ring, U., and Brandon, M.T., 1999, Ductile deformation and mass loss in the Franciscan subduction complex—Implications for exhumation processes in accretionary wedges, *in* Ring, U., Brandon, M.T., Lister, G.S., and Willett, S.D., eds., Exhumation Processes; Normal Faulting, Ductile Flow and Erosion: Geological Society [London] Special Publication 154, p. 180–203.

Ringwood, A.E., 1975, Composition and Petrology of the Earth's Mantle: New York, McGraw-Hill, 618 p.

Root, D.B., Hacker, B.R., Mattinson, J.M., and Wooden, J.L., 2004, Young age and rapid exhumation of Norwegian ultrahigh-pressure rocks: An ion microprobe and chemical abrasion study: Earth and Planetary Science Letters, v. 228, p. 325–341, doi: 10.1016/j.epsl.2004.10.019.

Root, D.B., Hacker, B.R., Gans, P., Eide, E., Ducea, M., and Mosenfelder, J., 2005, High-pressure allochthons overlie the ultrahigh-pressure Western Gneiss Region, Norway: Journal of Metamorphic Geology, v. 23, p. 45–61, doi: 10.1111/j.1525-1314.2005.00561.x.

Rubatto, D., and Hermann, J., 2001, Exhumation as fast as subduction?: Geology, v. 29, p. 3–6, doi: 10.1130/0091-7613(2001)029<0003:EAFAS>2.0.CO;2.

Rubatto, D., Liati, A., and Gebauer, D., 2003, Dating UHP metamorphism, *in* Carswell, D.A., and Compagnoni, R., eds., Ultrahigh Pressure Metamorphism: European Union Notes in Mineralogy, Volume 5: Budapest, European Union, p. 341–363.

Rubie, D.C., 1984, A thermal-tectonic model for high-pressure metamorphism in the Sesia zone, western Alps: The Journal of Geology, v. 92, p. 21–36.

Rubie, D.C., 1986, The catalysis of mineral reactions by water and restrictions on the presence of aqueous fluid during metamorphism: Mineralogical Magazine, v. 50, p. 399–415, doi: 10.1180/minmag.1986.050.357.05.

Rubie, D.C., 1990, Role of kinetics in the formation and preservation of eclogites, *in* Carswell, D.A., ed., Eclogite Facies Rocks: New York, Chapman and Hall, p. 111–140.

Sacks, P.E., and Secor, D.T., Jr., 1990, Delaminations in collisional orogens: Geology, v. 18, p. 999–1002, doi: 10.1130/0091-7613(1990)018<0999:DICO>2.3.CO;2.

Schlup, M., Carter, A., Cosca, M., and Steck, A., 2003, Exhumation history of eastern Ladakh revealed by $^{40}Ar/^{39}Ar$ and fission-track ages: The Indus River–Tso Morari transect, NW Himalaya: Geological Society [London] Journal, v. 160, p. 385–399.

Schmädicke, E., and Evans, B.W., 1997, Garnet-bearing ultramafic rocks from the Erzgebirge, and their relation to other settings in the Bohemian Massif: Contributions to Mineralogy and Petrology, v. 127, p. 57–74, doi: 10.1007/s004100050265.

Schmid, R., Wilke, M., Oberhänsli, R., Janssens, K., Falkenberg, G., Franz, L., and Gaab, A., 2003, Micro-Xanes determination of ferric iron and its application in thermobarometry: Lithos, v. 70, p. 381–392, doi: 10.1016/S0024-4937(03)00107-5.

Searle, M.P., 1996, Cooling history, erosion, exhumation, and kinetics of the Himalaya-Karakorum-Tibet orogenic belt, *in* Yin, A., and Harrison, T.M., eds., The Tectonic Evolution of Asia: Cambridge, Cambridge University Press, p. 110–137.

Searle, M.P., Hacker, B.R., and Bilham, R., 2001, The Hindu Kush seismic zone as a paradigm for the creation of ultrahigh-pressure diamond- and coesite-bearing continental rocks: The Journal of Geology, v. 109, p. 143–153, doi: 10.1086/319244.

Searle, M.P., Simpson, R.L., Law, R.D., Parrish, R.R., and Waters, D.J., 2003, The structural geometry, metamorphic and magmatic evolution of the Everest Massif, High Himalaya of Nepal–South Tibet: Geological Society [London] Journal, v. 160, p. 345–366.

Seno, T., 1985, Age of subducting lithosphere and back-arc basin formation in the western Pacific since the middle Tertiary, *in* Nasu, N., Kobayashi, K., Uyeda, S., Kushiro, I., and Kagami, H., eds., Formation of Active Ocean Margins: Tokyo, Terrapub, p. 469–481.

Sharp, Z.D., Essene, E.J., and Hunziker, J.C., 1993, Stable isotope geochemistry and phase equilibria of coesite-bearing whiteschists, Dora Maira Massif, western Alps: Contributions to Mineralogy and Petrology, v. 114, p. 1–12, doi: 10.1007/BF00307861.

Sobolev, N.V., and Shatsky, V.S., 1990, Diamond inclusions in garnets from metamorphic rocks: Nature, v. 343, p. 742–746, doi: 10.1038/343742a0.

Song, S., Yang, J., Liou, J.G., Wu, C., Shi, R., and Xua, Z., 2003, Petrology, geochemistry and isotopic ages of eclogites from the Dulan UHPM terrane, the north Qaidam: NW China: Lithos, v. 70, p. 195–211, doi: 10.1016/S0024-4937(03)00099-9.

Song, S.G., Zhang, L.F., and Niu, Y., 2004, Ultra-deep origin of garnet peridotite from the north Qaidam ultrahigh-pressure belt, northern Tibetan Plateau: NW China: American Mineralogist. v. 89, p. 1330–1336.

Song, S.G., Zhang, L.F., Niu, Y., Jian, P., and Liu, D., 2005, Geochronology of diamond-bearing zircons from garnet peridotite in the north Qaidam UHPM belt, northern Tibetan Plateau: A record of complex histories from oceanic lithosphere subduction to continental collision: Earth and Planetary Science Letters, v. 234, p. 99–118, doi: 10.1016/j.epsl.2005.02.036.

Spengler, D., van Roermund, H.L.M., Drury, M.R., Ottolini, L., Mason, P.R.D., and Davies, G.R., 2006, Deep orogen and hot melting of an Archaean orogenic peridotite massif in Norway: Nature, v. 440, p. 913–917, doi: 10.1038/nature04644.

Stern, C.R., Huang, W.L., and Wyllie, P.J., 1975, Basalt-andesite-rhyolite-H_2O: Crystallization intervals with excess H_2O and H_2O-undersaturated liquidus surfaces to 35 kilobars, with implications for magma genesis: Earth and Planetary Science Letters, v. 28, p. 189–196, doi: 10.1016/0012-821X(75)90226-5.

Stöckhert, B., and Renner, J., 1998, Rheology of crustal rocks at ultrahigh pressure, *in* Hacker, B.R., and Liou, J.G., eds., When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks: Dordrecht, Kluwer Academic Publishers, p. 57–95.

Suppe, J., 1972, Interrelationships of high-pressure metamorphism, deformation, and sedimentation in Franciscan tectonics, U.S.A., *in* 24th International Geological Congress, Reports, Section 3: Montreal, International Geological Congress, p. 552–559.

Terry, M.P., and Robinson, P., 2004, Geometry of eclogite-facies structural features: Implications for production and exhumation of UHP and HP rocks, Western Gneiss Region, Norway: Tectonics, v. 23, doi: 10.1029/2002TC001401.

Terry, M.P., Robinson, P., and Krogh Ravna, E.J., 2000a, Kyanite eclogite thermobarometry and evidence of thrusting of UHP over HP metamorphic rocks, Nordøyane, Western Gneiss Region, Norway: The American Mineralogist, v. 85, p. 1637–1650.

Terry, M.P., Robinson, P., Hamilton, M.A., and Jercinovic, M.J., 2000b, Monazite geochronology of UHP and HP metamorphism, deformation, and exhumation, Nordøyane, Western Gneiss Region, Norway: The American Mineralogist, v. 85, p. 1651–1664.

Tilton, G.R., Schreyer, W., and Schertl, H.P., 1991, Pb-Sr-Nd isotopic behavior of deeply subducted crustal rocks from the Dora-Maira Massif, western Alps: II. What is the age of the ultrahigh-pressure metamorphism?: Contributions to Mineralogy and Petrology, v. 108, p. 22–33, doi: 10.1007/BF00307323.

Treloar, P.J., O'Brien, P.J., Parrish, R.R., and Khan, M.A., 2003, Exhumation of early Tertiary, coesite-bearing eclogites from the Pakistan Himalaya: Geological Society [London] Journal, v. 160, p. 367–376.

Tsai, C.H., Liou, J.G., and Ernst, W.G., 2000, Petrological characterization and tectonic significance of the Raobazhai retrogressed garnet peridotites from the North Dabie Complex, central-eastern China: Journal of Metamorphic Geology, v. 18, p. 181–192, doi: 10.1046/j.1525-1314.2000.00237.x.

Tsujimori, T., Sisson, V.B., Liou, J.G., Harlow, G.E., and Sorensen, S.S., 2006, Very low-temperature record in subduction process: A review of global lawsonite-eclogites: Lithos, v. 92, p. 609–624, doi: 10.1016/j.lithos.2006.03.054.

van den Beukel, J., 1992, Some thermomechanical aspects of the subduction of continental lithosphere: Tectonics, v. 11, p. 316–329.

van Roermund, H.L.M., Drury, M.R., Barnhoorn, A., and De Ronde, A., 2000, Super-silicic garnet microstructures from an orogenic garnet peridotite, evidence for an ultra-deep (>6 GPa) origin: Journal of Metamorphic Geology, v. 18, p. 135–147, doi: 10.1046/j.1525-1314.2000.00251.x.

van Roermund, H.L.M., Drury, M.R., Barnhoorn, A., and De Ronde, A., 2001, Relict majoritic garnet microstructures from ultra-deep orogenic garnet peridotites in western Norway: Journal of Petrology, v. 42, p. 117–130, doi: 10.1093/petrology/42.1.117.

van Roermund, H.L.M., Carswell, D.A., Drury, M.R., and Heyboer, T.C., 2002, Microdiamonds in a megacrystic garnet websterite pod from Bardane on the island of Fjortoft, western Norway: Evidence for diamond formation in mantle rocks during deep continental subduction: Geology, v. 30, p. 959–962, doi: 10.1130/0091-7613(2002)030<0959:MIAMGW>2.0.CO;2.

Vielzeuf, D., and Schmidt, M.W., 2001, Melting relations in hydrous systems revisited: Application to metapelites, metagraywackes and metabasalts: Contributions to Mineralogy and Petrology, v. 141, p. 251–267.

von Blanckenburg, F., and Davies, J.H., 1995, Slab breakoff: A model for syncollision magmatism and tectonics in the Alps: Tectonics, v. 14, p. 120–131, doi: 10.1029/94TC02051.

Wain, A.L., 1998, Ultrahigh-Pressure Metamorphism in the Western Gneiss Region of Norway: [Ph.D. thesis]: Oxford, Oxford University.

Walsh, E.O., and Hacker, B.R., 2004, The fate of subducted continental margins: Two-stage exhumation of the high-pressure to ultrahigh-pressure Western Gneiss complex, Norway: Journal of Metamorphic Geology, v. 22, p. 671–689, doi: 10.1111/j.1525-1314.2004.00541.x.

Webb, L.E., Hacker, B.R., Ratschbacher, L., McWilliams, M.O., and Dong, S., 1999, ^{40}Ar-^{39}Ar thermochronologic constraints on deformation and cooling history of high and ultrahigh-pressure rocks in the Qinling-Dabie orogen: Tectonics, v. 18, p. 621–638, doi: 10.1029/1999TC900012.

Willett, S., Beaumont, C., and Fullsack, P., 1993, Mechanical model for the tectonics of doubly vergent compressional orogens: Geology, v. 21, p. 371–374, doi: 10.1130/0091-7613(1993)021<0371:MMFTTO>2.3.CO;2.

Yang, J.S., Xu, Z.Q., Li, H.B., Wu, C.L., Zhang, J.X., and Shi, R.D., 2000, A Caledonian convergent border along the southern margin of the Qilian terrane, NW China: Evidence from eclogite, garnet-peridotite, ophiolite, and S-type granite: Journal of Geological Society of China, v. 42, p. 142–160.

Yang, J.S., Xu, Z.Q., Zhang, J.X., Song, S.G., Wu, C.L., and Shi, R.D., 2002, Early Palaeozoic north Qaidam UHP metamorphic belt on the north-eastern Tibetan Plateau and a paired subduction model: Terra Nova, v. 14, p. 397–404, doi: 10.1046/j.1365-3121.2002.00438.x.

Young, D.J., Hacker, B.R., Andersen, T.B., Corfu, F., Gehrels, G.E., and Grove, M., 2007, Prograde amphibolite facies to ultrahigh-pressure transition along Nordfjord, western Norway: Implications for exhumation tectonics: Tectonics, v. 26, TC1007, doi: 10.1029/2004TC001781.

Zeitler, P.K., Koons, P.O., Bishop, M.P., Chamberlain, C.P., Craw, D., Edwards, M.A., Hamidullah, S., Jan, M.Q., Khan, M.A., Khattak, U.K., Kidd, W.S.F., Mackie, R.L., Meltzer, A.S., Park, S.K., Pecher, A., Poage, M.A., Sarker, G., Schneider, D.A., Seeber, L., and Shroder, J.F., 2001, Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion: Tectonics, v. 20, p. 712–728, doi: 10.1029/2000TC001243.

Zhang, R.Y., and Liou, J.G., 1994, Coesite-bearing eclogite in Henan Province, central China: Detailed petrology, glaucophane stability and *PT* path: European Journal of Mineralogy, v. 6, p. 217–233.

Zhang, R.Y., and Liou, J.G., 1999, Exsolution lamellae in minerals from ultrahigh-*P* rocks: International Geology Review, v. 41, p. 981–993.

Zhang, R.Y., and Liou, J.G., 2003, Clinopyroxenite from the Sulu ultrahigh-pressure terrane, eastern China: Origin and evolution of garnet exsolution in clinopyroxene: The American Mineralogist, v. 88, p. 1591–1600.

Zhang, R.Y., Liou, J.G., and Cong, B., 1994, Petrogenesis of garnet-bearing ultramafic rocks and associated eclogites in the Su-Lu ultrahigh-pressure metamorphic terrane, China: Journal of Metamorphic Geology, v. 12, p. 169–186.

Zhang, R.Y., Hirajima, T., Banno, S., Cong, B., and Liou, J.G., 1995a, Petrology of ultrahigh-pressure rocks from the southern Su-Lu region, eastern China: Journal of Metamorphic Geology, v. 13, p. 659–675.

Zhang, R.Y., Liou, J.G., and Cong, B., 1995b, Talc-, magnesite- and Ti-clinohumite–bearing ultrahigh-pressure meta-mafic and ultramafic complex in the Dabie Mountains: Journal of Petrology, v. 36, p. 1011–1037.

Zhang, R.Y., Rumble, D., Liou, J.G., and Wang, Q.C., 1998, Low $\delta^{18}O$, ultrahigh-*P* garnet-bearing mafic and ultramafic rocks from Dabie Shan, China: Chemical Geology, v. 150, p. 161–170, doi: 10.1016/S0009-2541(98)00051-5.

Zhang, R.Y., Shu, J.F., Mao, H.K., and Liou, J.G., 1999, Magnetite lamellae in olivine and clinohumite from Dabie UHP ultramafic rocks, central China: The American Mineralogist, v. 84, p. 564–569.

Zhang, R.Y., Liou, J.G., Yang, J.S., and Yui, T.F., 2000, Petrochemical constraints for dual origin of garnet peridotites from the Dabie-Sulu UHP terrane, eastern-central China: Journal of Metamorphic Geology, v. 18, p. 149–166, doi: 10.1046/j.1525-1314.2000.00248.x.

Zhang, R.Y., Liou, J.G., Yang, J.S., and Ye, K., 2003, Ultrahigh-pressure metamorphism in the forbidden zone: The Xugou garnet peridotite, Sulu terrane, eastern China: Journal of Metamorphic Geology, v. 21, p. 539–550, doi: 10.1046/j.1525-1314.2003.00462.x.

Zhang, R.Y., Liou, J.G., Yang, J.S., Li, L., and Jahn, B.-M., 2004, Garnet peridotites in UHP mountain belts of China: International Geology Review, v. 46, p. 981–1004.

Zhang, R.Y., Liou, J.G., Zheng, J.P., Griffin, W.L., Yui, T.-F., and O'Reilly, S.Y., 2005a, Petrogenesis of the Yangkou layered garnet peridotite complex, Sulu UHP terrane, China: The American Mineralogist, v. 90, p. 801–813, doi: 10.2138/am.2005.1706.

Zhang, R.Y., Yang, J.S., Wooden, J.L., Liou, J.G., and Li, T.F., 2005b, U-Pb SHRIMP geochronology of zircon in garnet peridotite from the Sulu UHP terrane, China: Implication for mantle metasomatism and subduction-zone UHP metamorphism: Earth and Planetary Science Letters, v. 237, p. 729–734, doi: 10.1016/j.epsl.2005.07.003.

Zhang, Z.M., Liou, J.G., Zhao, S., and Shi, Z., 2006, Petrogenesis of Maobei Fe-Ti rich eclogites from the southern Sulu UHP metamorphic belt, east-central China: Journal of Metamorphic Geology, v. 24, p. 727–741, doi: 10.1111/j.1525-1314.2006.00665.x.

Zhao, R., Zhang, R.Y., Liou, J.G., Booth, A.L., Pope, E.C., and Chamberlain, C.P., 2007, Petrochemistry, oxygen isotopes and U-Pb SHRIMP geochronology of mafic-ultramafic bodies from the Sulu UHP terrane, China: Journal of Metamorphic Geology, v. 25, p. 207–224.

Manuscript Accepted by the Society 22 March 2007