International Geology Review, Vol. 46, 2004, p. 1–27.

Global UHP Metamorphism and Continental Subduction/Collision: The Himalayan Model

J. G. LIOU,[1]

Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115

T. TSUJIMORI,

Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115 and Research Institute of Natural Sciences, Okayama University of Science, Okayama 700-0005, Japan

R. Y. ZHANG,

Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115

I. KATAYAMA,

Department of Geology and Geophysics, Yale University, New Haven, CT 06520 and Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan

AND S. MARUYAMA

Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan

Abstract

Continental crust (density ~2.8 g·cm^{-3}) resists subduction into the earth's mantle (~3.3 g·cm^{-3}) because of buoyancy. However, more than 20 recognized ultrahigh-pressure (UHP) terranes have been documented; these occurrences demonstrate that not only is continental crust subducted to depths as great as 150 km, but also that some supracrustal rocks were then exhumed to the earth's surface. UHP terranes are composed of mainly supracrustal rocks that contain minor amounts of minerals such as coesite or diamond, indicative of P > 2.5 GPa. In general, quartzofeldspathic units are thoroughly back reacted, and only mafic eclogite lenses and boudins retain scattered UHP phases. These index minerals are restricted to micron-scale inclusions in chemically and mechanically resistant zircon, garnet, and a few other strong container minerals, and are difficult to identify by conventional petrologic studies. The continental rocks were subjected to UHP metamorphism at T ranging from ~700 to 950°C and P > 2.8 to 5.0 GPa, corresponding to depths of ~100 to 150 km. These UHP units were subsequently exhumed to crustal depths and subjected to intense hydration and amphibolite-facies overprint. Widespread Barrovian-type metamorphism in many collisional orogens may mask an earlier, higher-pressure metamorphic history. We suspect that coesite-bearing UHP rocks were once generated in the majority of exhumed collisional orogens.

The recent finding of coesite inclusions in rare Himalayan eclogites and country rock gneisses is a typical example. We use the Himalayan model to illustrate UHP metamorphism and subduction of continental crustal rocks to mantle depths and later Barrovian-type overprint during exhumation. Himalayan UHP eclogites and adjacent gneisses were formed at mantle depths > 100 km at 46 to 52 Ma. These rocks were exhumed to crustal depths and subjected to Barrovian amphibolite- to granulite-facies metamorphism; associated magmatism occurred at 30 to 15 Ma. The Himalayan metamorphic belt was domally uplifted and the mountain-building process initiated since 11 Ma, when underthrusting of the Indian tectosphere beneath the Lesser Himalayas occurred.

Introduction

ULTRAHIGH-PRESSURE (UHP) metamorphism refers to the metamorphism of crustal rocks (both continental and oceanic) brought to pressures high enough to crystallize index minerals such as coesite at a minimum P > 2.7 GPa at T > 600°C and/or diamond. Prior to the initial discoveries of coesite in supracrustal rocks (Chopin, 1984; Smith, 1984), coesite and diamond were thought to occur only in meteorite impact craters and mantle xenoliths. Figure 1 shows the relevant P-T conditions defining

[1]Corresponding author; email: liou@pangea.stanford.edu

0020-6814/04/708/1-27 $25.00

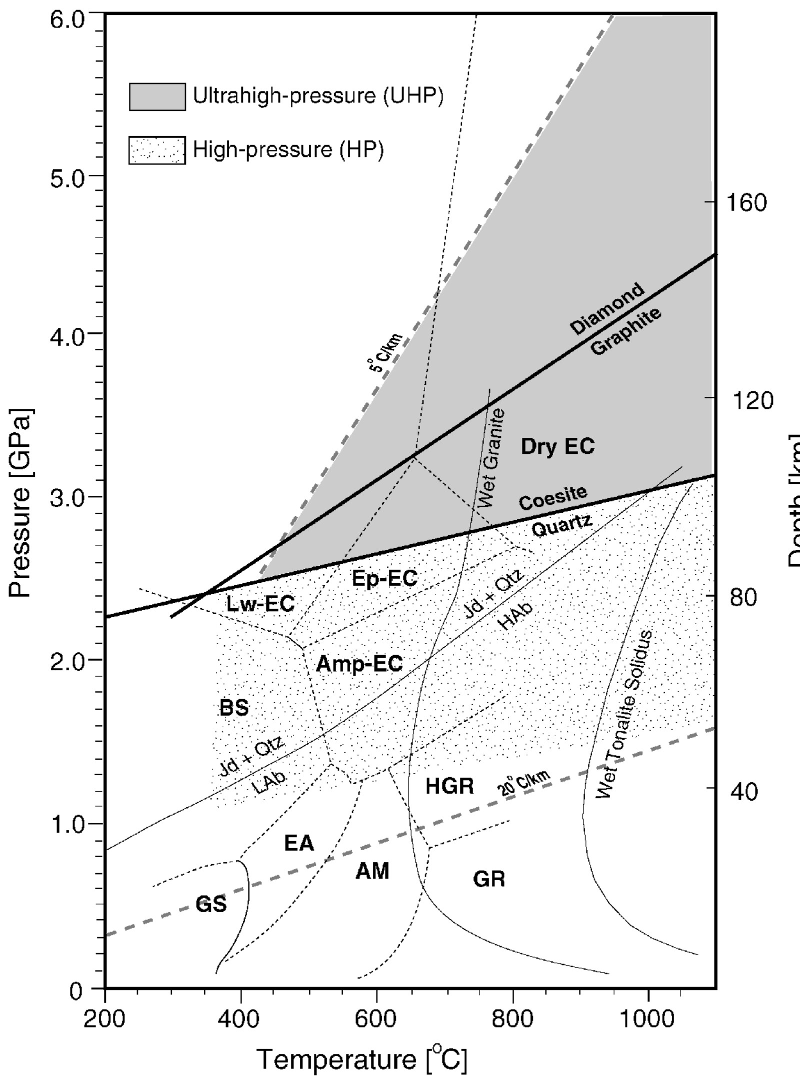

FIG. 1. P-T regimes assigned to various metamorphic types: (1) ultrahigh-P; (2) high-P; and (3) low-P. Geotherms of 5°C/km and 20°C/km are indicated. Stabilities of diamond, coesite, glaucophane, jadeite + quartz, aragonite, kyanite, sillimanite, andalusite, paragonite, and the minimum meltings of granite and tonalite are shown. P-T boundaries of various metamorphic facies [granulite, amphibolite, epidote amphibolite, greenschist, and subgreenschist facies] and subdivision of the eclogite field into amphibole (Amp) eclogite, epidote (Ep) eclogite, lawsonite (Lw) eclogite, and dry eclogite are indicated (for abbreviations, see Liou et al., 2000).

UHP, high-pressure (HP), and low-pressure (LP) metamorphism; in addition, geotherms of about 5°C·km^{-1} (extreme high P/T) and 20°C·km^{-1} (old plates) are illustrated.

The objective of the present article is to present a summary to the literature of continental crust subduction and UHP metamorphism and illustrate recent petrochemical research of various UHP rocks. To honor our teacher and mentor, W. G. Ernst, on the occasion of his retirement, we have prepared this review article to honor his contributions to the studies of both HP and UHP subduction-zone metamorphism and tectonics. We emphasize the interactions between metamorphism and tectonics in continental collision belts using the Himalayan orogen as an example. Distribution and mineralogical and petrological characteristics of other UHP terranes in the world are also described. Similar reviews for recent mineralogical-petrochemical-tectonic studies of global UHP rocks are included in Chopin (2003), Zheng et al. (2003), Rumble et al. (2003) and various chapters of the book *Ultrahigh-Pressure Metamorphism* published by the European Mineralogical Union and edited by Carswell and Compagnoni (2003).

The stabilities of coesite and other UHP minerals in metamorphic regime require abnormally low geothermal gradients, less than approximately 7°C·km^{-1}. Such environments can be attained only by the subduction of old, cold, oceanic crust–capped lithosphere ± pelagic sediments or ancient continental crust. Eclogites with compositions of mid-oceanic ridge basalt (MORB) + H_2O have been experimentally studied (e.g., Schmidt and Poli, 1998; Okamoto and Maruyama, 1999); the results shown in Figure 1 subdivide P-T regimes for the eclogite facies into those for amphibole eclogite, epidote eclogite, lawsonite eclogite, and dry eclogite. UHP and HP metamorphism can be separated conveniently by the P-T boundary for the quartz-coesite equilibrium. Eclogitic rocks formed at pressures greater or less than the transition boundary have been called "hot" or "cold" eclogite, respectively. The equilibrium boundary for the graphite-diamond transition further subdivides UHP regimes into diamond grade and coesite grade; for appropriate compositions and f_{O2} and X_{CO2} conditions, microdiamond ± coesite occur in diamond-grade UHP rocks.

We have classified global HP and UHP belts into two types according to protoliths (Maruyama et al., 1996). In active margins of the Pacific type, protoliths for HP metamorphism consist of rock assemblages forming an accretionary complex, including bedded cherts, MORB-origin greenstones, seamount fragments, and enclosing trench turbidites. On the other hand, protoliths of the collision-type HP-UHP rocks include continental basement complexes and the overlying sediment + volcanoclastic rocks of a variety of tectonic settings. Figure 2 is a schematic diagram showing the contrasting tectonic settings for accumulation of A-type protoliths in a rifted continental margin, and B-type protoliths in an active continental margin.

Most UHP rocks have A-type protoliths and are characterized by occurrences of continental shelf carbonates, bimodal volcanics, peraluminous sediments, and granite-gneiss basement rocks. Eclogites and garnet peridotites, although volumetrically small, are widespread in all recognized UHP terranes of the world. They are the most significant components inasmuch as they preserve most completely UHP index minerals such as coesite and microdiamond. These mafic-ultramafic rocks may have originated from different tectonic settings and were subjected to similar UHP metamorphism, deformation, and retrogression along with the enclosing granitic gneisses and supracrustal rocks. Because of better preservation of the effect of UHP metamorphism compared with adjacent gneissic rocks, eclogites and garnet peridotites have received the most intensive study; accordingly, they provide important petrochemical and isotopic constraints on tectonic models of continental subduction, collision, and exhumation for UHP terranes.

Global Distribution of UHP Metamorphic Terranes

Occurrences of UHP rocks have been increasingly recognized and reviewed extensively (e.g. Liou, 1999, 2002; Chopin, 2003, Carswell and Compagnoni, 2003). Thus far, more than 20 UHP terranes, shown in Figure 3, have been documented. These UHP terranes lie within major continental plate collision belts and extend for several hundred km or more; many are in Eurasia, but a few are in Africa, South America, or Antarctica. They share common structural and lithological characteristics. (1) UHP records are preserved mainly in eclogites and garnet peridotites enclosed as pods and slabs within gneissic units. A few of these rocks contain minute inclusions of coesite in zircon, garnet, and omphacite, and microdiamonds in garnet and zircon. (2) Most lithologies are continental in chemical composition. (3) Exhumed UHP units are now present in the upper continental crust as thin, subhorizontal slabs, bounded by normal faults on top, and reverse faults on bottom, and sandwiched in amongst HP or lower-grade metamorphic units. (4) Coeval island-arc volcanic and plutonic rocks do not occur, whereas post-collisional or late-stage anorogenic granitic plutons are common in some occurrences.

In this section, classical (Ernst and Liou, 2000), less intensively studied (Liou, 1999), and recently recognized UHP terranes are described below. Lithological and tectonic characteristics including index minerals, P-T conditions, size, and peak metamorphic ages of these UHP terranes are summarized in Table 1.

Classical UHP Terranes

Several classical UHP terranes including (1) the Dora Maira massif of the Western Alps (Chopin, 1984), (2) the Western Gneiss Region of Norway (Smith, 1984), (3) the Dabie-Sulu terrane of east-central China (Wang et al., 1989), (4) the Kokchetav massif of northern Kazakhstan (Sobolev and Shatsky, 1990), and (5) the Bohemian massif

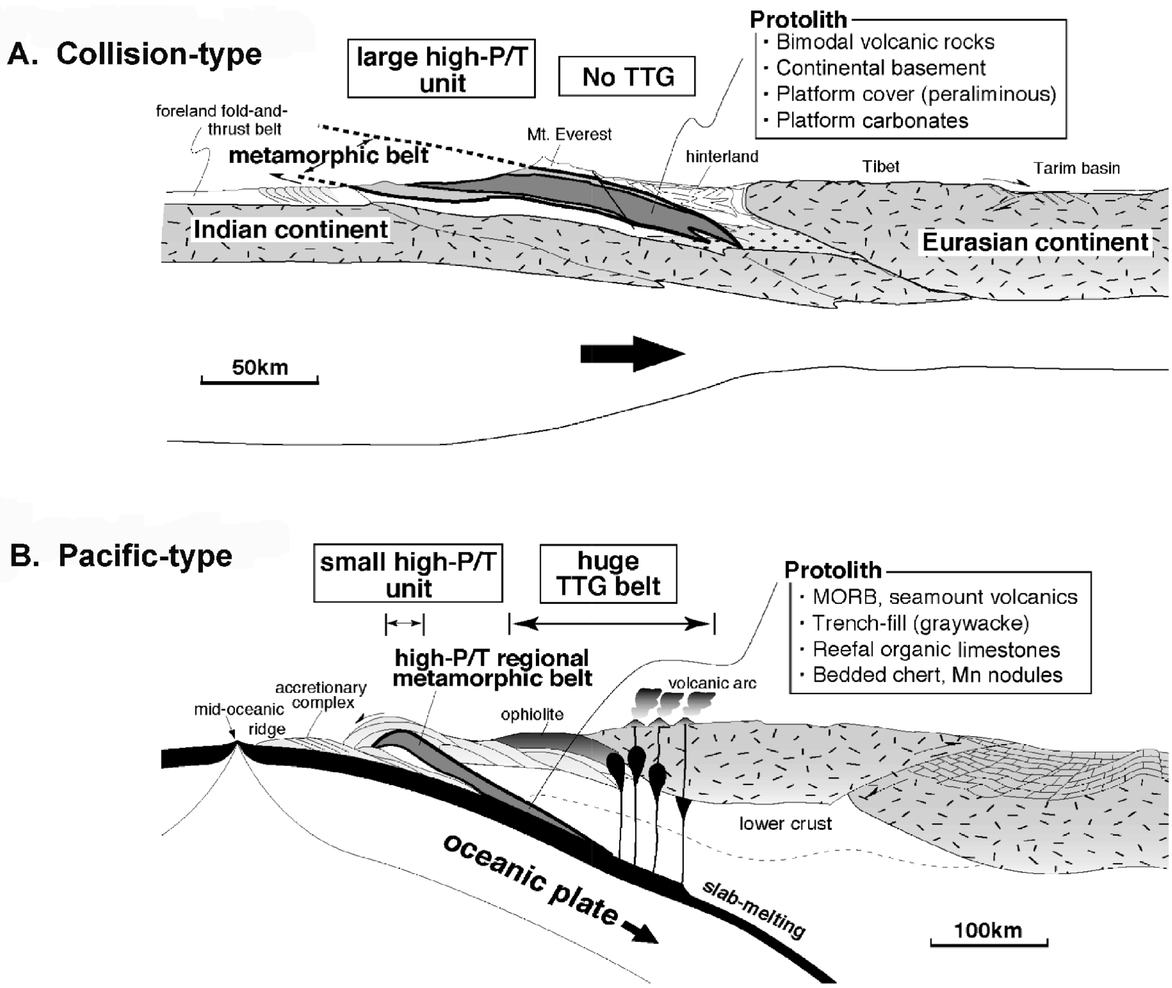

FIG. 2. Schematic cross-section contrasting the tectonic setting of generation and exhumation of (A) Collision (A)-type and (B) Pacific (B)-type HP-UHP metamorphic belts. Characteristics of the Pacific type include subduction of oceanic lithosphere and development of an accretionary complex, forearc basin, huge tonalite-trondhjeimite-granitoid (TTG) belt, and volcanic arc. Collision-type belts, which are associated with continental collision, lack those characteristics, and the high-P belt is generally of a much large extent (after Maruyama et al., 1996).

(Bakun-Czubarow, 1991) have been well studied and extensively reviewed (e.g. Ernst and Liou, 2000). Except for the Dora Maira massif, occurrences of microdiamond in these UHP terranes have been reported; petrochemical characteristics of these terranes are summarized below.

Dora Maira massif, Western Alps. The Dora Maira massif consists of Late Paleozoic and older continental basement rocks, metamorphosed under UHP and HP conditions as a result of Mesozoic–Cenozoic convergence of the European and African plates (for a recent review, see Compagnoni and Rolfo, 2003). The HP + UHP belt is a stack of four major units separated by low-angle faults. These units have been affected by Cenozoic HP metamorphism and later re-equilibration at lower pressures. The UHP unit consists of dark- and light-colored eclogites, pyrope quartzite with phengite schist and jadeite-rich rock inclusions, as well as orthogneiss country rocks and undeformed metagranites. Boudins of pyrope quartzite contain UHP relics such as coesite and other UHP minerals. This entity was subdivided into two metamorphic subunits: (a) a coesite-bearing, UHP subunit contains kyanite-eclogites with relict coesite and coesite pseudomorphs, and has estimated peak P-T conditions of 3.7 GPa and 790°C, within the diamond stability field (Schertl et al., 1991); and (b) a lower-P eclogite subunit was metamorphosed at 1.5 GPa and 500°C. The time of UHP/HP metamorphism has been considered to have culminated between 90 to 125 Ma, and retrograded between 35 to 41 Ma. However, recent

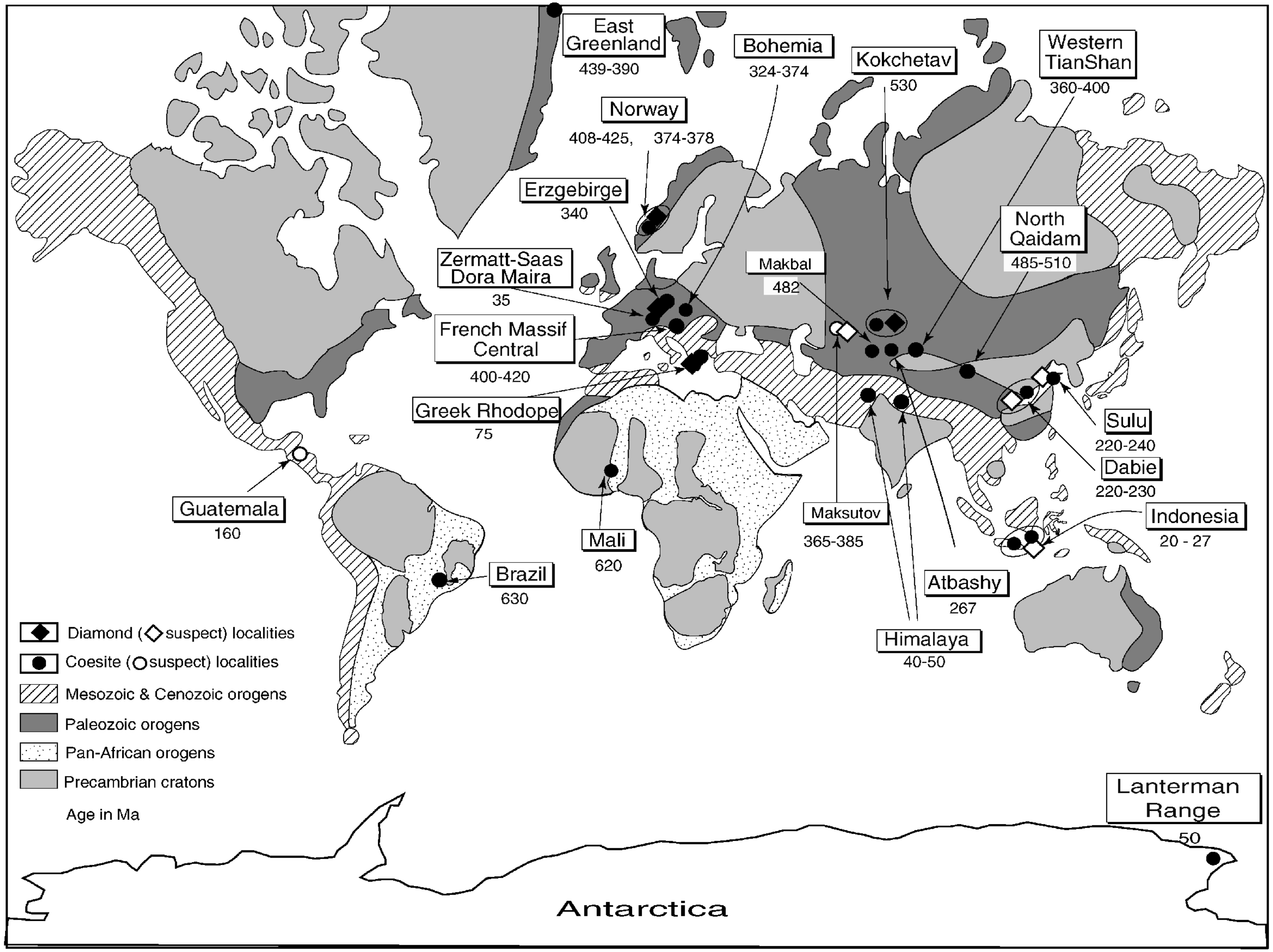

FIG. 3. Distribution and peak metamorphic age of recognized UHP terranes in the world (modified after Liou et al., 2000).

TABLE 1. Summary of Petrochemical Features of Recognized UHP Terranes in the World

UHP terrane	UHP rock type	Ages	P-T estimates	Special features
Classical terranes				
Dora Maira Massif, Western Alps, Italy	Eclogite Pyrope quartzite Pelites Whiteschist	35.4 ± 1.0 Ma (peak) 30 Ma (retrograde)	37 kbar, 790°C	1. Pyrope whiteschist contains Mg-Al silicates 2. No garnet peridotite
West Gneiss Region, Norway	Eclogite Garnet peridotite Diamond-bearing gneiss	408–425 Ma (peak) 374–378 Ma (retrograde)	P > 28 kbar T > 790°C	1. Rare diamond in country rock gneiss and garnet peridotite 2. Majoritic garnet in peridotite formed at mantle, ~1700 Ma
Dabie-Sulu terrane, East-Central China	Eclogite Garnet peridotite Jadeite quartzite Minor whiteschist	220–240 Ma (peak)	Eclogite: 26–40 kbar, 700–850°C Garnet peridotite: 50-60 kbar, 700–850°C	1. Abundant coesite in garnet, omphacite, kyanite, zoisite, zircon 2. Rare diamond in eclogite 3. Eclogite and garnet peridotite contain UHP hydrous phases 4. Dual origin for garnet peridotite 5. Majoritic garnet in eclogite
Kokchetav Massif, northern Kazakhstan	Eclogite Diamond-bearing gneiss and marble Whiteschist	537±9 Ma (peak) 507±9 Ma (retrograde)	Diamond grade: 40–60 kbar, 920–1000°C Coesite grade: 36 kbar, 750–800°C	1. Microdiamond is abundant in some garnet gneiss and dolomite marble 2. Coesite inclusions in whiteschist, eclogite, and garnet gneiss 3. Rare garnet peridotite
Bohemian Massif	Eclogite Garnet peridotite	379–395 Ma	> 30 kbar, 700–800°C	Garnet peridotite yields much higher P than coesite-eclogite
Less intensively studied terranes				
Zermatt-Saas area, Switzerland	Eclogite Mn-quartzite	52 ± 18 Ma (peak)	26–30 kbar, 590–630°C	1. Protoliths are oceanic affinity 2. Coesite inclusion in the mantle of garnet where garnet core has quartz
Saxonian Erzgebirge, Germany	Eclogite Diamond-bearing gneiss	360 ± 7 Ma (peak) 348–355 Ma (retrograde)	>42 kbar, 900–1000°C	1. Inclusions of microdiamond in zircon, kyanite, and garnet from gneiss 2. Rutile with α-PbO2 structure
Mali, Africa	Eclogite	620 Ma (peak)	>27 kbar, 700–750°C	1. Oldest age of UHP metamorphism
Makbal, western Kyrgyzstan	Eclogite Garnet-bearing pelitic schist	482 Ma	>26 kbar, 610–680°C	1. Inclusions of coesite pseudomorph in garnet from eclogite and schist

Atbashy, Kazakhstan	Eclogite	270 Ma	> 25 kbar, 660°C	1. Inclusions of coesite in garnet
Central Indonesia, SW Sulawesi	Eclogite Garnet peridotite	115–120 Ma	>27 kbar, 720–760°C 33–35 kbar,1150°C	1. Inclusions of coesite in zircon and coesite pseudomorph in jadeite
		Recently recognized terranes		
French Alps	Eclogite Metapelites	400–420 Ma (peak) 360–380 Ma (retrograde)	> 28 kbar, 750°C	1. Inclusions of coesite in garnet and omphacite
Northeast Greenland	Eclogite	400–440 Ma	24–28 kbar, 820°C	1. Inclusions of coesite pseudomorph in garnet
Southeast Brazil	Eclogite	630 Ma	> 27 kbar, 800°C	1. Inclusions of coesite in zircon
Chuacus Complex, northern Guatemala	Eclogite Banded gneiss	48–72 Ma (retrograde)	20–30 kbar, 700–800°C	1. Coesite pseudomorph in garnet and kyanite
Rhodope Massif, Greece	Eclogite Orthogneiss Pelitic gneiss Ultramafic rocks	30–42 Ma (peak) 8–12 Ma (retrograde)	> 30 kbar, ~1200°C	1. Microdiamond inclusion in garnet porphyroblast 2. Silica, rutile and apatite rods in garnet
Lanterman Range, Antarctica	Eclogite Felsic gneiss	500 Ma (peak) 486–490 Ma (retrograde)	> 29 kbar, > 850°C	1. Inclusions of coesite and its pseudomorph in garnet
Western Tian-Shan, northwest China	Eclogite Marble	< 310 ± 5 Ma (peak)	26–27 kbar, 500–600°C	1. Inclusions of coesite and its pseudomorph in garnet. 2. Possible coexistence of magnesite + aragonite
Qaidam, western China	Eclogite Gneiss Garnet peridotite	495 ± 7 Ma (peak) 467 ± 1 Ma (retrograde)	> 27 kbar, 700°C	1. Inclusions of coesite in zircon from paragneiss
Altun Mountains, western China	Eclogite Grt-lherzolite	504 ± 5 Ma (peak)	28–32 kbar, 820–850°°C	1. Coesite pseudomorph in garnet
North Qinling Mtns., Central China	Eclogite Gneiss	507 ± 38 Ma 400 ± 16 Ma	> 26 kbar, 590–760°C	1. Coesite in garnet 2. Microdiamond in zircons from eclogite and gneiss
Kaghan valley, Pakistan Himalayas	Eclogite Gneiss	46 ± 1 Ma (peak) 44 ± 1 Ma (retrograde)	27–29 kbar, 690–750°C	1. Inclusions of coesite and its pseudomorph in omphacite and zircon from eclogite and in zircon from gneiss
Tso Morari, Indian Himalayas	Eclogite Gneiss	55 Ma (peak) 47 Ma and 30 Ma (retrograde)	> 28 kbar, 700–800°C	1. Inclusions of coesite and its pseudomorph in garnet from eclogite

SHRIMP dating of zircons extracted from gneiss, schist, pyrope inclusion, and pyrope quartzite indicates the occurrence of 240–275 Ma old zircon cores and newly formed 35 Ma rims for some zircons (Gebauer et al., 1997). Thus, UHP metamorphism must have taken place during Oligocene time, with an estimated exhumation rate of 2 to 2.4 $cm \cdot yr^{-1}$.

Western Gneiss Region, Norway. The Western Gneiss Region lies within an Early Paleozoic collision zone; the gneissic unit, about 300 km long and 150 km wide, consists of interlayered pelite and migmatite, marble, quartzite, and amphibolite, with tectonic inclusions of gabbro and peridotite (for a recent review see Carswell and Cuthbert, 2003). The gneissic unit exhibits mainly amphibolite-facies assemblages, but relics of HP assemblages also occur. Eclogite boudins are widespread. Coesite was first reported from Grytting (Smith, 1984); several new localities of coesite and coesite pseudomorphs have been recognized recently in both eclogites and the adjacent gneissic rocks (Wain, 1997; Cuthbert et al., 2000; Wain et al., 2000; Carswell et al., 2003). Microdiamond grains 20–50 microns across have been described from residues separated from two gneisses (Dobrzhinetskaya et al., 1995); the associated kyanite-eclogites contain inclusions of coesite pseudomorphs in garnet. Relict majoritic garnets showing exsolution of pyroxene lamellae in peridotite bodies have been recently discovered on the islands of Otrogy and Flemsoy (van Roermund and Drury, 1998; van Roermund et al., 2000). These peridotite bodies originally must have had an even higher-pressure, deeper-mantle origin, probably within a rising mantle diapir at ~1700 Ma. In these garnet peridotites, diamond inclusions in sympletetic spinel after garnet have been discovered (van Roermund et al., 2002). Radiometric ages for eclogites of the Western Gneiss Region are 408–425 Ma for the peak metamorphism, and 374–378 Ma for the retrogressive mid-crustal metamorphic overprinting (for review, see Carswell et al., 1999). Carswell et al. (2003) provide new petrographic evidence and a review of the latest radiometric age data, and conclude that the UHP metamorphism of eclogites occurred at 400–410 Ma, significantly younger than the previous, widely accepted age of 425 Ma. A two-stage exhumation process is suggested: an initial exhumation to about 35 km depth by about 395 Ma at a mean rate of about 10 $m \cdot Ma^{-1}$, and subsequent exhumation to 8–10 km by about 375 Ma at a much slower rate of about 1.3 $m \cdot Ma^{-1}$.

The suture zone occupied by UHP/HP rocks of the Western Gneiss Region reflects collision of the eclogite-bearing Greenland sialic crust-capped lithospheric plate with Fennoscandia during the Caledonian orogeny (Gilotti, 1993; Krogh and Carswell, 1995; Brueckner and Medaris, 1998). Inclusions of coesite pseudomorph in garnet and omphacite from kyanite eclogites have been recently documented in the East Greenland eclogite province (Gilotti and Ravna, 2002); this new UHP/HP terrane is remote, but has excellent exposures and requires close examination.

Dabie-Sulu terrane of east-central China. The Dabie-Sulu terrane occupies a Triassic collision zone between the Sino-Korean and Yangtze plates (for a recent review, see Hirajima and Nakamura, 2003). The central UHP coesite-bearing eclogite belt (P = 2.7–5 GPa) is flanked to the north by a migmatite zone (P < 2 GPa), and to the south by a belt of blueschist, epidote amphibolite, and eclogite-facies rocks (P = 0.5–1.2 GPa). Prevalent rock types include felsic gneiss, orthogneiss, marble, and quartzite. Protolith ages range from Proterozoic to Ordovician, but the majority of reported ages are Neoproterozoic (Li et al., 1993; Hacker et al., 2000). Blocks, boudins, and layers of eclogites and garnet peridotites occur as enclaves in gneisses in the UHP unit. The Dabie-Sulu UHP rocks show several characteristics. (1) Widespread coesite with hydrous minerals such as talc, zoisite/epidote, and phengite occur in eclogites. (2) Two distinct types of mantle- and crustal-derived garnet peridotites are present. (3) Abundant exsolution textures were identified in UHP minerals from garnet peridotite and eclogite. (4) Diamond separates from both eclogite and garnet peridotite have been reported from few restricted regions (e.g., Xu et al., 1992, 2003). Some of these findings are not confirmed by thin-section observation and extensive studies of mineral inclusions in zircon (for review, see Liou et al., 2002). (5) Some garnet peridotites record much higher pressure than associated coesite-bearing eclogites, reaching 5–6 GPa (Yang et al., 1993; Zhang R. Y. et al., 2000, 2003). (6) Various isotopic age dating methods for UHP minerals and rocks from Dabie-Sulu terrane gives 220–240 Ma (Li et al., 1993; Hacker et al., 2000).

Eclogites in the Huwan shear zone from the northwestern Dabie Mountains have SHRIMP U/Pb dates of 309 ± 3 Ma (Sun et al., 2002) suggesting a discrete Carboniferous subduction/collision between North and South China. Farther to the west in North Qinling, inclusions of microdiamond were discovered in zircons from both eclogite and its gneissic country rocks (Yang et al., 2002a); SHRIMP U/Pb dating of zircons from granitic gneiss yielded 507 ± 38 Ma for metamorphic rims and 1200–1800 Ma for relic magmatic or old cores, suggesting an Early Paleozoic UHP metamorphic event. These new data suggest that episodic subduction and collision of continents occurred during stages of closures of paleo Tethys prior to the well-documented major Triassic continent-continent collision for the Dabie-Sulu terrane.

Kokchetav massif. The Kokchetav massif, northern Kazakhstan, is the type site for the UHP diamond-eclogite regional metamorphic facies (Sobolev and Shatsky, 1990; Parkinson et al., 2002; Shatsky and Sobolev, 2003). Diamonds occur as minute inclusions in garnet, diopside, and zircon porphyroblasts in marble, pyroxene-carbonate-garnet rock, and garnet-biotite gneiss and schist. Inclusions of coesite and coesite pseudomorphs occur in garnet and zircon from eclogite and diamond-bearing gneiss. The UHP/HP unit extends NW-SE for at least 80 km, and is about 17 km wide. The UHP slab is structurally overlain by a weak- to low-grade metamorphic unit and is underlain by a low-P metamorphic andalusite-staurolite facies unit (Kaneko et al., 2000). The UHP slab is composed of felsic gneiss with locally abundant eclogite lenses and minor orthogneiss, metacarbonate, and rare garnet peridotite, with a range of Proterozoic protolith ages. A well-constrained P-T-time path deduced from mineral inclusions and SHRIMP geochronology of zircons is illustrated in Figure 4. Zoned zircons from diamond-bearing gneiss yield the following ages: a quartz-bearing inherited core with 1100–1400 Ma as the protolith age, coesite-bearing mantle with 537 ± 9 Ma for UHP metamorphism, and the plagioclase-bearing rim with 507 ± 8 Ma for amphibolite-facies overprint (Katayama et al., 2001). Many diamond-grade marbles contain clinopyroxene with exsolution lamellae of quartz, K-feldspar, phengite, and phlogopite (Katayama et al., 2002; Zhu and Ogasawara, 2002), and titanite with coesite lamellae (Ogasawara et al., 2002); these occurrences suggest that UHP metamorphism occurred at $P > 6$ GPa and 1000°C.

C^{-13} isotopic data of diamond suggest biogenic sources; inclusions of water, carbonate, and nanometric oxide in diamonds indicate that metamorphic microdiamonds in this and other UHP terranes were precipitated from C-O-H supercritical fluids (e.g., Stockhert et al., 2001). Ogasawara et al. (2002) further suggested a two-stage growth mechanism for microdiamonds. Masago et al. (2003) reported negative ^{18}O values (-3.9 per mil) for minerals in eclogite and whiteschist of the Kokchetav Massif, similar to the Chinese UHP rocks first described by Yui et al. (1995). The Kokchetav Massif is the second recognized UHP region that preserves a significant effect of the interaction of cold meteoric water with the protolith prior to subduction.

Saxonian Erzgebirge, Germany. The Erzgebirge Crystalline Complex (ECC) at the northern margin of the Bohemian massif is in fault contact with a low-grade Paleozoic sequence at its margins (for a recent review, see Massonne and O'Brien, 2003). The Variscan ECC consists of abundant gneisses that include numerous lenses of eclogites. The "Gneiss-Eclogite Unit" at the core of this massif contains UHP rocks typified by inclusions of coesite pseudomorph in garnets from eclogite (Schmadicke, 1991) and inclusions of microdiamonds in garnet, kyanite, and zircon from gneisses (Massonne, 1999). Thus far, the diamondiferous gneisses seem to occur only in a 1 km long strip near the eastern shore of the Saidenbach Reservoir. Diamond micro-inclusions occur exclusively in garnet, kyanite, and zircon of several gneissic rocks. Besides completely preserved diamonds with grain sizes between 1 to 25 μm, partially graphitized diamonds and graphite pseudomorphs after diamond occur. Such microdiamond inclusions in garnet and zircon are similar to those in Kokchetav diamondiferous biotite gneiss. Some of these inclusions contain additional fluid-bearing phases including apatite, phengitic mica, and possible fluid inclusions; the morphologies of inclusions and mineral associations suggest that microdiamonds from both the Erzgebirge and the Kokchetav were crystallized from supercritical fluids under UHP conditions (Stockhert et al., 2001; Hwang et al., 2001; Dobrzhnetskaya et al., 2001, 2003).

Schmadicke et al. (1995) reported Sm-Nd isochrons for garnet-Cpx-WR at 360 ± 7 Ma for eclogite and 353 ± 6 Ma for garnet pyroxenite from Erzgebirge UHP rocks. $^{40}Ar/^{39}Ar$ spectra of phengite from two eclogite samples give plateau ages of 348 ± 2 and 355 ± 2 Ma. Diamond-bearing zircons yield SHRIMP U/Pb dates at 336 ± 2 Ma (Massonne, 2001). Such similarity in ages for garnet peridotites and eclogite enclosed in gneiss suggests a coeval Variscan UHP in-situ metamorphism of the ECC around 340–360 Ma.

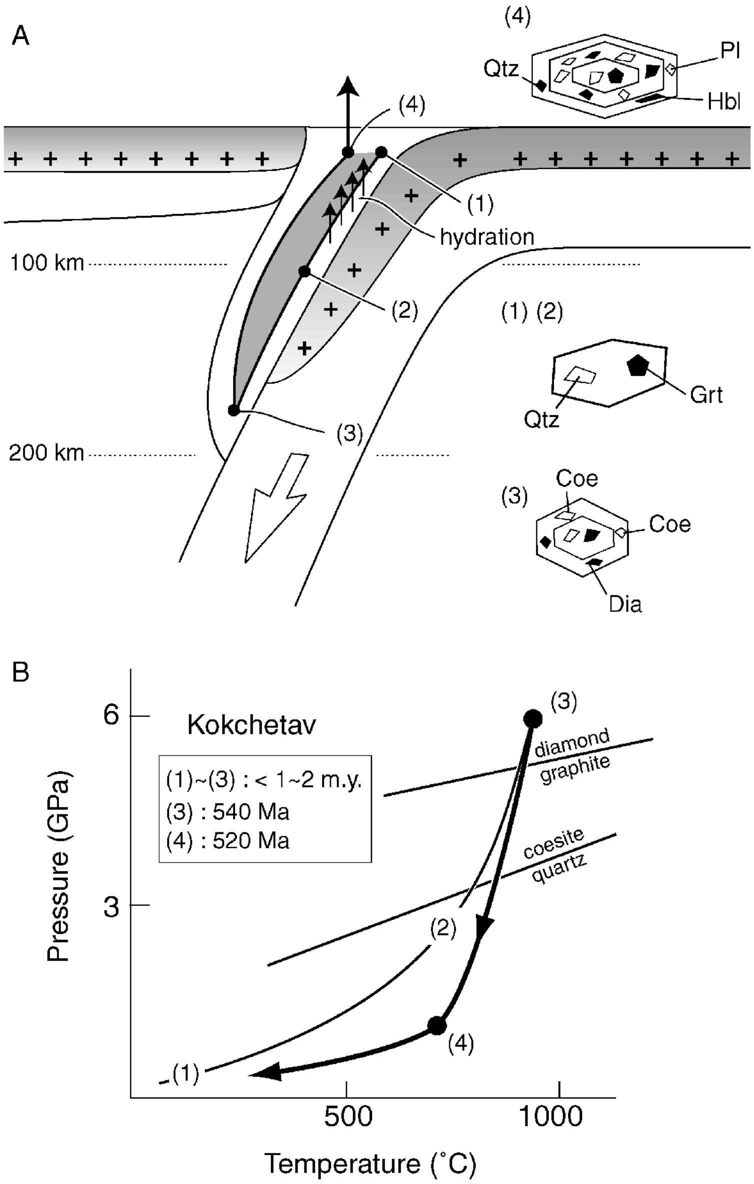

FIG. 4. A. Schematic diagram showing the growth of detrital zircon (stage 1) through subduction (stage 2 and peak stage 3) and exhumation (stage 4) of supracrustal rocks. Mineral inclusions in various stages of zircon growth are shown. B. SHRIMP U-Pb dating of zoned zircons from a Kokchetav diamond-bearing gneiss yields a well constrained P-T-time path (for details, see Katayama et al., 2001).

Less Intensively Studied UHP terranes

Several UHP terranes described below, except for the Maksyvtov Complex, have received less intensive study mainly due to remoteness and difficult access, despite their long recognition.

Maksyutov Complex, Southern Urals. The Maksyutov Complex is an elongated (10 × 120 km) N-S belt between the Russian and Siberian cratons in the southern Ural Mountains (Coleman and Wang, 1995; Dobretsov et al., 1996), and contains blocky graphitized diamond(?) in pelitic schist (Leech and Ernst, 1998). The complex is the locality from which quartz aggregates within garnet exhibiting radial cracks were first recognized as coesite-pseudomorphs by Chesnokov and Popov (1965), nearly 20 years prior to the independent finding of coesite inclusions by Chopin (1984) and Smith (1984). The eclogite-bearing unit contains boudins of eclogite, layers of eclogitic gneiss, and rare ultramafic bodies within host metasedimentary mica schist and quartzite.

Some Maksyutov eclogites were recrystallized at 594–637°C with a minimum pressure from 1.5 to 1.7 GPa (Beane et al., 1995; Leech and Ernst, 1998) or up to 2.7 GPa if coesite pseudomorphs (Chesnokov and Popov, 1965; Dobretsov and Doretsova, 1988) are indeed present. However, subsequent studies have not revealed the occurrence of inclusions of coesite or coesite pseudomorph in garnet and zircon (Beane et al., 1995; Shatsky et al., 1995). Leech and Ernst (1998) described unusual graphite aggregates (up to 13 mm edge length) that may be diamond pseudomorphs. This suggestion was based on the blocky morphology of the cuboid graphite aggregates cross-cutting rock foliation, pressure shadows, biogenic isotopic signatures, and other spectroscopic characters similar to those graphitized diamonds from the Beni Bousera massif. Recent study of several microdiamond inclusions in garnet has yielded further suggestive possibility that the eclogitic unit of the Maksyutov Complex experienced diamond-grade UHP metamorphism (Bostick et al., 2003). The UHP/HP metamorphism with peak metamorphic ages of 370–374 Ma (Shatsky et al., 1995; Beane and Connelly, 1998) may be related to the collision of the Russian platform with a fragment of the Siberian craton during Devonian time, but was affected by the Triassic collision of the Kazakhstan block with the Russian platform (e.g., Matte, 1998).

Zermatt-Saas area, Western Alps. In contrast to most other UHP terranes in which the protolith is continental crust, eclogites and metasediments at Lago di Cignana of the Western Alps were derived from oceanic crust and constitute the ophiolite sequence of the Zermatt-Saas zone. Inclusions of coesite and coesite pseudomorphs occur in tourmaline and garnet of manganiferous quartzite, and in omphacite and garnet of the underlying mafic eclogite (Reinecke, 1991). The metasediments are mainly garnet-phengite-quartz schist, with variable amounts of garnet-clinopyroxene quartzite, and piedmontite-phengite-quartz schist. Eclogites and retrograded eclogites with preserved UHP mineral parageneses consist of garnet, omphacite, glaucophane, zoisite, phengite, and dolomite. Zoned garnets preserve prograde quartz crystals in their cores and coesite inclusions in mantles and rims. Coesite inclusions are much more common in omphacite than in garnet. UHP conditions were estimated at 2.6–3.0 GPa and 590–630°C. Sm-Nd isotopic analyses of eclogites yield UHP metamorphism at 52 ± 18 Ma (Bowtell et al., 1994), consistent with a Tertiary age of eclogitization recently established for Alpine metamorphism in the Western Alps (Gebauer et al., 1997).

Thus far, the recognized areal extent of the coesite-bearing rocks is ~ 2 km^2. The apparent thickness of the UHP slice does not exceed a few hundred meters. This area is the best example for subduction of oceanic lithosphere to mantle depth, and later exhumation as a fragmented tectonic slab. Similarly, the Allalin metagabbro, part of the oceanic Piemonte zone, contains magnesite + talc + kyanite + garnet recrystallized at ~600°C and 3.5 GPa, with an estimated geothermal gradient of 5–6°C·km^{-1}; however, inclusions of coesite or coesite pseudomorphs have not been reported from the Allalin metagabbro.

Mali, Africa. Eclogitic rocks in the Pan-African collision zone cropping out in northern Mali contain inclusions of coesite in omphacite from mafic nodules within a calc-silicate layer enclosed in impure marble, and coesite pseudomorphs in garnets from the surrounding eclogitic metasediments (Caby, 1994). These UHP eclogitic mica schists have P-T estimates of 700–750°C and > 2.7 GPa; phengite yields a well-defined plateau ^{39}Ar/^{40}Ar age of 1045 ± 9 Ma. Recent Sm/Nd ages of 620 Ma were obtained by Jahn et al. (2001) for peak UHP metamorphism. This may be the oldest UHP terrane in the world.

The coesite-bearing UHP eclogitic unit about 3 km thick lies within an internal nappe as a flat, thin slice bounded on the top by a thick passive-margin shaly formation, and on the bottom by low-grade greenschist-facies phyllites. Caby (1994) suggested that a large portion of the terrigenous metasediments of passive-continental-margin affinity of the West African plate was subducted eastward to mantle depths (>90 km) beneath an oceanic domain. Collision of the West African plate with an island arc resulted in a low-angle, westward subhorizontal extrusion of this subducted slice of sialic materials to its present position. The coesite-bearing eclogite unit may also crop out 1500 km to the south in Togo, where kyanite-bearing eclogites occur as part of the passive-margin assemblage.

Makbal (480 Ma) and Atbashy (270 Ma), Kazakhstan. The Tian-Shan is divided into three mountain ranges—northern, middle, and southern. Within the Kyrgyzstan Tian-Shan, UHP eclogite localities with coesite pseudomorph inclusions in garnet and omphacite from the northern and southern Tian-Shan represent Caledonian and Hercynian orogenic belts, respectively (Tagiri and Bakirov, 1990; Tagiri et al., 1995). The Makbal Formation in the western Kyrgyz Ridge of the northern Tian-Shan consists of quartzose schist alternating with pelitic schists intercalated with thin layers or lenses of marble, eclogite, and amphibolitized eclogite. Tagiri and Bakirov (1990) found inclusions of coesite pseudomorphs in garnet from a garnet-chloritoid-talc schist with a peak metamorphic assemblage of coesite + almandine + chloritoid + talc + phengite (Si = 3.42 p.f.u) + phlogopite + rutile. Makbal coesite-grade eclogite has a paragonite K/Ar age of 480 Ma.

The eclogite-bearing complex of Atbashy Ridge from the southern Tian-Shan is composed of pelitic and siliceous schists alternating with thin UHP eclogitic layers, and is unconformably overlain by Upper Paleozoic molasse and silicic volcanic rocks. Inclusions of coesite pseudomorphs occur in omphacite cores and in garnet. Eclogites from the Atbashy area preserve prograde and retrograde paths with a peak metamorphic condition at 660°C, 2.5 GPa. The Atbashy coesite-eclogites yielded a Rb/Sr mineral isochron age of 270 Ma (Tagiri et al., 1995).

Central Indonesia UHP terrane. The pre-Tertiary basement of the Indonesian region comprises a variety of imbricate terranes, mélange, ophiolite, and variably metamorphosed accretionary complexes; some contain HP to UHP metamorphic rocks resulting from the collision of an Australia-derived continent with Eurasia (Parkinson, 2003). HP rocks including eclogites and garnet peridotites are widely distributed in Cretaceous accretionary complexes. Many of these rocks occur as imbricate slices of carbonate, quartzite, and pelitic schist of shallow-marine or continental-margin parentage, interthrust with subordinate mafic schist and serpentinite; some yield mica K/Ar ages of 110–120 Ma (Parkinson, 2003).

HP and UHP rocks are sporadically exposed as tectonic blocks throughout the Cretaceous accretionary complexes. They include eclogite, garnet-glaucophane rock (P = 1.8–2.4 GPa, T = 580–620°C), and jadeite-garnet quartzite (P > 2.7 GPa, T = 720–760°C) in Bantimala, southwest Sulawesi, eclogite and garnet granulite in west-central Sulawesi, eclogite and jadeite-glaucophane-quartz rock (P ~2.2 GPa, T ~530°C) in central Java, Mg chloritoid–bearing whiteschists (P ~1.8 GPa) in southeast Kalimantan, garnet lherzolites in east-central Sulawesi (P = 2.2–2.8 GPa, T = 1000–1100°C), west-central Sulawesi (P = 1.6–2.0 GPa, T = 1050–1100°C), and garnet pyroxenite (P ~2 GPa, T ~ 850°C) in Sabah, northeast Borneo. Evidence for UHP rocks include: (1) inclusions of coesite in zircon and coesite pseudomorphs in jadeite from jadeite quartzite and eclogite of the Bantimala Complex of south Sulawesi (Parkinson, 2003); and (2) P-T estimates of peak-stage recrystallization at 2.7–3.5 GPa and 1000–1100°C for most garnet peridotites (Kardarusman and Parkinson, 2000). Many of these rocks were probably recrystallized in a N-dipping subduction zone at the margin of the Sundaland craton in the Early Cretaceous. Exhumation may have been facilitated by the collision of a Gondwana continental fragment with the Sundaland margin at ~120–115 Ma.

Recently Recognized UHP Terranes

Several new UHP terranes were recently identified, inasmuch as they contain partially preserved trace index minerals in strong containers such as zircon or garnet. In fact, zircon has been considered to be the best container and many new terranes were discovered through positive identification of inclusions of coesite or coesite pseudomorphs, or diamond in zircons. Detailed examination of mineral inclusions in core, mantle, and rims of zircon separates from eclogites and their enclosing country-rock gneisses have yielded both prograde and retrograde P-T-time paths for various UHP terranes mentioned above (see Katayama et al., 2001 for details; also see the section on the Himalayan eclogite for an example).

The latest recognized UHP terranes include the following: (1) coesite in the French Massif Central (Lardeaux et al., 2001); (2) coesite and diamond from the Greek Rhodope metamorphic province (Mposkos and Kostopoulos, 2001); (3) coesite pseudomorphs in the Northeast Greenland Eclogite Province (Gilotti and Ravna, 2002); (4) coesite in granulite-facies overprinting eclogites of Southeast Brazil (Parkinson et al., 2001); (5) coesite in Himalayan eclogite from the Upper Kaghan Valley, Pakistan (O'Brien et al., 2001; Kaneko et al., 2003) and coesite from the Tso-Morari crystalline complex of India (Mukherjee et al., 2003); (6) coesite inclusions in gneissic rocks from the North Qaidam belt, western China (Yang et al., 2001; Song et al., 2003); (7) diamond inclusions in garnets of eclogite and gneiss from North Qinling (Yang et al., 2002a); (8) inclusions of quartz pseudomorphs and minor coesite in garnets of mafic eclogites from the Lanterman Range in Antarctica (Ghiribelli et al., 2002); (9)

inclusions of calcite pseudomorphs after aragonite + magnesite in dolomite in metapelites from the western Tian-Shan inferred as metamorphism in a UHP region of dolomite decomposition (Zhang L. et al., 2002); and (10) inclusion of possible coesite pseudomorphs in garnet, lamellar inclusions in garnet, kyanite, and high sodium content of garnet from eclogites of the Chuacus Complex of north-central Guatemala (Solari et al., 2003). The results of petrochemical and geochronological data for these new terranes are summarized below. The Himalayan UHP terrane in the Upper Kaghan Valley and the Tso-Morari complex are used to illustrate the processes of continental subduction and collision in a later section.

French Massif Central. The French Massif Central in the western part of the Variscan Belt has experienced Late Silurian–Early Devonian to Late Carboniferous orogenic events (e.g., Matte, 1986). High-pressure metamorphic rocks occur mainly in the upper gneissic unit within the leptyno-amphibolite group. The latter consists of an association of metagreywacke, mica schist, metabasalt, leptynite, metagranite, and peridotite. Eclogites are associated with silicic and mafic HP granulites (Lardeaux et al., 2001) and also with spinel and/or garnet lherzolites (Gardien et al., 1990). Inclusions of coesite and coesite pseudomorphs occur in garnets of kyanite-bearing eclogite (Lardeaux et al., 2001). Only two coesite grains are preserved as relics; most coesite grains are completely transformed into polycrystalline radial quartz (palisade texture) or into polygonal quartz surrounded by radial cracks. Metamorphic temperatures were estimated to be 740-780°C, and subsequent amphibolite-facies overprinting at 750°C at 1.5–1.7 GPa during decompression. UHP metamorphism occurred between 420 and 400 Ma (Paquette et al., 1995); $^{40}Ar/^{39}Ar$ data from amphibole separates from retrogressed eclogites yielded 339 ± 4 Ma (Costa et al., 1993).

Northeast Greenland Caledonides. The first evidence for UHP metamorphism in the Greenland Caledonites was reported from kyanite eclogites and associated host gneisses on an island in Jokelbugt (Gilotti and Ravna, 2002). Inclusions of quartz pseudomorphs exhibiting palisade structure and radiating fractures occur in garnet and omphacite of eclogites and in garnet of the host gneisses. P-T estimates of peak-stage metamorphism of eclogite at ~972°C and 3.6 GPa lie well within the coesite stability field. SHRIMP U/Pb dates of 403 ± 5 Ma for zircon rims from HP metapsammite and 404 ± 4 Ma for zircons from anatectic melt derived from metapelite are coeval with the estimated ages of exhumation of UHP terranes in the Scandinavian Caledonides described in a previous section (McClelland and Gilotti, 2003).

Neoproterozoic nappes in Southeast Brazil. Neoproterozoic nappes of Southeast Brazil consist mainly of coarse-grained kyanite-garnet granulite with intercalations of impure quartzite, calc-silicate rock, and minor lenses and sills of mafic-ultramafic rocks, including eclogite. Early eclogitic phases were strongly obliterated during granulite-facies overprinting during a major Pan-African continent collision at 640–630 Ma (Campos Neto and Caby, 1999). Rare ultramafic lenses consist of phlogopite-orthopyroxene rocks and garnet clinopyroxenite. Cores of granulite boudins retain eclogitic assemblages; some quartz inclusions within the mantle regions of zoned garnet porphyroblasts are surrounded by intense radial fractures, suggestive of the former presence of coesite. In fact, coarse-grained zircons in some granulites contain numerous micro-inclusions of K-feldspar + kyanite + coesite, as confirmed by Raman spectroscopy (Parkinson et al., 2001). Many exsolution microstructures observed in other UHP terranes also occur. This area represents the first coesite-grade UHP rocks in the Americas, and it can be correlated with the Mali UHP terrane of equatorial Africa (Caby, 1994). It has been suggested that eclogitic assemblages and probable UHPM components may be present in several other correlative nappe systems at the margins of the Sao Francisco craton in Brazil.

Chuacus Complex, north-central Guatemala. HP eclogites within banded gneisses, schists, and migmatites of the Chuacus Complex contain relict textures and mineralogical features that suggest UHP metamorphism (Solari et al., 2003). These include inclusions of possible coesite pseudomorphs in garnet and kyanite, lamellar inclusions of rutile/ilmenite in garnet, high sodium content of some garnets (up to 1200 ppm), and preliminary P-T estimates of 700–800°C, and 2–3 GPa. Although K-Ar dating of mica and hornblende yield ages of 48–72 Ma possible for amphibolite facies retrogression, regional and structural data support a pre-Mesozoic age for the multi-stage HP-UHP recrystallization. Such a discovery opens up a new interpretation regarding the tectonic evolution of Maya-Chortis-Oaxaquia microcontinental blocks forming the structural backbone of Mesoamerica.

Greek Rhodope. The Greek Rhodope Metamorphic Province (RMP) at the border between Greece and Bulgaria represents a syn-metamorphic nappe system of Alpine age that was formed during the Cretaceous to Mid-Tertiary collision of Apulia and paleo-Europe. The Kimi nappe complex comprises crustal eclogites, leucocratic orthogneisses, pelitic gneisses, and volumetrically minor mantle-derived ultramafic rocks; these units contain many mineralogical indicators of UHP metamorphism (Mposkos and Kostopoulos, 2001). The ultramafic lithologies include garnet spinel–bearing lherzolite and layers of spinel-garnet clinopyroxenite, garnet pyroxenite, and clinopyroxene garnetite. These rocks were subjected to UHP recrystallization at P-T conditions of ~1200°C and >3.0 GPa. The pelitic gneiss contains microdiamond inclusions in garnet porphyroblasts as well as rods or needles of silica, rutile, biotite, and apatite in sodic garnet, suggesting the prior occurrence of majoritic garnet. The growth of such supersilicic garnet was suggested to be at a pressure of ~7 GPa. Inclusions of polycrystalline quartz aggregates surrounded by radial cracks occur in eclogitic garnet. Exsolution lamellae of quartz in eclogitic clinopyroxene also indicate an UHP precursor of supersilicic clinopyroxene.

Lanterman Range, Antarctica. The Lanterman Range in northern Victoria Land of Antarctica consists of several metamorphic complexes. The Gateway Hills Metamorphic Complex is a thin discontinuous belt more than 50 km long, consisting of mafic and ultramafic rocks including lenses and pods of eclogite within felsic gneiss. Some less foliated eclogites contain inclusions of coesite and coesite pseudomorphs in garnet porphyroblasts as confirmed by *in situ* Raman spectroscopy, as well as radial fractures around the inclusions (Ghiribelli et al., 2002). The eclogites were subjected to UHP metamorphism at T > 850°C and P > 2.9 GPa, then amphibolite-facies overprinting during isothermal decompression. The UHP event is dated by Sm/Nd and $^{238}U/^{206}Pb$ data at 500 Ma, $^{40}Ar/^{39}Ar$ ages of 490–486 Ma for Ca-amphibole (amphibolite-facies overprinting) suggest rapid cooling, with an average exhumation rate of 3–4 km_Ma^{-1} for the UHP terrane (Di Vincenzo and Palmeri, 2001).

Western Tian-Shan, China. Caledonian eclogites of the western Tian-Shan, China have been classified into three types (Zhang L. et al., 2002). Type I eclogite pods are layered with mafic blueschists and Type II eclogites preserved pillow structures, whereas Type III eclogites are banded with marbles. This 200 km long eclogite-bearing belt extends westward to connect with the Atbashy UHP belt in Kazakhstan (Tagiri et al. 1995). Reported UHP evidence includes inclusions of coesite pseudomorphs in garnets from Type I and III eclogites, quartz exsolution lamellae in omphacite from Type II eclogites, and relict magnesite within matrix dolomite in Type III eclogites (Zhang, J. X. et al., 2002; Zhang L. et al., 2002). P-T estimates of the peak UHP stage of metamorphism are T = 500–600°C and P = 2.6–2.7 GPa (Wei et al., 2003).

North Qaidam Mountains, western China. Many lenses and layers of garnet peridotite and eclogite occur in an amphibolite-facies terrane in the North Qaidam Mountains along the northeastern rim of the Qaidam Basin. This belt comprises mainly felsic gneiss, quartz schist, garnet-bearing gneiss, amphibolite, and minor eclogite + garnet peridotite; it extends westward for more than 1000 km to the Altun Mountains and was displaced by the left-lateral Altyn-Tagh fault. At the eastern end of this UHP belt at Dulan, occurrences of coesite inclusions in zircon separates from paragneiss, inclusions of coesite pseudomorph in garnet and omphacite of eclogites, quartz rods in eclogitic omphacite, and P-T estimates of eclogites (P = 2.87–3.17 GPa, and T = 631–687°C) demonstrate that this is a typical UHP metamorphic terrane (Yang et al., 2001; Song et al., 2003a, 2003b). The Dulan eclogites have an Sm-Nd mineral isochron age of 497 ± 87 Ma and a SHRIMP U/Pb zircon age of 495 Ma (Yang et al., 2002b).

Altun Mountains, western China. This UHP terrane, about 200 km long in the southern margin of the Altun Mountains, is the western extension of the North Qaidam belt. Eclogitic lenses and blocks of various sizes together with garnet-lherzolite and clinopyroxenite are enclosed within an Early Proterozoic sequence of amphibolite, amphibole schist, garnet-bearing granitic gneiss, and pelitic schist. Garnet lherzolite contains magnesite that reacted to form dolomite; P-T estimates of the peak magnesite-bearing assemblage yield P > 3.6 GPa and 850°C (Liu et al., 2001). Garnet porphyroblasts include exsolution lamellae of clinopyroxene and rutile similar to that of eclogite reported by Ye et al. (2000) as majoritic garnet. The associated eclogites contain inclusions of coesite pseudomorphs in garnet with characteristic radial fractures; this together with the exsolved quartz rods in omphacite and P-T estimates of 820–850°C and 2.8 to 3.2 GPa provide additional evidence for UHP (Zhang J. X. et al.,

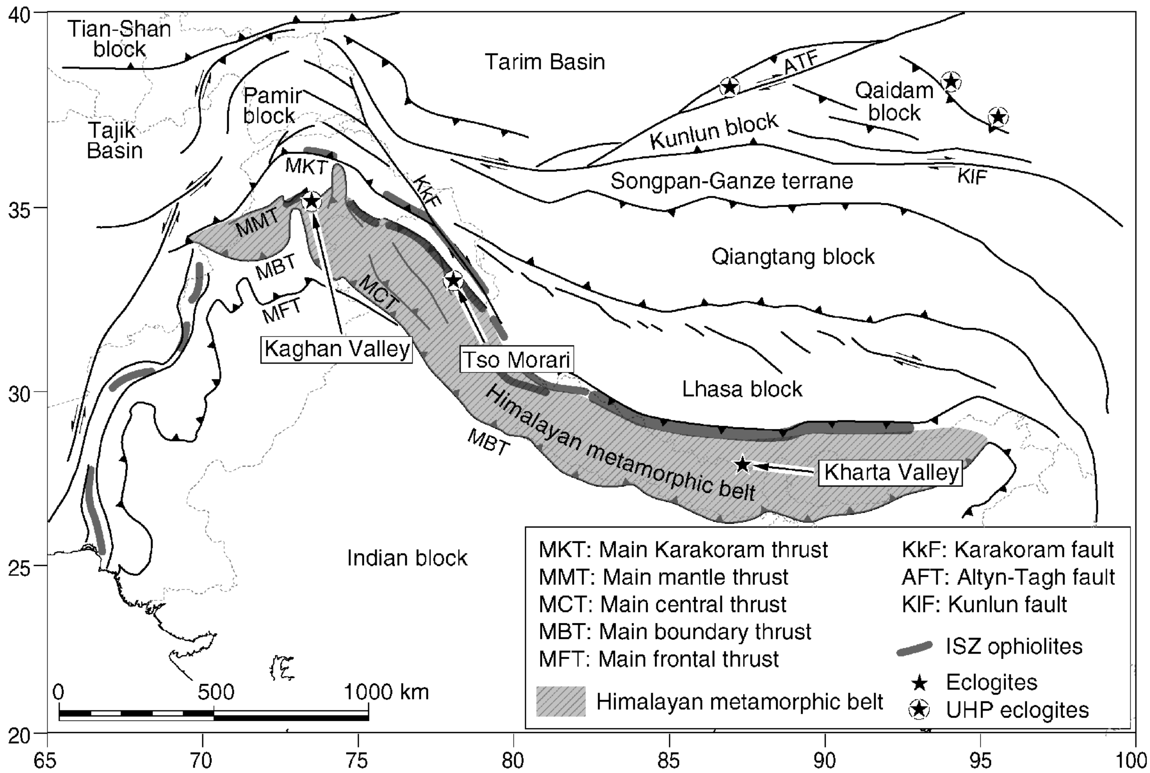

FIG. 5. A simplified tectonic map of the western Himalaya, Hindu Kush, Pamir, Karakoran, and western Tibet modified after Figure 3 of Searle et al. (2001). This map shows the locations of eclogite and UHP eclogites from both Himalayan and North Qaidam, Indus Suture Zone (ISZ) ophiolites and major structures.

2001). An Sm/Nd mineral isochron for eclogitic garnet, omphacite, and the whole rock yields 500 ± 10 Ma, whereas an U/Pb isochron for zircon separates from eclogite gives an age of 504 ± 5 Ma (Zhang J. X. et al., 2000).

North Qinling Mountains, central China. Lenses and blocks of eclogitic rocks in northern Qinling are enclosed in amphibolite-facies gneiss and garnet-bearing quartz + phengite mica schist. Inclusions of coesite in eclogitic garnet (Hu et al., 1995) and microdiamonds in zircon separates from both eclogite and gneiss (Yang et al., 2002a) have been recently reported. Although individual outcrops are no more than a few meters wide, the belt of eclogites extends more than 10 km. P-T estimates of amphibolitized, coesite-bearing eclogite yield T = 590–758°C and P > 2.6 GPa. An Sm-Nd isochron for garnet, omphacite, rutile, amphibole, and whole-rock yields 400 ± 16 Ma. Microdiamonds were recently discovered as inclusions in zircon from both eclogite and its gneissic country rocks (Yang et al., 2002a); SHRIMP U/Pb dating of zircons from granitic gneiss yields 507 ± 38 Ma for peak UHP metamorphism (Yang et al., 2002a). These data indicate that two discrete collision events occurred between the North China and Yangtze cratons: (1) an Early Paleozoic North Qinling UHP suturing; and (2) a Triassic suturing along the Dabie-Sulu UHP-HP belt. The Early Paleozoic belt extends westward to the North Qaidam–Altun Mountains for more than 4000 km (Yang et al., 2002b).

Himalayan UHP Eclogites

The Himalayan orogen has long been considered a classic locality of continental collision between the Indian and Eurasian continents (Fig. 5). Several eclogite-facies HP rocks in the Himalayas have been reported since the late 1980s (e.g., Chaudary and Ghazanfar, 1987; Pognante and Spencer, 1991; de Sigoyer et al., 1997; Lombardo and Rolfo, 2000). Inclusions of coesite were recently discovered in omphacite and garnet in several Himalayan eclogites from the upper Kaghan Valley, Pakistan (O'Brien et al., 2001; Kaneko et al., 2003). Subsequent findings of additional coesite localities in the Tso Morari area (Sachan et al., 2001; Mukherjee et al., 2003) have established the presence of a UHP belt in the Himalayas, an active ongoing collision since the Eocene (Massonne and O'Brien, 2003). However, UHP relics are volumetrically very minor constituents of the metamorphic belts dominated mostly by later Barrovian overprintings. In these rocks, hydration related to Barrovian-zone metamorphism has resulted in remarkably pervasive recrystallization during the later exhumation; this event has almost entirely masked the preceding UHP record.

The finding of HP-UHP evidence has led to new insights into the Himalayan tectonic model. England and Houseman (1986) showed that, in a model of homogeneous thickening of the Himalayan-Tibet boundary, the maximum crustal thickness should be less than 70 km. However, the occurrences of coesite-bearing eclogites and gneisses in the Himalayan orogen cannot be explained by a homogeneous thickening of the crust, but rather by continental subduction as described below. According to available geochronological data, (e.g., Treloar et al., 2003) the exhumation rate of the Himalayan UHP rocks has been estimated to range from ~1 $cm \cdot yr^{-1}$ (O'Brien et al., 2001) to >3 $cm \cdot yr^{-1}$ (Treloar et al., 2003; Massone and O'Brien, 2003). These estimates are higher than those calculated from other UHP-HP terranes. This requires tectonic emplacement of the UHP-HP Himalayan slab into shallow crust, following isostatic rebound due to slab decoupling between the Indian continent and the oceanic crust initiated during the Middle Eocene. UHP rocks from both the Kaghan Valley and Tso-Mori are described below.

Kaghan Valley. The Kaghan nappe, in the northwestern Himalayan syntaxis, lies between the Indus suture (also called main mantle thrust: MMT) to the north and the main central thrust (MCT) to the southwest (Pognante and Spear, 1991; Spencer, 1993) (Fig. 5). The Cretaceous Kohistan island-arc sequence lies north of the Indus suture. It developed as a result of intra-oceanic subduction. The main central thrust separates an underlying Salkhala unit from an overlying higher Himalayan crystalline (HHC) unit. The Kaghan nappe consists mainly of granitic gneiss and paragneiss, with minor intercalated layers of amphibolite, marble, and quartzite. Eclogites are preserved in the cores of mafic boudins (less than 1 m thick) in gneiss, and are significantly overprinted by amphibolite assemblages. They contain fine-grained (< 1 mm) garnet and omphacite, together with aggregates of quartz, chains of rutile rimmed by titanite, and mm-sized phengitic micas overgrown by randomly oriented amphiboles up to 1 cm in length. Coesite and coesite pseudomorphs occur as inclusions in omphacite, and show the characteristic palisade-quartz aggregate texture; fractures radiating from these inclusions are characteristically developed in the host pyroxene.

Garnet pyroxene–phengite barometry was applied to the eclogites, and yielded peak P-T conditions of 2.7–2.9 GPa and 690–750°C (O'Brien et al., 2001) (Fig. 6). Retrograde textures are common in the eclogites, including symplectic intergrowths of augite, amphibole, and plagioclase after omphacite; thermobarometric analyses of these assemblages yielded 1.0–1.3 GPa and 600–710°C (Kaneko et al., 2003). On the other hand, the dominant granitic gneisses and metapelites of the higher Himalayan crystalline unit contain typical Barrovian-zone amphibolite-facies assemblages, represented by kyanite- and staurolite-bearing garnetiferous metapelites (Treloar, 1995). Extensive overprinting has mostly obliterated the peak assemblages; matrix minerals of the gneisses yielded P-T conditions of 0.7–1.1 GPa and 600–700°C (Treloar, 1995), consistent with retrogression of the eclogites. However, relict coesite is preserved as inclusions in zircon; the inclusions are ovoid and approximately 10 μm in diameter (Fig. 7A). This discovery of coesite-bearing zircons from Himalayan quartzofeldspathic gneisses demonstrates subduction of Indian continental crust to the depths of UHP conditions (Kaneko et al., 2003).

Geochronological studies using Sm/Nd (garnet-omphacite), Rb/Sr (phengite), and U/Pb (rutile, zircon) methods suggest that the eclogite-facies event took place at 40–50 Ma (Tonarini et al., 1993; Spencer and Gebauer, 1996). $^{40}Ar/^{39}Ar$ cooling ages for hornblende and mica from gneisses were reported to be ~43 Ma and ~25 Ma, respectively (Chamberlain et al., 1991). Recent SHRIMP U/Pb dates of zoned zircons with mineral inclusions formed at different stages indicate the ages of non-UHP mineral-bearing mantle domains of zircon and UHP mineral-bearing rims are at about 50 and 46 Ma, respectively (Kaneko et al. 2003). A new U-Pb age of 44 ± 1.1 Ma was obtained for rutile from Kaghan coesite-bearing eclogite (Treloar et al., 2003); this together with available data implies that exhumation of the UHP rocks from mantle depth to mid-crustal level occurs within a few million years.

Tso Morari. The Tso Morari crystalline dome is located between the Indus suture zone on the north, bordered by the Zildat detachment fault, and the

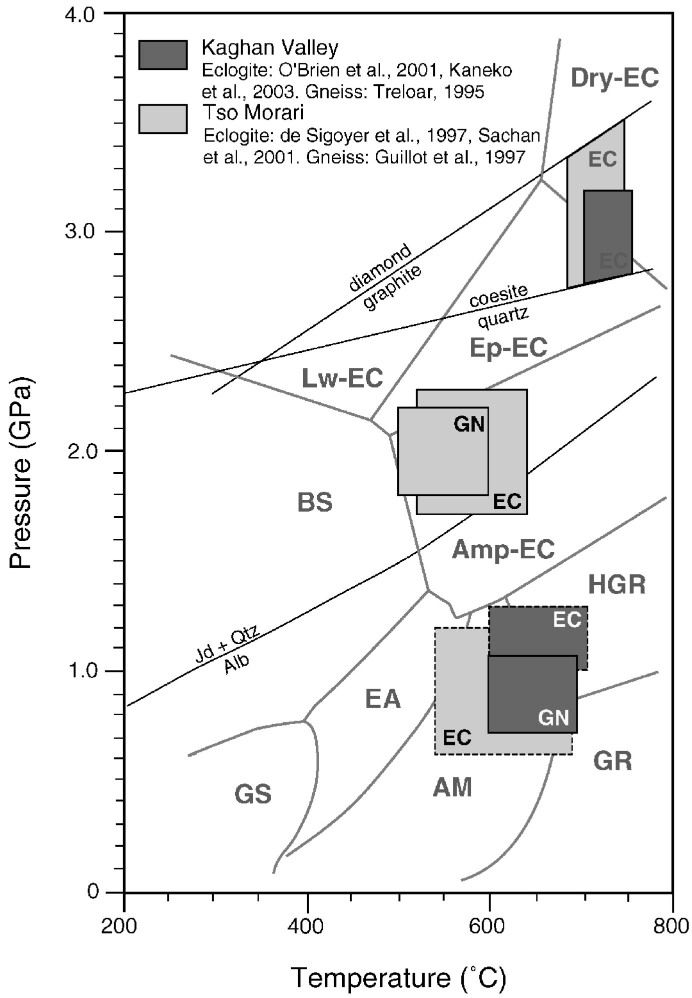

FIG. 6. P-T estimates of peak- and retrograde-stage metamorphism for coesite-bearing eclogites and the country-rock gneisses from the Kaghan Valley and Tso Morari.

Zanskar sedimentary unit on the south (de Sigoyer et al. 1997). The dome represents an internal massif of the northern part of the higher Himalaya. The Tso Morari area has been considered a typical Indian Tethyan margin because of a stratigraphic succession similar to the Nimaling antiform in the core of the dome; a metamorphic basement consists of Cambro-Ordovician augen gneisses (Stutz, 1988). This complex is covered by a metasedimentary series of Cambrian to Devonian quartzite, schist, and conglomerate, and is overlain by Lower Carboniferous to Triassic marble and metapelite. Eclogites occur as lenses or irregular bodies within the basement and cover gneisses, and are strongly overprinted by amphibolite-facies assemblages. de Sigoyer et al. (1997) reported peak P-T conditions for the eclogites at 1.7–2.3 GPa and 520–640°C (Fig. 7). However, relics of coesite 30–80 μm in size were recently found as inclusions in garnet (Sachan et al., 2001; Mukherjee et al., 2003) typified by radial fractures (Figs. 7B and 7C); for the SiO_2 inclusions, a characteristic Raman spectrum is centered at 523 cm^{-1} (Fig. 7D). The country rock metasediments with jadeite + chloritoid + paragonite + garnet assemblages have peak P-T estimates of 1.8–2.2 GPa and 500–600°C, and record retrogression at the eclogite-blueschist facies transition of 1.3–1.8 GPa and 490–590°C (Guillot et al., 1997).

The geochronology of the Tso Morari eclogites has been extensively studied and subdivided into three different stages (de Signoyer et al., 2000). Eclogitization at ~55 Ma was obtained by Lu-Hf and Sm-Nd methods on garnet, omphacite, glaucophane, and the whole rock. An amphibolite-facies overprint occurred at 47 Ma, judging by Rb/Sr dating on phengite, apatite, and whole rock from metapelites.

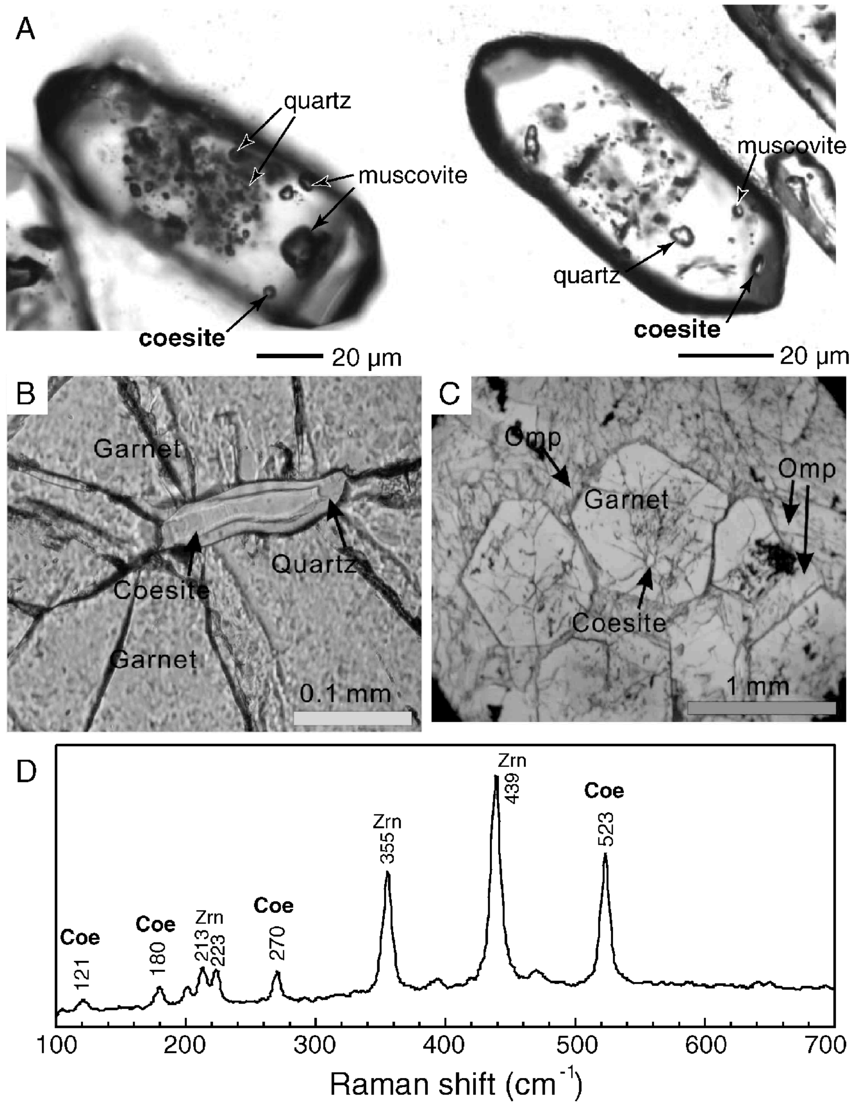

FIG. 7. A. Inclusions of low-P phases (quartz and muscovite) at core and coesite at rim from zircon separates of gneissic rocks from Kaghan Valley (Kaneko et al., 2003). B. Photomicrograph of coesite inclusion in garnet from Tso Morari eclogite showing thin palisade quartz around coesite and radial fractures in host garnet (from Fig. 2 of Mukherjee et al., 2003). C. Inclusion of coesite in eclogitic garnet from Tso Morari (from Fig. 2 of Mukherjee et al., 2003). D. Laser Raman spectra of coesite inclusion in zircon separates of Figure 7A.

$^{40}Ar/^{39}Ar$ ages of biotite and muscovite at ~30 Ma suggest that the Tso Morari unit rose to upper crustal levels and recrystallized at the end of the exhumation (de Signoyer et al., 2000). Recent SHRIMP U/Pb dating of zoned zircons from country gneissic rocks to eclogite from the Tso Morari yields 48 ± 1 Ma for the peak eclogite-facies metamorphism and protolith ages of 700 ± 6 Ma to 1668 ± 14 Ma (Leech et al., 2003), consistent with the 46 ± 1 Ma UHP ages for Kaghan eclogite (Kaneko et al., 2003). Diffusion modeling of garnet overgrowth composition steps by O'Brien and Sachan (2000) yields an exhumation rate of 23–45 mm·yr^{-1} from the UHP stage to low greenschist-facies stage occuring within about 3 Ma (45–48 Ma) (Massone and O'Brien, 2003). The similarity in the tectonic setting, lithologies, and UHP ages suggest they belong to a single UHP belt.

Continental Subduction And Collision (the Himalayan Model)

Continental subduction and UHP metamorphism at 45 to 52 Ma

The Himalayan orogeny was controlled principally by subduction of the Indian continental crust beneath the Asian continental lithosphere; this may

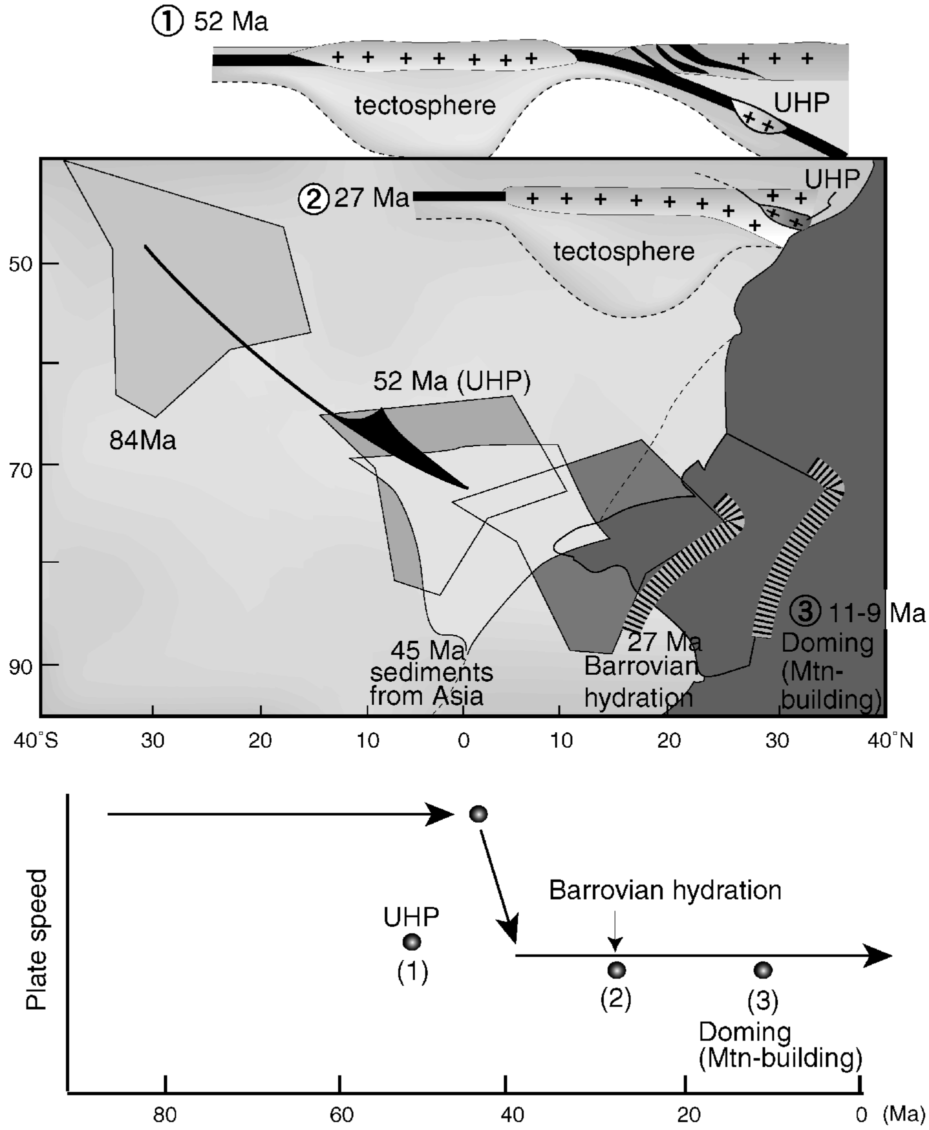

FIG. 8. Subduction and collision of the Indian and Eurasian continents showing the subduction of microcontinent for formation of UHP rocks at 52 Ma (1) and exhumation of UHP rocks from the Himalayan metamorphic belt. Exhumation of the UHP slab includes (2) wedge extrusion from mantle depth to crustal level at >27 Ma and (3) a doming event at 11–9 Ma. Paleogeographic positions of the Indian continent at 84, 52, 45, 27, and 11–9 Ma are shown together with the rate estimates of northeastward motion of the Indian plate. The doming event was responsible for the mountain-building processes for the High Himalayan Mountain chain.

provide a present-day analog for UHP metamorphism. So far, numerous tectonic models for the Himalayan orogeny have been proposed (for a review, see Hodges, 2000); most contributions have focused on the dynamics of unusual crustal thickening (up to 75 km) that resulted in a regional Barrovian-zone metamorphic sequence. In general, the closure of Neo-Tethys to form the Indus suture was followed by the India-Asia continental collision at 52–50 Ma (Fig. 8). Both Asian and Indian margins were thickened and metamorphosed, and the intra-oceanic convergence generated a continental suture (e.g., Rowley, 1996). During the infant stage of the Himalayan orogeny (~80–50 Ma), a Pacific-type arc-trench system was produced, and huge, multiple volcanic/plutonic calc-alkaline arcs formed, cored by the Kohistan-Ladakh and Trans-Himalayan batholiths. Pacific-type subduction formed a Cretaceous accretionary complex along the southern margin of the Kohistan-Ladakh arc; the accretionary complex contains 80 Ma blueschists (e.g., Anczkiewicz et al., 2000). Granitic arc-magmatism continued until 50 Ma at Ladakh (Weinberg and Dunlap, 2000), when collision was initiated at the western syntax and propagated to the SE. Since then, subduction of the Indian continent has occurred, and the India-Asia convergence rate drastically decreased from 19 to 5 cm·yr^{-1} at about Middle Eocene time (e.g. Klootwijk et al., 1992). Continental collision closed the intervening ocean and terminated arc magmatism (Fig. 8); hence 45 Ma lacustrine deposits on the Indian subcontinent contain detritus derived from the Asian mainland.

Recent seismologic studies of the ongoing Himalayan orogeny have provided important constraints on its tectonic evolution. In the western Himalaya, the Hindu Kush region is seismically most active, with abundant intermediate-depth seismicity (Pegler and Das, 1998). The seismic zone extends to a depth of 100-250 km, and steepens with increasing depth. A seismic reflection profile through the region shows the presence of subducted continental crust and a trapped oceanic basin at depth. On the basis of the available seismic data, Searle et al. (2001) proposed a continental subduction model for the formation of UHP metamorphic rocks beneath the Hindu Kush. Their model suggests that a cold lower crust of the Indian block comprising Precambrian granulite-facies basement and a cover sequence of Paleozoic–Lower Mesozoic supracontinental sediments was subducting beneath the Hindu Kush; subsequently the crustal rocks underwent UHP metamorphism at about 150 km depth and ~800–900°C at 4–6 GPa. Kaneko et al. (2003) obtained a sinking rate of 1.2–1.6 cm·yr^{-1} for the downgoing Indian crust to ~110 km depth, based on SHRIMP U/Pb ages of zoned zircon in UHP rocks from the Kagan Valley. These data suggest a time-integrated subduction angle of 18–22°, similar to the estimated angle of the present Moho between the Himalaya foreland and southern edge of the Tethyan Himalaya (Zhao et al., 1993). The timing of UHP metamorphism at 46 Ma (Kaneko et al., 2003) is synchronous with that of the rapid cooling (Weinberg and Dunlap, 2000) of the youngest plutons of the Ladakh batholith.

Barrovian metamorphic overprint at >30–15 Ma

The Himalayan orogeny involves crustal thickening that resulted in a regional Barrovian-type kyanite-sillimanite series metamorphism. This metamorphism is well documented in metapelites of the Higher Himalaya (including the Zanskar Himalayan series) and the north Himalayan gneiss domes. Most Oligocene kyanite-grade rocks were metamorphosed at P = 0.6–1.0 GPa and T = 450–600°C; Early Miocene sillimanite-grade rocks were formed at higher T (650–770°C) but lower P (0.4–0.7 GPa). The U/Pb and Sm/Nd geochronology in the Zansker and Lahoul regions yields ~37–29 Ma for regional Barrovian-type kyanite-grade metamorphism (e.g., Vance and Harris, 1999; Walker et al., 1999). The $^{40}Ar/^{39}Ar$ cooling ages of muscovite in the metapelites yield 22–21 Ma (Walker et al., 1999) and overlap those in the Himalayan leucogranite (24–17 Ma: Searle et al., 1988). Monazite from sillimanite-bearing metapelites of the greater Himalayan series in the Everest region yielded U/Pb ages of 32 Ma (Simpson et al., 2000); monazite U/Pb ages of 23 Ma from sillimanite-cordierite–bearing granitic gneiss represent the timing of cordierite-grade low-P metamorphism related to crustal melting.

The kyanite- and staurolite-bearing mineral assemblage occurs as a retrograde phase of the Tso Morari eclogitic metapelites (Guillot et al., 1997) in the largest gneiss dome of the Himalayan chain. $^{40}Ar/^{39}Ar$ plateau ages of 31–29 Ma from low-Si muscovite and biotite of retrograded metapelites represent thermal relaxation at upper crustal levels (de Sigoyer et al., 2000). A series of gneiss domes (north Himalayan gneiss domes) that are mantled by Barrovian-type kyanite-grade metamorphic rocks can be traced for at least 2000 km; their cooling age is similar to the Barrovian overprint of the Tso Morari UHP eclogites.

Domal uplift and mountain-building since 11 Ma

The uplift of the higher Himalayas apparently occurred in the Late Miocene, as documented by sedimentary flooding demonstrated on ODP Leg 116, by on-land geology, and by climate change in central Asia. Drilling of the distal Bengal fan in the central Indian Ocean revealed that the sedimentation rate drastically increased at 10.9 Ma (Amano and Taira, 1992). Paleontological evidence suggests that glaciation began in the higher Himalayas at about 7 Ma (Lakhanpal et al., 1983). The loess-paleosol sequence of the Chinese Loess Plateau is known to have formed by eolian transport of particles from the inland deserts of northwestern China and possibly, Central Asia. In recent years, uplift of the Himalayan-Tibetan Plateau (Manabe and Broccoli, 1990; An et al., 2001) and changes in land-sea distribution (Ramstein et al., 1997) have been considered principal driving forces for long-term

Cenozoic climatic change. A very surprising result has just been published in Nature (Guo et al., 2003), which recounts the discovery of a 22 Ma old loess deposit in Gansu Province, and the onset of Asian desertification has been linked to the uplift of the Tibetan Plateau.

The doming event at 15–11 Ma is also suggested by mica $^{40}Ar/^{39}Ar$ thermochronology of the Kangmar dome (Maluski et al., 1988; Lee et al., 2000). This doming event raised the Himalayan Mountain chain more than 5 km in elevation; active erosion has continued and thick flysch sequences have accumulated in the Bengal fan. The major driving force for the domal uplift is not well understood. The Miocene underthrusting of the Indian tectosphere beneath the Lesser Himalayas may have elevated the Higher Himalaya.

These data clearly show a two-step exhumation process for the Himalayan UHP and high-grade metamorphic terrane. (1) Emplacement of the Himalayan high-grade metamorphic rocks at shallow crustal levels occurred at > 30 to 20 Ma, when no topographic mountain building was apparent, and (2) Himalayan mountain building began at 10.9 Ma, when extensive surface erosion commenced. Figure 8 schematically shows such events together with the paleogeography of the Indian and Eurasian continents since 80 Ma.

Acknowledgments

We submit this review article for the retirement celebration of W. G. Ernst, who has documented subduction-zone metamorphism for both Pacific-type and Alpine-type blueschist terranes. This manuscript was initiated in 2000–2001 while S. Maruyama held a sabbatical position as a Cox Professor at Stanford; both T. Tsujimori and I. Katayama were supported by a JSPS Research Fellowship for Young Scientists, and a Grant-in-Aid for JSPS Fellows. The paper represents a product of the U.S.–Japan project supported by the NSF Global Partnership Fellowship INT-9820171, and the NSF US-China project EAR 0003355. We thank Y. Kaneko and Himanshu Sachan for preprints and photomicrograph of coesite inclusions in UHP rocks respectively from the Kaghan Valley of Pakistan and Tso-Mori. We appreciate a constructive review of the manuscript by our mentor W. G. Ernst.

REFERENCES

Amano, K., and Taira, A., 1992, Two-phase uplift of Higher Himalayas since 17 Ma: Geology, v. 20, p, 391–394.

An, Z. S., Kutzbach, J. E., Prell, W. L., and Porter, S. C., 2001, Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan Plateau since Late Miocene times: Nature, v. 411, p. 62–66.

Ankiewicz, R., Burg, J. P., Villa, I. M., and Meier, M., 2000, Late Cretaceous blueschist metamorphism in the Indus suture zone, Shangla region, Pakistan Himalaya: Tectonophysics, v. 324, p. 111–134.

Bakun-Czubarow, N., 1991, On the possibility of occurrence of quartz pseudomorphs after coesite in the eclogite-granulite rock series of the Zlote Mountains in the Sudetes, SW Poland: Archiwum Mineralogy, v. 48, p. 3–25.

Beane, R. J., and Connelly, J. N., 1998, $^{40}Ar/^{39}Ar$, U-Pb, and Sm-Nd constraints on the timing of metamorphic events in the Maksyutov Complex, southern Ural Mountains: Journal of the Geological Society of London, v. 157, p. 811–822.

Beane, R. J., Liou, J. G., Coleman, R. G., and Leech, M. L., 1995, Petrology and retrograde P-T path for eclogites of the Maksyutov complex, southern Ural Mountains, Russia: The Island Arc, v. 4, p. 254–266.

Bostick,B., Jones, R. E., Ernst, W. G., Chen, C., Leech, M. L., and Beane, R. J., 2003, Low-temperature microdiamond aggregates in the Maksyutov metamorphic complex, south Ural Mountains, Russia: American Mineralogist, v. 88, p. 1709–1717.

Bowtell, S. A., Cliff, R. A., and Barnicoat, A. C., 1994, Sm-Nd isotopic evidence on the age of eclogitization in the Zermatt-Saas ophiolite: Journal of Metamorphic Geology, v. 12, p. 187–196.

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 ultra-high-pressure metamorphic terranes of the Norwegian Caledonides and the Czech Variscides: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 78, p. 293–307.

Caby, R., 1994, Precambrian coesite from N. 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., Brueckner, H. K., Cuthbert, S. J., Mehta, K., and O'Brien, P. J., 2003, The timing of stabilisation and the exhumation rate for ultra-high pressure rocks in the Western Gneiss Region: Journal of Metamorphic Geology, v. 21, p. 601–612.

Carswell, D. A., and Compagnoni, R., eds., 2003, Ultra-high pressure metamorphism: European Mineralogical Union, Notes in Mineralogy, v. 5, p. 51–74.

Carswell, D. A., and Cuthbert, S. J., 2003, Reviews of representative UHPM terranes: The Western Gneiss

Region of Norway: *in* Carswell, D. A., and Compagnoni, R., eds., Ultra-high pressure metamorphism: European Mineralogical Union, Notes in Mineralogy, v. 5, p. 51–74.

Carswell, D. A., Cuthbert, S. J., and Krogh Ravna, E. J., 1999, Ultrahigh-pressure metamorphism in the western Gneiss Region of the Norwegian Caledonides: International Geology Review, v. 41, p. 955–966.

Campos Neto, M. da C., and Caby, R., 1999, Tectonic constraint on Neoproterozoic high-pressure metamorphism and nappe system south of the San Francisco craton, southeast Brazil: Precambrian Research, v. 97, p. 3–26.

Chamberlain, C. P., Zeitler, P. K., and Erickson, E., 1991, Constraints on the tectonic evolution of the northwestern Himalaya from geochronologic and petrologic studies of Babusar Pass, Pakistan: Journal of Geology, v. 99, p. 829–849.

Chaudary, M. N., and Ghazanfar, M., 1987, Geology, structure and geomorphology of upper Kaghan valley, Northwestern Himalaya, Pakistan: Geological Bulletin, University of Punjab, v. 22, p. 13–57.

Chesnokov, B. V., and Popov, V. A., 1965, Increasing volume of quartz grains in eclogites of the south Urals: Doklady Akademii Nauk, v. 162, p. 176–178 (in Russian).

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.

______, 2003, Ultrahigh-pressure metamorphism: Tracing continental crust into the mantle: Earth and Planetary Science Letters, v. 212, p. 1–14.

Coleman, R. G., and Wang, X., 1995, Ultrahigh pressure metamorphism: Cambridge, UK, Cambridge University Press.

Compagnoni, R., and Rolfo, F., 2003, Reviews of representative UHPM terranes: The Western Alps, *in* Carswell, D. A., and Compagnoni, R., eds., Ultra-high pressure metamorphism: European Mineralogical Union, Notes in Mineralogy, v. 5, p. 13–50.

Costa, S., Maluski, A., and Lardeaux, J. M., 1993, $^{40-39}$Ar chronology of Variscan tectono-metamorphic events in an exhumed crustal nappe: The Monts du Lyonnais complex (Massif Central France): Chemical Geology, v. 105, p. 339–359.

Cuthbert, S. J., Carswell, D. A., Krogh-Ravna, E. J., and Wain, A., 2000, Eclogites and eclogites in the Western Gneiss Region, Norwegian Caledonides: Lithos, v. 52, p. 165–195.

de Sigoyer, J., Chavagnac, V., Blichert-Toft, J., Villa, I. M., Luais, B., Guillot, S., Cosca, M., and Mascle G., 2000, Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: Multichronology of the Tso Morari eclogites: Geology, v. 28, p. 487–490.

de Sigoyer, J., Guillot, S., Laudeaux, J. M., and Mascle, G., 1997, Glaucophane-bearing eclogites in the Tso Morari dome, eastern Ladakh, NW Himalaya: European Journal of Mineralogy, v. 9, p. 1073–1083.

Di Vincenzo, G., and Palmeri, R., 2001, An ^{40}Ar-^{39}Ar investigation of high-pressure metamorphism and the retrogressive history of mafic eclogites from the Lanterman Range, Antarctica: Evidence against a simple temperature control on argon transport in amphibole: Contributions to Mineralogy and Petrology, v. 141, p. 15–35.

Dobretsov, N. L., and Dobretsova, L. V., 1988, New mineralogic data on the Maksyutov eclogite-glaucophane schist complex, southern Urals: Doklady Akademii Nauk, v. 300, p. 111–116.

Dobretsov, N. L., Shatsky, V. S., Coleman, R. G., Lennykh, V. I., Valizer, P. M., Liou, J. G., Zhang, R. Y., and Beane, R. J., 1996, Tectonic setting and petrology of ultrahigh-pressure metamorphic rocks in the Maksyutov Complex, Ural Mountains, Russia: International Geology Review, v. 38, p. 136–160.

Dobrzhinetskaya, L. F., Eide, E. A., Larsen, R. B., Sturt, B. A., Tronnes, R. G., Smith, D. C., Taylor, W. R., and Posukhova, T. V., 1995, Microdiamond in high-grade metamorphic rocks of the Western Gneiss region, Norway: Geology, v. 23, p. 597–600.

Dobrzhinetskaya, L. F., Green, H. W., Mitchell, T. E., and Dickerson, R. M., 2001, Metamorphic diamonds: Mechanism of growth and inclusion of oxides: Geology, v. 29, p. 263–266.

Dobrzhinetskaya, L. F., Green, H. W., Weschler, M., Darus, M., Wang, Y. C., Massonne, H., and Stöckert, B., 2003, Focused ion beam technique and transmission electron microscope studies of microdiamonds from the Saxonian Erzgebirge, Germany: Earth and Planetary Science Letter, in press.

England, P. C. and Houseman, G. A., 1986, Finite strain calculations of continental deformation. II. Application to the India-Asia plate collision: Journal of Geophysical Research, v. 91, p. 3664–3676.

Ernst, W. G., and Liou, J. G., eds., 2000, Ultrahigh-pressure metamorphism and geodynamics in collision-type orogenic belts: Geological Society of America, International Book Series, v. 4, 293 p.

Gardien, V., Tegyey, M., Lardeaux, J. M., Misseri, M., and Dufour, E., 1990, Crustal-mantle relationship in French Variscan chain: The example of the southern Monts du Lyonnais unit (eastern French Massif Central): Journal of Metamorphic Geology, v. 8, p. 477–492.

Gebauer, D., Schertl, H. P., Brix, 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.

Ghiribelli, B., Frezzotti, M.-L., and Palmeri, R., 2002, Coesite in eclogites of the Lanterman range, Antarctica: Evidence from textural and Raman studies: European Journal of Mineralogy, v. 14, p. 355–360.

Gilotti, J. A., 1993, Discovery of a medium-temperature eclogite province in the Caledonides of North-East Greenland: Geology, v. 21, p. 523–526.

Gilotti, J. A., and Ravna, E. J. K., 2002, First evidence for ultrahigh-pressure metamorphism in the Northeast Greenland Caledonides: Geology, v. 30, p. 551–554.

Guillot, S., de Sigoyer, J., Lardeaux, J. M., and Mascle, G., 1997, Eclogitic metasediments from the Tso Morari area, Ladakh, Himalaya.: Evidence for continental subduction during India-Asia convergence: Contributions to Mineralogy and Petrology, v. 128, p. 197–212.

Guo, Z. T., Ruddiman, W. F., Hao, Q. Z., Wu, H. B., Qiao, Y. S., Zhu, R. X., Peng, S. Z., Wei, J. J., Yuan, B. Y. and Liu, T. S., 2003, Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China: Nature, v. 416, p. 159–162.

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.

Hirajima, T., and Nakamura, D., 2003, Reviews of representative UHPM terranes: The Dabie Shan and Sulu region of China, *in* Carswell, D. A., and Compagnoni, R., eds., Ultra-high pressure metamorphism: European Mineralogical Union, Notes in Mineralogy, v. 5, p. 105–144.

Hodges, K. V., 2000, Tectonics of the Himalaya and southern Tibet from two perspectives: Geological Society of America Bulletin, v. 112, p. 324–350.

Hu, N., Zhao, D., Xu, B., and Wang, T., 1995, Petrography and metamorphic study on high-ultrahigh pressure eclogite from Guanpo area, northern Qinling Mountain: Journal of Mineralogy and Petrology, v. 15, p. 1–9 (in Chinese).

Hwang, S. L., Shen, P., Chu, H. T., Yui, T. F., and Lin, C. C., 2001, Genesis of microdiamonds from melt and associated multiphase inclusions in garnet of ultrahigh-pressure gneiss from Erzegebirge, Germany: Earth and Planetary Science Letters, v. 188, p. 9–15.

Jahn, B. M., Caby, R., and Monie, P., 2001, The oldest UHP eclogites of the World: Age of UHP metamorphism, nature of protoliths, and tectonic implications: Chemical Geology, v. 178, p. 143–158.

Kaneko, Y., Katayama, I., Yamamoto, H., Misawa, K., Ishikawa, M., Rehman, H. U., Kausar, A. B., and Shiraishi, 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.

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 UHP-HP metamorphic belt, Northern Kazakhstan: The Island Arc, v. 9, p. 264–283.

Kardarusman, A., and Parkinson, C. D., 2000, Petrology and P-T evolution of garnet peridotites from central Silawesi, Indonesia: Journal of Metamorphic Geology, v. 18, p. 193–209.

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.

Katayama, I., Ohta, M., and Ogasawara, Y., 2002, Mineral in zircon from diamond-bearing marble in the Kokchetav massif, northern Kazakhstan: European Journal of Mineralogy, v. 14, p. 1103–1108.

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, UK, Cambridge University Press, p. 244–298.

Klootwijk, C., Gee, J., Peirce, J., Smith, G., and McFadden, P., 1992, An early India-Asia contact: Paleomagnetic constraints from the Ninetyeast Ridge, ODP Leg 121: Geology, v. 20, p. 395–398.

Lakhanpal, R. N., Sah, S. C. D., Kewal, K., Sharma, K. K., and Guleria, J. S., 1983, Occurrence of Livistona in the Hemis conglomerate horizon of Ladakh, *in* Thakur, V. C., and Sharma, K. K., eds., Geology of Indus suture zone of Ladakh: New Delhi, India, Hindustan Book Publishing Corporation, p. 179–185.

Lardeaux, J. M., Ledru, P., Daniel, I., and Duchene, S., 2001, The Variscan French Massif Central—a new addition to the ultrahigh pressure metamorphic "club": Exhumation processes and geodynamic consequences: Tectonophysics, v. 332, p. 143–167.

Lee, J., Hacker, B. R., Dinklage, W. S., Gans, P. B., Calvert, A., Wang, Y., Wan, J., and Chen, W., 2000, Evolution of the Kangmar Dome, southern Tibet: Structural, petrologic, and thermochronologic constraints: Tectonics, v. 19, p. 872–895.

Leech, M. L., and Ernst, W. G., 1998, Graphite pseudomorphs after diamond? A carbon isotope and spectroscopic study of graphite cuboids from the Maksyutov complex, south Ural Mountains, Russia: Geochimica et Cosmochimica Acta, v. 62, p. 2143–2154.

Leech, M. L., Singh, S., Jain, A. K., and Manickavasagam, R. M., 2003, New U-Pb SHRIMP ages for the UHP Tso-Morari crystallines, eastern Ladakh, India [abs.]: Geological Society of America, Abstracts with Programs, v. 34, p. 637.

Li, S., Chen, Y., Cong, B., Zhang, Z., Zhang, R., Liou, D., Hart, S. R., and Ge, N., 1993, Collision of the North China and Yangtze blocks and formation of coesite-bearing eclogites: Timing and processes: Chemical Geology, v. 109, p. 70–89.

Liou, J. G., 1999, Petrotectonic summary of less-intensively studied UHP regions: International Geology Review, v. 41, p. 571–586.

Liou, J. G., and Zhang, R. Y., 2002, Ultrahigh-pressure metamorphic rocks: Encyclopedia of Physical sciences and technology, third ed., v. 17, p. 227–244: Tarzana, CA, Academia Press.

Liou, J. G., Zhang, R. Y. Katayama, I., Maruyama, S., and Ernst, W. G., 2002, Petrotectonic characterization of the Kokchetav Massif and the Dabie-Sulu terranes—Ultrahigh-P metamorphism in the so-called P-T Forbidden-Zone: Western Pacific Earth Sciences, v. 2, p. 119–148.

Liu, F., Xu, Z., Katayama, I., Yang, J. S., Maruyama, S., and Liou, J. G., 2001, Mineral inclusions in zircons of para- and orthogneiss from pre-pilot drillhole CCSD-PP1, Chinese Continental Scientific Drilling Project: Lithos, v. 59, p. 199–215.

Lombardo, B., and Rolfo, F., 2000, Two contrasting eclogite types in the Himalaya: implications for the Himalayan orogeny: Journal of Geodynamics, v. 30, p. 37–60.

Maluski, H., Matte, P., and Brunel, M., 1988, Argon 39-argon 40 dating of metamorphic and plutonic events in the North and High Himalaya belts (southern Tibet-China): Tectonics, v. 7, p. 299–326.

Manabe, S., and Broccoli, A.J., 1990, Mountains and arid climates of middle latitudes: Science, v. 247, p. 192–195.

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.

Masago, H., Rumble, D., Ernst W. G., Parkinson, C., and Maruyama, S., 2003, O^{18} depletion in eclogites from the Kokchetav massif, northern Kazakhstan: Journal of Metamorphic Geology, v. 21, p. 579–587.

Massonne, H. J., 1999, A new occurrence of microdiamonds in quartzofeldspathic rocks of the Saxonian Erzgebirge, Germany, and their metamorphic evolution: Proceedings of 7th International Kimberlite Conference, Capetown, v. 2, p. 533–539.

______, 2001, First find of coesite in the ultrahigh-pressure metamorphic region of the Central Erzgebirge, Germany: European Journal of Mineralogy, v. 13, p. 565–570.

Massonne, H. J., and O'Brien, P., 2003, Reviews of representative UHPM terranes: The Bohemian Massif and the NW Himalaya: *in* Carswell, D. A. and Compagnoni, R. (eds.), Ultra-high pressure metamorphism: European Mineralogical Union, Notes in Mineralogy, v. 5, p. 145–188.

Matte, P., 1986, Tectonics and plate tectonics model for the Variscan belt of Europe: Tectonophysics, v. 126, p. 329–374.

Matte, P., 1998, Continental subduction and exhumation of HP rocks in Paleozoic orogenic belts: Uralides and Variscides: Geologiska Foreningen i Stockholm Forhandlingar, v. 20, p. 209–222.

McClelland, W. C., and Gilotti, J. A., 2003, Late-stage extensional exhumation of high-pressure granulites in the Greenland Caledonides: Geology, v. 31, p. 259–262.

Mposkos, E. D., and Kostopoulos, D. K., 2001, Diamond, former coesite, and supersilicic garnet in metasedimentary rocks from the Greek Rhodope: A new ultrahigh-pressure metamorphic province established: Earth and Planetary Science Letters, v. 192, p. 497–506.

Mukherjee, B. K., Sachan, H. K., Ogasawara, Y., Muko, A., and Yoshioka, N., 2003, Carbonate-bearing UHPM rocks from the Tso-Morari region, Ladakh, India: Petrological implications: International Geology Review, v. 45, p. 49–69.

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

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.

Ogasawara, Y., Fukasawa, K., and Maruyama, S., 2002, Coesite exsolution from supersilicic titanite in UHP marble from the Kokchetav Massif, northern Kazakhstan: American Mineralogist, v. 87, p. 454–461.

Ogasawara, Y., Ohta, M., Fukasawa, K., Katayama, I., and Maruyama, S., 2000, Diamond-bearing and diamond-free metacarbonate rocks from Kumdy-Kol in the Kokchetav massif, northern Kazakhstan: The Island Arc, v. 9, p. 400–416.

Okamoto, K., and Maruyama, S., 1999, The high-pressure synthesis of lawsonite in the MORB + H_2O system: American Mineralogist, v. 84, p. 362–373.

Paquette, J. L., Monchoux, P., and Couturier, M., 1995, Geochemical and isotopic study of a norite-eclogite transition in the European Variscan belt. Implications for U-Pb zircon systematics in metabasic rocks: Geochimica et Cosmochimica Acta, v. 59, p. 1611–1622.

Parkinson, C. D., 2003, Coesite-bearing quartzites from Sulawesi, Indonesia: A first record of UHP metamorphism in SE Asia: Tectonophysics, in press.

Parkinson, C. D., Katayama, I. Liou, J. G., and Maruyama, S. eds., 2002, The diamond-bearing Kokchetav Massif, Kazakhstan: Petrochemistry and tectonic evolution of an unique ultrahigh-pressure metamorphic terrane: Tokyo, Japan, Universal Academy Press, Inc. 527 p.

Parkinson, C. D., Motoki, A., Onishi, C. T., and Maruyama, S., 2001, Ultrahigh-pressure pyrope-kyanite granulites and associated eclogites in Neoproterozoic Nappes of Southeast Brazil: UHPM Workshop 2001, Waseda University, p. 87–90.

Pegler, G., and Das, S., 1998, An enhanced image of the Pamir–Hindu Kush seismic zone from relocated earthquake hypocentres: Geophysical Journal International, v. 134, p. 573–595.

Pognante, U., and Spear, D. A., 1991, First record of eclogites from the High Himalayan belt, Kaghan Valley (northern Pakistan): European Journal of Mineralogy, v. 3, p. 613–618.

Ramstein, G., Fluteau, F., Besse, J., and Joussaume, S., 1997, Effect of orogeny, plate motion, and land-sea distribution on Eurasian climate change over the past 30 million years: Nature, v. 386, p. 788–795.

Reinecke, T., 1991, Very-high-pressure metamorphism and uplift of coesite bearing metasediments from the Zermatt-Saas zone, Western Alps: European Journal of Mineralogy, v. 3, p. 7–17.

Rowley, D. Y., 1996, Age of initiation of collision between India and Asia: A review of stratigraphic data: Earth and Planetary Science Letters, v. 145, p. 1–13.

Rumble, D., Liou, J. G., and Jahn, B. M., 2003, Continental crust subduction and UHP metamorphism, *in* Rudnick, R. L., ed., The crust: Oxford, UK, Elsevier, Treatise on Geochemistry, v. 3 (Holland, H. D., and Turekian, K. K., eds.), p. 293–319.

Sachan, H., Mucherjee, B. K., Ishida, H., Muko, A., Yoshioka, N., Ogasawara, Y., and Maruyama, S., 2001, New discovery of coesite from the Indian Himalaya, *in* Fluid/slab/mantle interactions and ultrahigh-P minerals: UHPM Workshop 2001, Waseda, Japan, p. 124–128.

Schertl, H. P., Schreyer, W., and Chopin, C., 1991, The pyrope-coesite rocks and their country rocks at Parigi, Dora Maira massif, western Alps: Detailed petrography, mineral chemistry, and PT-path: Contributions to Mineralogy and Petrology, v. 108, p. 1–21.

Searle, M. P., Cooper, D. J. W., and Rex, A. J., 1988, Collision tectonics of the Ladakh-Zanskar Himalaya, *in* Shackleton, R. M., Dewey, J. F., and Windley, B. F.,eds., Tectonic evolution of the Himalayas and Tibet: London, UK, The Royal Society, p. 117–149.

Searle, M., Hacker, B. R., Bilham, R., 2001, The Hindu Kush seismic zone as a paradigm for the creation of ultrahigh-pressure diamond and coesite-bearing rocks: Journal of Geology, v. 109, p. 143–154.

Schmadicke, E., 1991, Quartz pseudomorphs after coesite in eclogites from the Saxonian Erzgebirge: European Journal of Mineralogy, v. 3, p. 231–238.

Schmadicke, E., Mezger, K., Cosca, M. A., and Okrusch, M., 1995, Variscan Sm-Nd and Ar-Ar ages of eclogite facies rocks from the Erzgebirge, Bohemian Massif: Journal of Metamorphic Geology, v. 13, p. 537–552.

Schmidt, M. W., and Poli, S., 1998, Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation: Earth and Planetary Science Letters, v. 163, p. 361–379.

Shatsky, V. S., and Sobolev, N. V., 2003, Reviews of representative UHPM terranes: The Kokchetav massif, Kazakhstan, *in* Carswell, D. A., and Compagnoni, R. eds., Ultra-high pressure metamorphism: European Mineralogical Union, Notes in Mineralogy, v. 5, p. 75–104.

Shatsky, V. S., Sobolev, N. V., and Vavilov, M. A., 1995, Diamond-bearing metamorphic rocks of the Kokchetav massif, N. Kazakhstan, *in* Coleman, R. G., and Wang, X., eds., Ultrahigh pressure metamorphism: Cambridge, UK, Cambridge University Press, p. 427–455.

Simpson, R. L., Parrish, R. R., Searle, M. P., and Waters, D. J., 2000, Two episodes of monazite crystallization during metamorphism and crustal melting in the Everest region of the Nepalese Himalaya: Geology, v. 28, p. 403–406.

Smith, D. C., 1984, Coesite in clinopyroxene in the Caledonides and its implications for geodynamics: Nature, v. 310, p. 641–644.

Sobolev, N. V., and Shatsky, V. S., 1990, Diamond inclusions in garnets from metamorphic rocks: A new environment for diamond formation: Nature, v. 343, p. 742–746.

Solari, L., Ortega, F. Sole-vinas, J., Gomez-Tuena, A., Ortega-Obregon, C., Reher-Salas, M., Martens, U., and Moran, S., 2003, Petrologic evidence for possible ultrahigh pressure metamorphism in the Chuacus Complex of north-central Guatemala [abs.]: Geological Society of America, Abstracts with Programs, v. 34, p. 639.

Song, S. G., Yang, J. S., Liou, J. G., Wu, C. L., Shi, R. D., and Xu, Z. Q., 2003a, Petrology, geochemistry and isotopic ages of eclogites from the Dulan UHPM terrane, the North Qaidam, NW China: Lithos, v. 70, p. 195–211.

Song, S. G., Yang, J. S., Xu, Z. Q., Liou, J. G., and Shi, R. D., 2003b, Metamorphic evolution of the coesite-bearing ultrahigh-pressure terrane in the North Qaidam, Northern Tibet, NW China: Journal of Metamorphic Geology, v. 21, p. 631–644.

Spencer, D. A., 1993, Tectonics of the Higher- and Tethyan Himalaya, upper Kaghan Valley, NW Himalaya, Pakistan: Implications of an early, high-pressure, eclogite-facies metamorphism to the Himalayan belt: Unpubl. Ph.D. dissertation, ETH Zurich, Switzerland, 1050 p.

Spencer, D. A., and Gebauer, D., 1996, SHRIMP evidence for a Permian age and a 44 Ma metamorphic age for the Himalayan eclogites, Upper Kaghan, Pakistan: Implications for the subduction of Tethys and the subdivision terminology of the NW Himalaya [ext. abs.]: 11th Himalaya-Karakoram-Tibet Workshop, Flagstaff, Arizona, USA, Abstracts, p. 147–150.

Stöckhert, B., Duyster, J., Trepmann, C. and Massonne, H. J., 2001, Microdiamond daughter crystals precipitated from supercritical COH + silicate fluids included in garnet, Erzegebirge, Germany: Geology, v. 29, p. 391–394.

Stutz, E., 1988, Geologie de la chaine du Nyimaling aux confines du Ladakh et du Rupshu, NW-Himalaya, Indes—evolution paleogeographique et tectonique d'un segment de la marge nord-indienne: Memorie de Geologie, Lausanne, no. 3, 149 p.

Sun, W. D., Williams, I. S., and Li, S. G., 2002, Carboniferous and Triassic eclogites in the western Dabie Mountains, east-central China. Evidence for protracted convergence of the North and South China Blocks: Journal of Metamorphic Geology, v. 20, p. 873–886.

Tagiri, M., and Bakirov, A., 1990, Quartz pseudomorph after coesite in garnet from a garnet-chloritoid-talc schist, northern Tien-Shan, Kirghiz, USSR: Proceedings of the Japan Academy, v. 66, p. 135–139.

Tagiri, M., Yano, T., Bakirov, A., Nakajima, T., and Uchiumi, S., 1995, Mineral parageneses and metamorphic P-T paths of ultrahigh-pressure eclogites from Kyrghyzstan Tien-Shan: The Island Arc, v. 4, p. 280–292.

Tonarini, S., Villa, I. M., Oberli, F., Meier, M., Spencer, D. A., Pognante, U., and Ramsay, J. R., 1993, Eocene age of eclogite metamorphism in Pakistan Himalaya: Implications for India-Eurasia collision: Terra Nova, v. 5, p. 13–20.

Treloar, P. J., 1995, Pressure-temperature-time paths and the relationship between collision, deformation, and metamorphism in the north-west Himalaya: Geological Journal, v. 30, p. 333–348.

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

van Roermund, H. L. M., Carswell, D. A., Drury, M. R., and Heijboer, 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.

van Roermund, H. L. M., and Drury, M. R., 1998, Ultrahigh pressure ($P > 6$ Gpa) garnet peridotites in western Norway: Exhumation of mantle rocks from > 185 km depth: Terra Nova, v. 10, p. 295–301.

van Roermund, H. L. M., Drury, M. R., Barnhoom, A., and 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. 135–148.

Vance, D., and Harris, N. B. W., 1999, The timing of prograde metamorphism in the Zanskar Himalaya: Geology, v. 27, p. 395–398.

Wain, A., 1997, New evidence for coesite in eclogite and gneisses: Defining an ultrahigh-pressure province in the Western Gneiss Region of Norway: Geology, v. 25, p. 927–930.

Wain, A., Waters, D., Jephcoat, A. and Olijynk, H., 2000, The high-pressure to ultrahigh-pressure eclogite transition in the Western Gneiss Region, Norway: European Journal of Mineralogy, v. 12, p. 667–687.

Walker, J., Martin, M. W., Bowring, S. A., Searle, M. P., Waters, D. J., and Hodges, K. V., 1999, Metamorphism, melting, and extension: Age constraints from the High Himalayan slab of southeast Zanskar and northwest Lahaul: Journal of Geology, v. 107, p. 473–495.

Wang, X., Liou, J. G., and Mao, H. K., 1989, Coesite-bearing eclogite from the Dabie Mountains in central China: Geology, v. 17, p. 1085–1088.

Wei, C. J., Powell, R., and Zhang, L. F., 2003, Eclogites from the south Tianshan, NW China: Petrological characteristic and calculated mineral equilibria in the Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O system: Journal of Metamorphic Geology, v. 21, p. 163–180.

Weinberg, R. F., and Dunlap, W., 2000, Growth and deformation of the Ladakh Batholith, NW Himalayas: Implications for timing of continental collision and origin of calc-akaline batholiths: Journal of Geology, v. 108, p. 303–320.

Xu, S., Liu, Y., Chen, G., Compagnoni, R., Rolfo, F., He, M., and Liu, H., 2003, New findings of microdiamonds in eclogites from Dabie-Sulu region in central-eastern China: Chinese Science Bulletin, v. 48, p. 988–994.

Xu, W., Okay, A. I., Ji, S., Sengor, A. M. C., Su, W., and Jiang, L., 1992, Diamond from the Dabie Shan metamorphic rocks and its implication for tectonic setting: Science, v. 256, p. 80–82.

Yang, J. J., Godard, G., Kienast, J. R., Lu, Y., and Sun, J., 1993, Ultrahigh-pressure, 60 kbar magnesite-bearing garnet peridotite from Northeastern Jiangsu, China: Journal of Geology, v. 101, p. 541–554.

Yang, J., Xu, Z., Pei, X., Shi, R., Wu, C., Zhang, J., Li, H., Meng, F., and Rong, H., 2002a, Discovery of diamond in North Qiling: Evidence for a giant UHPM belt across central China and Recognition of Paleozoic and Mesozoic dual deep subduction between North China and Yangtze plates: Acta Geologica Sinica, v. 76, p. 484–495 (in Chinese).

Yang, J. S., Xu, Z., Song, S., Zhang, J., Shi, R., Li, H., and Brunel, M., 2001, Discovery of coesite in the North Qaidam Early Paleozoic ultrahigh pressure, UHP metamorphic belt, NW China: Comptes Rendus de l'Academie des Sciences, Paris, Sciences de la Terre et des Planets, v. 333, p. 719–724.

Yang, J. S., Xu, Z., Zhang, J., Chu, C., Zhang, R. and Liou, J. G., 2001, Tectonic significance of early Paleozoic high-pressure rocks in Altun-Qaidam-Qilian Mountains, northwest China, *in* Hendrix, M. S., and Davis, G. A., eds., Paleozoic and Mesozoic tectonic evolution of central Asia: From continental assembly to intracontinental deformation: Geological Society of America Memoir, v. 194, p. 151–170.

Yang, J. S., Xu, Z. Zhang, J., Song, S., Wu, C., Shi, R., Li, H., and Brunel, M., 2002b, 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.

Ye, K., Cong, B., and Ye, D., 2000, The possible subduction of continental material to depths greater than 200 km: Nature, v. 407, p. 734–736.

Yui, T. F., Rumble, D., and Lo, C. H., 1995, Unusually low d[18]O ultrahigh-pressure metamorphic rocks from Su-Lu terrane, China: Geochimica et Cosmochimica Acta, v. 59, p. 2859–2864.

Zhang, J. X., Yang, J. S., Xu, Z. Q., Meng, F. C., Li, H. B., and Shi, R., 2002, Evidence for UHP metamorphism of eclogite from the Altun Mountains: Chinese Science Bulletin, v. 47, p. 751–755.

Zhang, J. X., Zhang, Z. M., Xu, Z. Q., Yang, J. S., and Cui, J. W., 2001, Petrology and geochronology of eclogites from the western segment of the Altyn Tagh, northwestern China: Lithos, v. 56, p. 187–206.

Zhang, L., Ellis, D. J., Arculus, R. J., and Jiang, W., 2003, "Forbidden zone" subduction of sediments to 150? km depth—the reaction of dolomite to magnesite + aragonite in the UHPM metapelites from western Tianshan, China: Journal of Metamorphic Geology, v. 21, p. 523–529.

Zhang, L., Ellis, D. J., and Jiang, W., 2002, Ultrahigh-pressure metamorphism in western Tianshan, China: Part I. Evidence from inclusions of coesite pseudomorphs in garnet and from quartz exsolution lamellae in omphacite in eclogites; Part II. Evidence from magnesite in eclogite: American Mineralogist, v. 87, p. 853-860; 860–866.

Zhang, R. Y., Liou, J. G., and Yang, J. S., 2000, Petrochemical constraints for dual origin of garnet peridotites of the Dabie-Sulu UHP terrane, China: Journal of Metamorphic Geology, v. 18, p. 149–166.

Zhang, R. Y., Liou, J. G., Yang, J., 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.

Zheng, Y. F., Fu, B., Gong, B., and Li, L., 2003, Stable isotope geochemistry of ultrahigh-pressure metamorphic rocks from the Dabie-Sulu orogen in China: Implications for geodynamics and fluid regime: Earth Science Review, v. 62, p. 105–161.

Zhao, W., Nelson, K. D., and Team, P. I., 1993, Deep seismic reflection evidence for continental underthrusting beneath southern Tibet: Nature, v. 366, p. 557–559.

Zhu, Y.-F., and Ogasawara, Y., 2002, Phlogopite and coesite exsolution from super-silicic clinopyroxene: International Geology Review, v. 44, p. 831–836.