Permo-Triassic Collision, Subduction-Zone Metamorphism, and Tectonic Exhumation Along the East Asian Continental Margin

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ultrahigh-pressure metamorphism, high-pressure metamorphism, Permo-Triassic East Asian margin, crustal accretion, crustal evolution, continental collision

Abstract

Convergent plate motion at ~320–210 Ma generated the Tongbai-Dabie-Sulu (east-central China)-Imjingang-Gyeonggi (central Korea)-Renge-Suo (Southwestern Japan)-Sikhote-Alin orogen along the paleo-Pacific edge of cratonal Asia. This amalgamated belt reflects collision between the Sino-Korean and Yangtze cratons on the SW portion, and accretion of outboard oceanic arcs ± sialic fragments against the NE margin. Subducted Proterozoic-Paleozoic continental and oceanic crustal complexes underwent high- and ultrahigh-pressure metamorphism at low to moderate temperatures. Tectonic slices of sialic crust episodically disengaged from the downgoing plate and, driven by buoyancy, ascended rapidly to midcrustal levels from depths exceeding 90–200 km after continental collision in east-central China plus or minus Korea, and from ~30–50 km after arrival of far-traveled oceanic terranes in SW Japan and the Russian Far East. On achieving neutral buoyancy and stalling out at 10–20 km depth, later doming, gravitational collapse, and erosion exposed parts of the high- and ultrahigh-pressure complexes. This curvilinear orogen has been segmented and offset by major and minor transverse faults. Also, regional backarc spreading opened marginal basins behind the Permo-Triassic convergent suture zone, further disturbing portions oceanward.

CIRCUMPACIFIC AND ALPINE SUBDUCTION ZONES

We summarize lithologic assemblages plus structural architectures and provide an interpretive petrotectonic evolution for the Permo-Triassic Tongbai-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin orogenic belt of East Asia. The ultrahigh-pressure (UHP) Dabie and Sulu terranes represent the most deeply subducted sectors of the belt and are its most thoroughly studied portions. Our review assesses the general nature of Phanerozoic mountain building. Two principal but intergradational tectonic end-member types, Circumpacific and Alpine, are generally distinguished.

(*a*) Circumpacific high-pressure (HP) metamorphic belts, such as the Franciscan Complex of western California and the Torlesse terrane of South Island, New Zealand, are characterized by voluminous quantities of terrigenous debris supplied to the subduction realm by nearby calc-alkaline arcs generated by the underflow of thousands of kilometers of oceanic lithosphere. (*b*) In contrast, Alpine HP-UHP orogens mark convergent plate junctions involving consumption of an intervening ocean basin followed by introduction of an arc, microcontinent, or promontory of sialic crust into the subduction zone. During collision, some crustal sections reach depths of at least 90–140 km, as indicated by the metamorphic crystallization of indicator minerals stable only at UHPs, including coesite or diamond, K-bearing pyroxenes, or Si-excess garnets and/or pyroxenes (Liou et al. 1998, 2000). On exhumation, many, but not all, collisional UHP terranes consist of an imbricate stack of tabular, low-aggregate-density sheets (Ernst et al. 1997). The Dabie-Sulu belt, the Western Alps, the Kokchetav Massif of northern Kazakhstan, the western Himalayan syntaxis of northern Pakistan, and the Western Gneiss Region of Norway constitute well-documented examples of such deep-seated rocks. In these largely quartzofeldspathic complexes, UHP phases are partially preserved in strong, tough, refractory zircon, pyroxene, and garnet. The host minerals are typified by great tensile strengths and low rates of intracrystalline diffusion. Armoring of the UHP mineral inclusions allows the maintenance of high confining pressures, provides spatial isolation from rate-enhancing intergranular aqueous fluids that promote recrystallization of the matrix minerals, and protects the inclusions from complete back reaction during decompression.

Ductilely deformed nappes and thrust sheets form in subduction channels (Koons et al. 2003, Hacker et al. 2004, Terry & Robinson 2004) during underflow and exhumation; they constitute the structures of most exposed HP and UHP complexes. Ascent to shallow crustal levels is accomplished by one or more process: tectonic extrusion (Maruyama et al. 1994, 1996; Searle et al. 2003; Mihalynuk et al. 2004), corner flow blocked by a hanging-wall backstop (Cowan & Silling 1978; Cloos & Shreve 1988a,b; Cloos 1993), underplating combined with extensional or erosional collapse (Platt 1986, 1987, 1993; Ring & Brandon 1994, 1999), and/or buoyant ascent (Ernst 1970, 1988; England & Holland 1979; Hacker 1996). Old, cool, rapidly sinking oceanic lithosphere may cause oceanward trench retreat more rapidly than encroachment of the forearc on the nonsubducted plate (Molnar & Atwater 1978, Seno
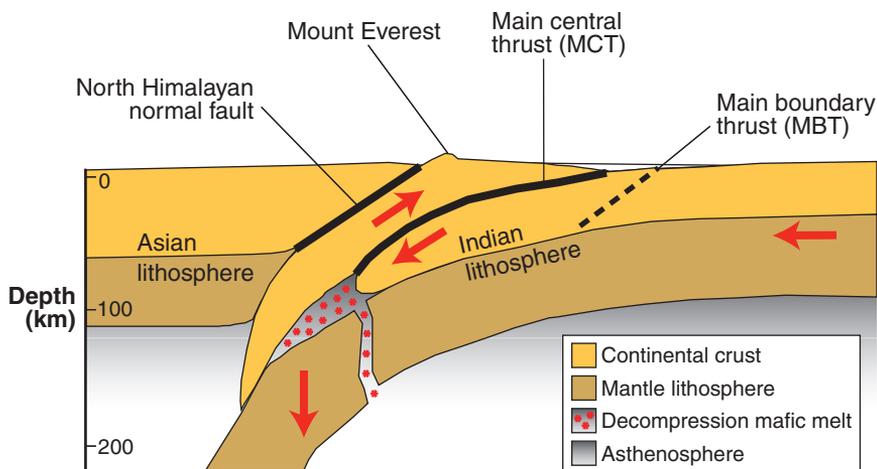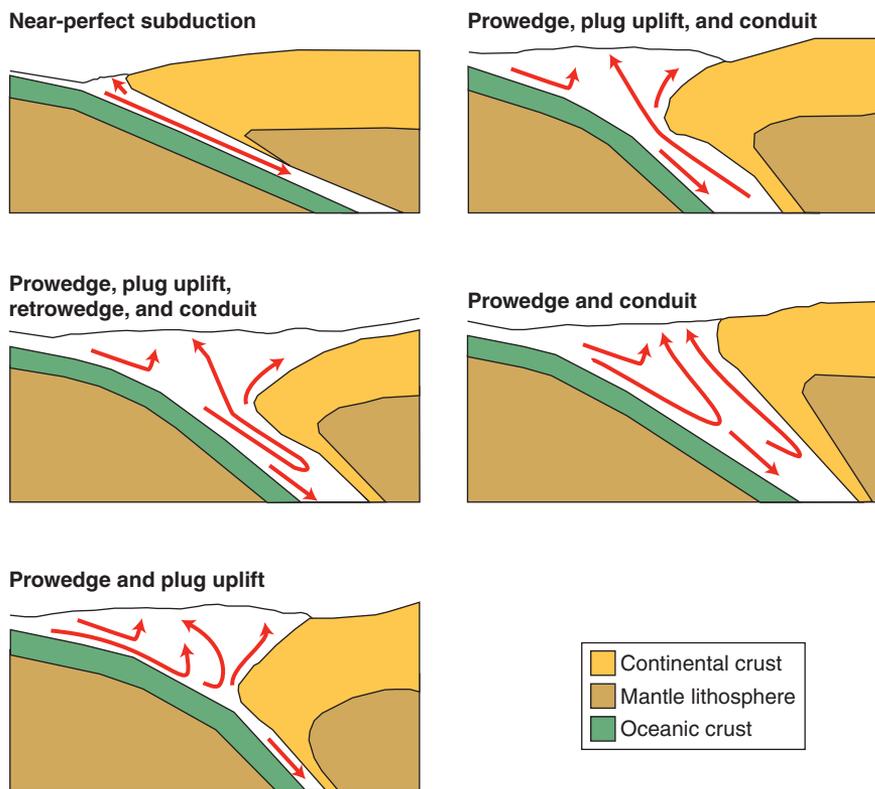
Figure 1

Simplified structural evolution of an Alpine-type collisional mountain belt, based chiefly on scale-model experiments by Chemenda et al. (1995, 1996, 2000). Delamination of the sialic crust from the downgoing lithosphere is a consequence of gravitational instability and subduction underthrusting. The Tongbai-Dabie-Sulu-Imjingang-Gyeonggi portion of the East Asian Permo-Triassic orogen evidently was subjected to plate convergence similar to that depicted here.

1985, Hamilton 1995); in such settings, compression and extrusion of subducted sialic sections cannot be responsible for their exhumation. Constriction by a rigid backstop requires buoyancy or tectonic contraction to produce the return flow of subducted continental material. Extension and erosion help to unroof HP-UHP terranes after they reach midcrustal levels, but do not produce the major pressure discontinuities that mark fault boundaries between deeply subducted and nonsubducted crust (Ernst 1970, Ernst et al. 1970, Suppe 1972).

Buoyancy coupled with erosional decapitation provides a plausible mechanism to account for the regurgitation of low-aggregate-density crustal slices. Geologic relationships, laboratory-scale models (Chemenda et al. 1995, 1996, 2000; **Figure 1**), and numerical simulations (Beaumont et al. 1996, 1999; Pysklywec et al. 2002; **Figure 2**) schematically illustrate this process (Parkinson et al. 2002, Carswell & Compagnoni 2003, Malpas et al. 2004). The strength/ductility and integrity of the subducted lithospheric materials, extents of deep-seated devolatilization, and rates of recrystallization strongly influence characteristics of the resultant HP-UHP metamorphic belts (Ernst et al. 1998). In all cases, however, low temperatures and high pressures generated by rapid underflow of poorly conducting rocks results in clockwise-type decompression paths. Schematic, generalized P-T (pressure-temperature)-time trajectories for examples of Alpine and Circumpacific subduction-zone orogenic belts are illustrated in **Figure 3**.

Near-perfect subduction

Prowedge, plug uplift, and conduit

Prowedge, plug uplift, retrowedge, and conduit

Prowedge and conduit

Prowedge and plug uplift
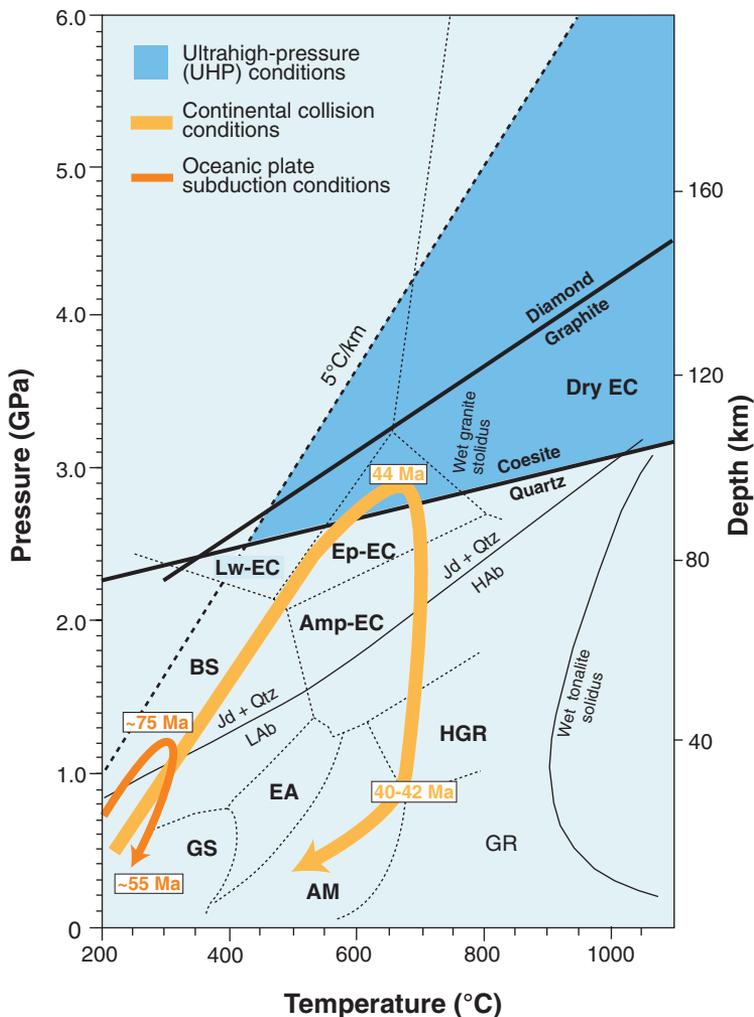
Continental crust
Mantle lithosphere
Oceanic crust

Figure 2

Schematic architectural development of Pacific-type subduction orogens derived through numerical modeling, simplified after Beaumont et al. (1996, 1999) and Pysklywec et al. (2002). Exhumation paths (red arrows) are a function of many input variables, including convergence rate, adherence to the downgoing plate, frictional resistance, temperature profile, and viscosity of the imbricated mélange. The Renge-Suo-Sikhote-Alin segment of the East Asian Permo-Triassic orogenic belt underwent somewhat more heterogeneous accretion, including the suturing of exotic terranes, than shown here, but relationships are topologically similar to those illustrated.

FRAMEWORK OF THE PERMO-TRIASSIC EAST ASIAN COLLISIONAL OROGEN

Figure 4 presents a simplified tectonic map of eastern Asia. In east-central China, the EW-trending Tongbai-Hong'an-Dabie-Sulu belt exhibits a general progression involving feeble blueschist-greenschist facies metamorphism in the south, passing northward to amphibolitized HP eclogitic gneiss + metamafic layers or pods, and then to UHP units, including garnet peridotites (Liou et al. 1996). Protoliths range from Middle and Late Proterozoic granitic gneisses through bimodal igneous rocks, platform carbonates, and turbidite strata, including Vendian–Early Paleozoic (Sinian) peraluminous sediments and volcanic rocks. Farther north, the Dabie-Sulu portion
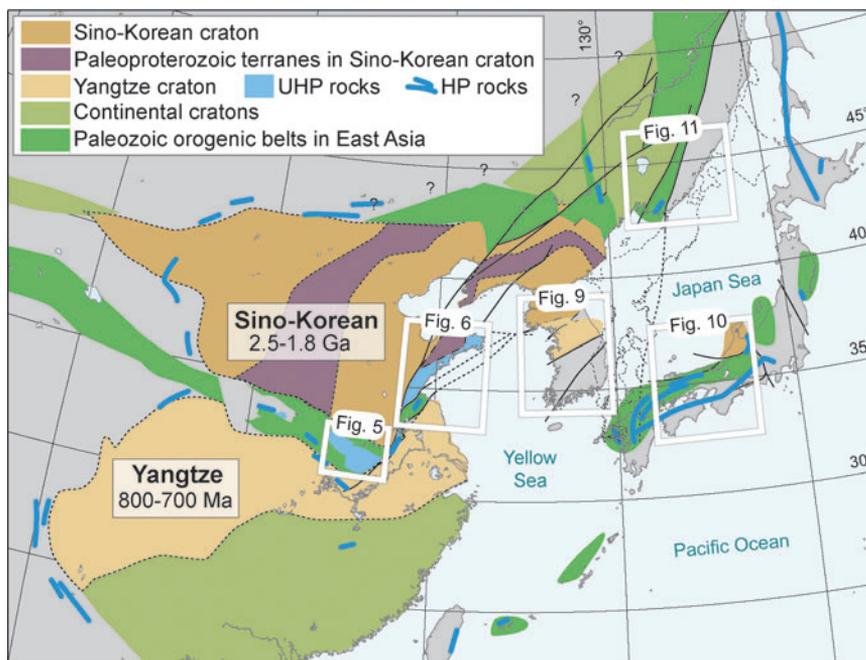
Figure 3

Pressure-temperature-time paths for subduction, then exhumation to midcrustal levels for (*a*) continental collision conditions typical of UHP imbricate thrust sheets, such as those exposed in the Kaghan Valley, western Himalayan syntaxis, after O'Brien et al. (2001) and Kaneko et al. (2003), and (*b*) oceanic plate subduction conditions diagrammatically illustrated for the Late Cretaceous Diablo Range portion of the eastern Franciscan HP belt (Ernst 1993, Dalla Torre et al. 1996).

of the terrane is widely invaded by Late Mesozoic granitoids. Triassic (220–240 Ma) HP-UHP mineral parageneses developed on the leading edge of the Yangtze (South China) craton passive margin (Hacker et al. 2000, 2004). Several NE-trending faults subparallel to the major left-lateral Tan-lu fault separate the collisional orogen into distinct blocks. Reflecting differential unroofing, the degree of metamorphism of exhumed units varies from block to block. The UHP belt is best exposed in the Sulu and Dabie regions, whereas the HP belt crops out widely in Hong'an and Tongbai. The stable, nonsubducted, Late Archean–Early Proterozoic Sino-Korean (North China) craton lies directly north of the convergent plate junction and was not affected by the Triassic HP-UHP subduction event.

The central and southern Korean Peninsula consists of four major geologic belts displaying Permo-Triassic HP metamorphism. From south to north, the disposition

Figure 4

Generalized tectonic map of the Tongbai-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin orogen accreted against the North China craton along the Permo-Triassic margin of East Asia. See text for map sources and discussion.

and formational ages of these units are the Proterozoic Yeongnam cratonal massif, the Neoproterozoic–Early Mesozoic Ogcheon belt, the Archean-Proterozoic Gyeonggi microcontinental massif (M. Cho, personal communication, 2006), and the Late Proterozoic–Middle Paleozoic Imjingang belt. The Late Archean and younger Nagrim massif, part of the North China craton, lies to the north across a profound suture zone. Mafic eclogites that recrystallized at ~230 ± 30 Ma have been reported from the SW Gyeonggi block (Kim et al. 2006); the Permo-Triassic Imjingang belt (249–253 Ma) is made up of HP rocks (Ree et al. 1996, Cho et al. 2006). Unlike east-central China, the essentially uniform upper amphibolite metamorphic grade of the Gyeonggi massif does not increase northward toward the plate boundary juxtaposing South China cratonal rocks against the North China block. Even so, the convergent suture apparently lies along, or directly south of the Imjingang HP belt.

The Yangtze and Sino-Korean cratons of east-central China, as well as the micro-cratonal blocks of the Korean Peninsula, are lacking in Southwestern Japan. Instead, a series of accretionary prisms, oceanic crustal slices (i.e., ophiolites), and subduction complexes sequentially collided with the East Asian margin during Paleozoic and Triassic time (Tsujimori 2002, Tsujimori & Liou 2005, Tsujimori et al. 2006). The East Asian sialic crust grew seaward episodically, with ages of recrystallization and suturing of exotic terranes against the continental margin generally decreasing toward the

subducting paleo-Pacific oceanic plate. The Renge and Suo HP blueschist-eclogite terranes were metamorphosed and accreted to the East Asian margin at ~305 ± 25 and 210 Ma, respectively. As is characteristic of exhumed subduction complexes, the intensity of recrystallization increases landward toward the stable, nonsubducted Middle Paleozoic continental margin (i.e., toward the Hida and Oki belts, floored by Archean-Proterozoic basement apparently of Sino-Korean affinities).

More speculative is a conjectured northern extension of the Renge-Suo composite terrane into the Paleozoic and Mesozoic accretionary complexes of Sikhote-Alin (Zonenshain et al. 1990, Khanchuk et al. 1996). Metamorphic conditions preserved in these exhumed subduction-zone rocks are attested to by the presence of low-T blueschists (Ishiwatari & Tsujimori 2003). Similar to other segments of the orogen, this feebly recrystallized HP terrane was sutured against the Asian continental margin by Triassic time.

Lack of participation by the stable, nonsubducted Sino-Korean craton in the Permo-Triassic deformation and HP-UHP recrystallization, as well as the observed northward progression in HP and UHP exhumed slices suggests that the approaching margin of the Yangtze craton and yet farther north oceanic lithosphere were subducted beneath the East Asian margin prior to collisional decoupling of slices from the downgoing plate and ascent to midcrustal levels. We infer that an original curvilinear paleogeometry of the Permo-Triassic convergent suture zone was segmented and offset by later differential plate motions and faulting. For example, in the SW sector in east-central China, the Tongbai-Dabie terrane was displaced ~500 km from the formerly contiguous Sulu belt by Cretaceous-Cenozoic sinistral slip on the Tan-lu fault (Yin & Nie 1993). In addition, Miocene and younger sea floor spreading opened the marginal Sea of Japan, displacing the Japanese archipelago, including the Renge-Suo amalgamated complex ~400 km SE of its projected western extension through the Korean Peninsula, as well as its hypothesized northern analogue in Sikhote-Alin (Ernst & Liou 1995).

GEOLOGIC SKETCH OF EAST-CENTRAL CHINA

Tongbai Area

The Dabie-Sulu Mountains pass WNW through the adjacent Hong'an and contiguous Tongbai areas to the far-western Qinling Range and even more remote Qilian Mountains (**Figure 4**). Formerly correlated with the Dabie-Sulu belt, the latter two terranes contain HP-UHP metamorphic units of Cambrian age (~450–500 Ma), hence must have collided with the North China block long before the Permo-Triassic subduction-zone recrystallization of the orogenic belt on the east (Hacker et al. 2004, Ratschbacher et al. 2006). The EW-trending, 5–10-km-wide Huwan mylonitic zone defines the tectonic contact between the more inboard Qinling belt on the NW and the outboard Tongbai-Hong'an-Dabie complex on the SE. Consisting of Late Proterozoic basement recrystallized at ~240 Ma to mafic, HP eclogitic lenses and quartzofeldspathic gneisses on the north, the Tongbai belt grades southward to less intensely deformed, weakly recrystallized platform strata and

relatively massive greenstone-blueschist lithologies. Feebly metamorphosed HP rocks are also present to the WSW directly north of Wudangshan.

Dabie-Hong'an Terrane

The Dabie-Hong'an HP-UHP terrane consists of a series of fault-bounded metamorphic units. Proceeding southward, these units are a low metamorphic-grade flysch series: the northern Dabie high-T metamorphic complex, the central Dabie UHP belt, the south-central Dabie HP eclogite belt, and the southern Dabie epidote-amphibolite-blueschist belt (**Figure 5**). Widespread postcollisional Mesozoic granitic plutons contain xenoliths of granitic gneiss and mafic ± ultramafic rocks and have significantly modified earlier HP-UHP structures and phase assemblages in the northern Dabie Mountains (Jahn et al. 1999; Hacker et al. 2000, 2004; Zhao 2005). The feebly metamorphosed flysch is separated from the northern Dabie unit by the Xiaotian-Mozitan fault and is overlain by Jurassic-Cretaceous coarse-grained, shallow-water sedimentary and volcanic rocks. This section consists mainly of greenschist-facies slate, phyllite, metasandstone, and schist plus incipiently recrystallized shale, coal beds, and limestone.

The northern Dabie high-T metamorphic complex consists of abundant upper amphibolite- and granulite-facies to migmatitic gneisses (Zhang et al. 1996) and is
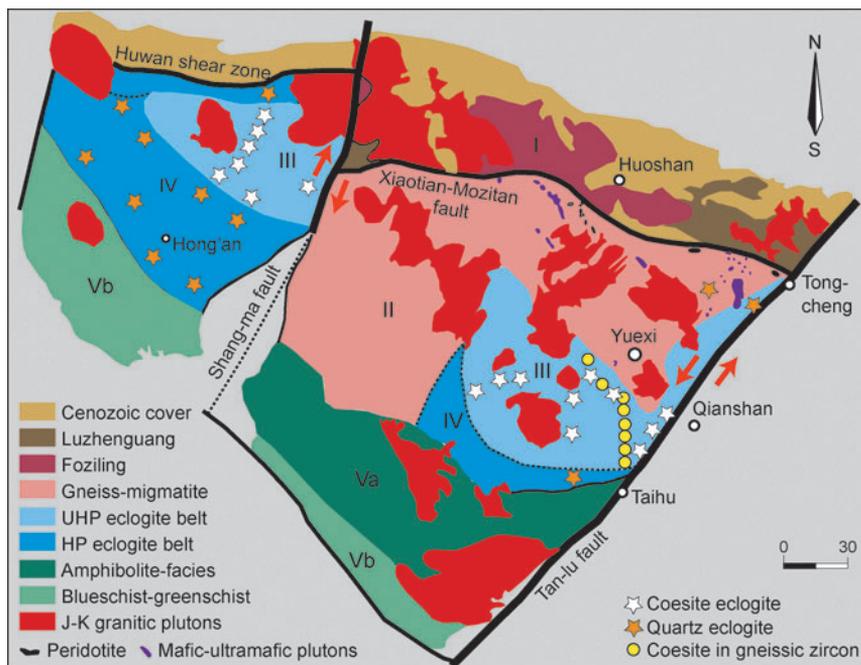
Figure 5

General geologic-tectonic map of the Dabie Mountains showing metamorphic units and locations of eclogite and coesite inclusions in gneissic zircons (after Liou et al. 1996).

regarded as part of the Yangtze craton (Hacker et al. 2000, Bryant et al. 2004). Ion microprobe U-Pb ages of zircons from orthogneisses reveal two stages of granitic intrusions at 749 ± 18 and 127 ± 4 Ma. Minor eclogite lenses are purported to occur in both peridotite and gneiss (Wei et al. 1998, S. Xu et al. 2000). However, the so-called eclogites enclosed in peridotite are actually garnet clinopyroxenite bodies; rare omphacite occurs only as trace inclusions in garnet, and the matrix clinopyroxenes are diopside. Recently, S. Xu et al. (2005) reported the presence of inclusions of microdiamond in garnet, but these findings need further confirmation. Eclogites enclosed in gneiss have been extensively retrogressed to amphibolites, retaining only minor garnet and rutile relics; omphacite is totally replaced by a symplectite of fine-grained plagioclase and amphibole. True omphacite-bearing eclogite has only been found as float (Wei et al. 1998). In addition to the mantle-derived Raobazhai peridotite, postcollisional mafic-ultramafic intrusives, including gabbro ($\pm$ diorite) with or without pyroxenite and hornblendite, are common in the northern Dabie. The Raobazhai ultramafic body consists mainly of Cr-spinel harzburgite and dunite with minor garnet pyroxenite and records early mantle crystallization at $\sim$2.2 GPa and $>1100^{\circ}$C, rather than subduction-zone UHP metamorphism (Zhang et al. 1996).

The central Dabie is the classic locality where inclusions of coesite (Wang et al. 1989, Okay et al. 1989) and microdiamond (S. Xu et al. 1992) were discovered as inclusions in eclogitic garnet. Coesite inclusions were found later in omphacite, kyanite, zoisite, zircon, and dolomite from mafic eclogitic pods and lenses in gneiss and marble (Cong et al. 1995, Zhang et al. 1995a, Zhang & Liou 1996, Liou et al. 1998, Carswell & Zhang 1999). The country rocks also contain UHP relics. Garnet peridotites, pyroxenites, and spatially associated eclogites at Bixiling and Maowu are mafic-ultramafic cumulate layers or lenses, interpreted as crust-hosted UHP metaperidotites (Liou & Zhang 1998, Jahn et al. 2003b).

Although present to the west in the adjoining Tongbai Mountains and to the east in the Dabie complex, the HP eclogite belt is most widely developed in Hong'an; the eclogites lack inclusions of coesite and recrystallized at lower pressures and temperatures than eclogites of the UHP belt. The central and south-central Dabie and Hong'an terranes are comparable in terms of lithologies and structures, thus appearing to represent portions of a crustal continuum. The intergradational amphibolite-blueschist unit is tectonically juxtaposed against the more northerly HP eclogite belt, along a normal (?) fault. In the southern Dabie, a coherent sequence of epidote-amphibolite-facies rocks, including felsic gneiss, pelitic schist, and amphibolite, lies north of the blueschist unit. These HP epidote amphibolites differ from the high-T northern Dabie amphibolites in the common occurrence of rutile, garnet, and zoisite/epidote and the lack of clinopyroxene. On the south, the blueschist-greenschist belt typically consists of sodic amphibole + actinolite + epidote + chlorite + titanite.

Sulu Terrane

Similar to the Dabie-Hong'an terrane, the Sulu area consists of fault-bounded UHP and HP belts, unconformably overlain by Jurassic clastic strata + Cretaceous volcanosedimentary cover and intruded by postorogenic Mesozoic granites. The Sulu
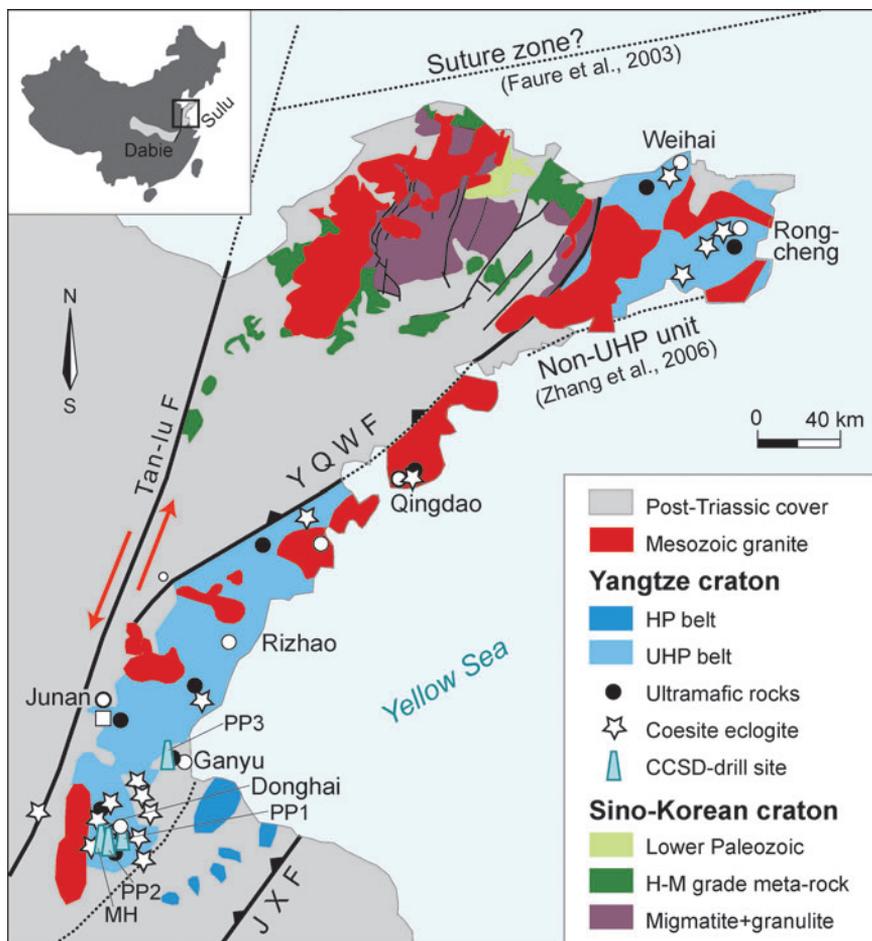
Figure 6

General geologic-tectonic map of the Shandong Peninsula, showing major metamorphic units, distribution of eclogites, and the CCSD drill site (after Zhang & Liou 1998). YQWF, Yantai-Qingdao-Wulian fault; JXF, Jiashan-Xiangshui fault; H-M, high-medium-grade metamorphic rocks.

terrane is bounded by the Yantai-Qingdao-Wulian fault (YQWF) on the NW against the Sino-Korean craton and the Jiashan-Xiangshui fault (JXF) on the south against the Yangtze craton (**Figure 6**). The UHP belt consists mainly of amphibolite-facies gneisses, with minor garnet peridotite, eclogite, amphibolite, kyanite-topaz-bearing quartzite, and marble. Numerous small (meters to kilometers) serpentinite and garnet peridotite bodies occur sporadically as blocks and lenses throughout the Sulu belt. Coesite and quartz pseudomorphs after coesite are present as inclusions in garnet, omphacite, kyanite, and epidote, or as an intergranular phase in eclogite (Hirajima et al. 1990, Zhang et al. 1995a, Liou & Zhang 1996, Zhang & Liou 1997). The HP belt

lying to the SE of the UHP terrane consists of quartz-mica schist, chloritoid-kyanite-bearing mica quartz schist, kyanite + OH-rich topaz-bearing quartzite, marble, and rare blueschist (Zhang et al. 1995b, 2002a).

Northwest of the YQWF, the Proterozoic-Archean high- to medium-grade metamorphic Sino-Korean basement is overlain by Lower Paleozoic metasedimentary rocks and Mesozoic volcaniclastic rocks plus coeval granitoids (Zhang et al. 1995a). Recent studies have significantly modified this simple subdivision. For example, Zhai & Liu (2005) considered the area NW of the YQWF, a magmatic-metamorphic complex approximately 40–60 km wide bordered by the Muping and Mishan faults, as a segment of the Sino-Korean craton juxtaposed against the Sulu terrane. Similarly, Hacker et al. (2006) suggested that the region between the YQWF and Tan-lu faults is part of the Qinling microcontinent, with the YQWF fault representing the Triassic suture between the Sino-Korean craton and the subducted Yangtze block. In contrast, Faure et al. (2003) divided the entire Shandong Peninsula to the east of the Tan-lu fault into (*a*) a southern UHP belt, (*b*) an eastern eclogite + migmatite area in Weihai, and (*c*) a northern migmatite area; these authors proposed a possible ENE-trending suture zone located north of Shandong Peninsula (**Figure 6**). We favor the interpretation of the YQWF as the tectonic boundary between North and South China cratons.

To clarify the structure and thickness of the Sulu UHP slab, and tectonic evolution of the collisional orogen, the Chinese Continental Scientific Drilling (CCSD) project was established in 1998. Three prepilot holes (PP-1 = 432 m; PP-2 = 1008 m; PP-3 = 705 m) and a 5-km main hole were drilled in Donghai, southern Sulu (**Figure 6**). The project recovered more than 80% core samples of para- and orthogneiss, garnet peridotite, and eclogite; many cores are continuous and quite fresh, particularly those of garnet peridotite. These samples have been intensively investigated, corroborating prior studies of the surface outcrops (Z. Xu et al. 2003, 2006).

Characteristics of Hong'an-Dabie-Sulu UHP Rocks

Available structural (Hacker et al. 1996, 2000, 2006; Webb et al. 1999; Faure et al. 2003; Z. Xu et al. 2003, 2006; Leech et al. 2006), metamorphic (Hacker & Wang 1995; Cong 1996; Zhang & Liou 1996, 1998; Zhang et al. 1995a,b, 2000; Liou et al. 1996), and geochronologic (e.g., Li et al. 1993; Bryant et al. 2004; X. Liu et al. 2004; Hacker et al. 2000, 2006; Jahn et al. 2003a,b) data reveal that the UHP rocks were exhumed from depths of 90–200 km between 240 and 220 Ma by a combination of normal-sense shear from beneath the hanging-wall Sino-Korean craton, southeastward thrusting onto the footwall Yangtze craton, orogen-parallel eastward extrusion, and subvertical thinning. Characteristics of Hong'an-Dabie-Sulu UHP rocks include (*a*) occurrence of widespread coesite and HP hydrous phases (such as talc, zoisite/epidote, nyböite, and phengite) in eclogite (Hirajima & Nakamura 2003, Rumble et al. 2003) and OH-rich topaz in kyanite quartzite (Zhang et al. 2002a); (*b*) world-record lowest $\delta^{18}O$ values (e.g., -15% for rutile) for mineral separates from eclogites and metasediments (for reviews, see Zheng et al. 2003, Rumble et al. 2003); (*c*) highest global bulk-rock ε_{Nd} values of approximately $+170$ to 260 for Weihai eclogites (Jahn et al. 1996, 2003b);

(*d*) widespread garnet peridotites of mantle origin occurring in the Sulu terrane (Zhang et al. 2000, 2004); (*e*) abundant exsolution textures in UHP minerals from garnet peridotite and eclogite (Zhang & Liou 1998, 1999, 2003; Zhang et al. 2000; Chen & Xu 2005); and (*f*) thin clinoenstatite lamellae in peridotitic orthoenstatite (Zhang et al. 2002b).

Preservation of extraordinary $\delta^{18}O$ and ε_{Nd} values in Dabie-Sulu UHP rocks indicates that closed-system recrystallization and a near absence of a pervasive aqueous fluid disfavored reequilibration of oxygen isotopes and temperatures too low to reset Nd isotopes during roundtrip subduction/exhumation of the supercrustal rocks (Rumble et al. 2003, Jahn et al. 2003b). This conclusion is consistent with the described preservation of protolith structures such as pillows and unconformities (Dong et al. 2002, Oberhänsli et al. 2002), igneous textures, and metastable igneous minerals including biotite, orthopyroxene, and plagioclase (Hirajima et al. 1990, Zhang & Liou 1997).

Dabie-Sulu UHP Metamorphism as Documented by Coesite Inclusions in Zircon

Quartzofeldspathic gneisses are the predominant rock type in the Dabie-Sulu UHP terrane; most lack discernable evidence of UHP metamorphism. Field observations suggest that some eclogite pods in country gneisses are not fault bounded; rather, the lithologic contacts seem to have retained structural coherence throughout subduction, metamorphism, and exhumation. Rare mineralogic indicators of UHP metamorphism are present in country rock gneisses, quartzites, and marbles. Tiny coesite inclusions have been reported in (*a*) zircons from felsic gneiss (Tabata et al. 1998; Ye et al. 2000a,b; J. Liu et al. 2001; F. Liu et al. 2001, 2002, 2004b) and marble (F. Liu et al. 2006), (*b*) dolomite and garnet from calc-silicate rocks and dolomite-bearing eclogite (Schertl & Okay 1994, Zhang & Liou 1996), and (*c*) garnet and jadeite from jadeite-bearing quartzite (Zhang et al. 1995a,b; Liou et al. 1997). Study of mineral compositions in Dabie felsic gneisses and UHP schists and thermobarometric computations (Carswell et al. 1997, 2000) have shown that these lithologies recrystallized under P-T conditions similar to those of the intercalated coesite eclogites and garnet peridotites.

Evidence of HP-UHP metamorphism is typically preserved as rare mineral inclusions and relict phase assemblages within host rocks that later reequilibrated under crustal conditions. Among the various types of evidence, zircons from HP-UHP rocks provide the most useful information concerning the P-T-time path of a subduction complex because zircon is stable and extremely resistant to back reaction over a wide range of conditions. During growth, individual zircon zonal domains may include and preserve inclusions of phases in equilibrium with the matrix assemblages. Moreover, as Hermann et al. (2001) and Rubatto & Hermann (2001) showed, zircon growth attending eclogite-facies P-T conditions can be distinguished from zircon crystallization under plagioclase-stable conditions: Zircons formed in equilibrium with garnet display a characteristic HREE (heavy rare earth element) depletion and no Eu anomaly, whereas those grown at crustal depths in equilibrium with

plagioclase have pronounced HREE enrichment and a negative Eu anomaly. Consequently, identification of mineral inclusions and characterization of the REE patterns of zoned zircons combined with ion microprobe U-Pb dating has allowed elucidation of the P-T-time paths for some UHP terranes (Hermann et al. 2001, McClelland et al. 2006, Mattinson et al. 2006).

Inclusions of coesite and other HP-UHP minerals are present in zircons separated from Dabie-Sulu eclogites and their country rocks as noted above, but thus far, the approach using REE patterns has not been applied to constrain prograde ages for individual zoned zircon domains. Nevertheless, zoned zircons from Dabie-Sulu UHP rocks from both surface and core samples (eclogite and amphibolite, para- and orthogneisses, and marble) retain low-P mineral-bearing inherited cores, UHP mineral-bearing (e.g., coesite) mantles, and low-P phase-bearing (e.g., quartz, plagioclase) rims. Examples of such studies are illustrated in **Figure 7** for PP-2 drill hole cores. Ion microprobe U-Pb analyses of these zoned zircons have identified three discrete age groups, shown schematically in **Figure 8**: latest Proterozoic protolith ages (>680 Ma) in inherited cores, the culminating UHP metamorphic event in coesite-bearing mantles at 220–240 Ma, and a late amphibolite-facies retrogressive overprint in quartz-bearing rims at 210 ± 10 Ma. These studies demonstrate that supercrustal and mafic-ultramafic rocks were subjected to in situ UHP metamorphism. Using the same approach, the boundary between the HP and UHP belts in the vicinity of the Donghai drill sites has been traced (F. Liu et al. 2004a).

GEOLOGIC SKETCH OF THE KOREAN PENINSULA

The geology of the Korean Peninsula consists of five distinct lithotectonic belts, as presented in **Figure 9**. From NW to SE, these are the Nagrim massif, the Imjingang belt, the Gyeonggi massif, the Ogcheon belt, and the Yeongnam massif. The Nagrim massif is part of the North China craton; it includes Late Archean to Paleoproterozoic gneisses associated with younger metaigneous and metasedimentary rocks. This Precambrian basement is covered by Cambro-Ordovician and Permo-Carboniferous strata. The Nagrim massif was not significantly affected by the Permo-Triassic contractional HP accretionary event considered in this review. We regard the four belts to the south as possessing Yangtze affinities, but this correlation remains controversial (Cluzel et al. 1991, Yin & Nie 1993, Chough et al. 2000).

The Imjingang belt is an EW-trending, Barrovian-style metamorphic belt consisting chiefly of metasedimentary and metavolcaniclastic sequences with minor marble (Cho et al. 1995, 2006; Ree et al. 1996). Cho et al. published a U-Pb ion microprobe age of 253 ± 2 Ma for zircon growth attending metamorphic conditions of 0.85–1.15 GPa, 660–780°C for the garnet amphibolite unit, as well as a Neoproterozoic U-Pb age of 861 Ma from relict igneous zircon in amphibolite.

The Gyeonggi massif is a polymetamorphosed granulitic gneiss terrane, located between the Imjingang belt and Ogcheon belt. The southern boundary with the Ogcheon belt is defined by a mylonitic alkaline metagranitoid (Lee et al. 2003). The Gyeonggi massif consists of Archean to Proterozoic continental basement and a Paleo-Mesoproterozoic supercrustal series; minor serpentinized peridotite crops out
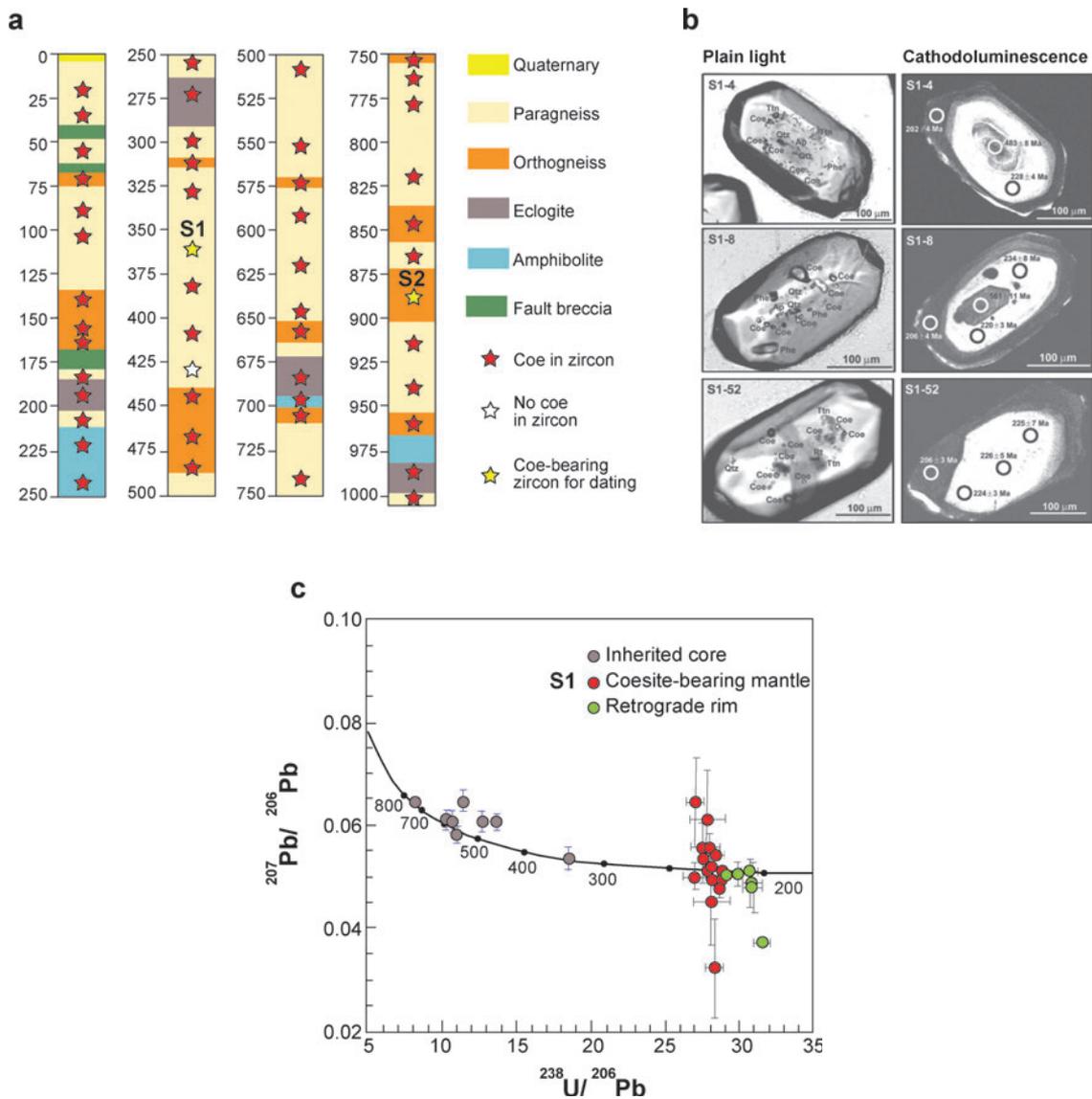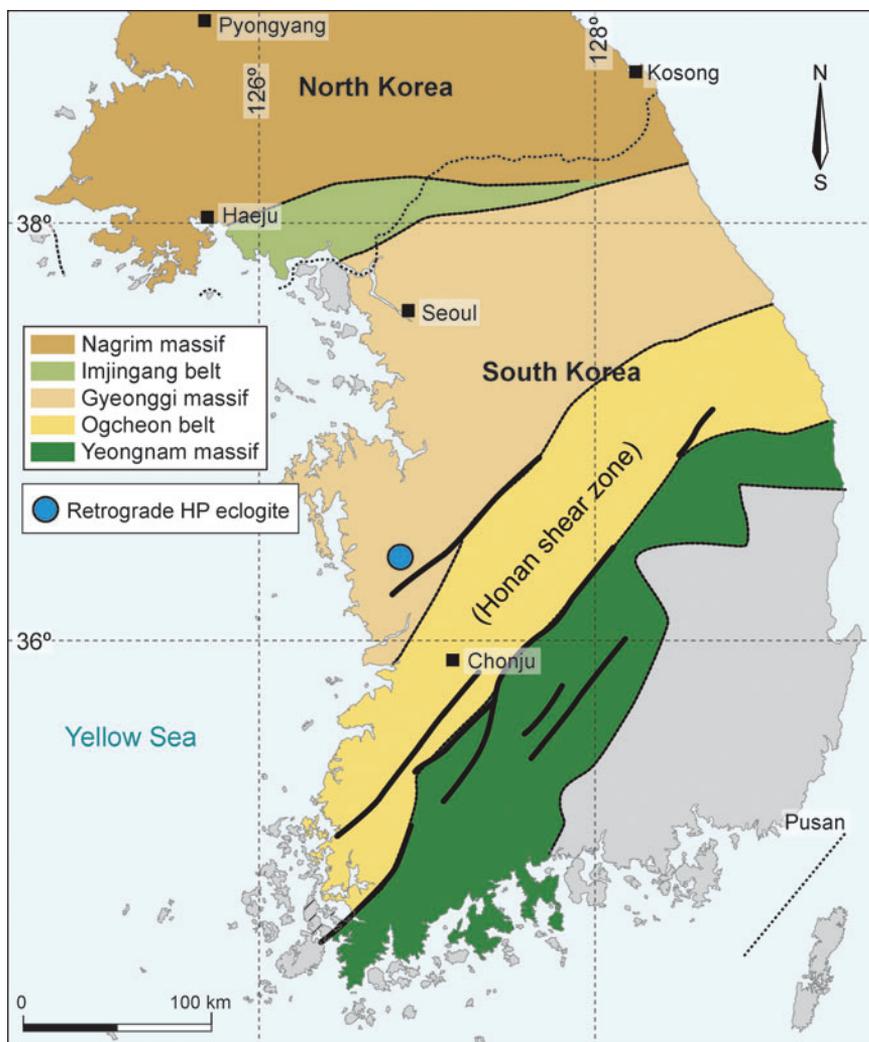
Figure 7

(*a*) Lithologic column of CCSD hole PP-2 indicating locations of zircon separates containing coesite inclusions. (*b*) Zircons from mafic eclogites and felsic gneisses shown in plain light and in cathodoluminescence; images after F. Liu et al. (2004a,b). (*c*) Tera-Wasserburg diagram for SHRIMP U-Pb zircon ages of a paragneiss (S1) recovered from the bore-hole depth of 362 m.
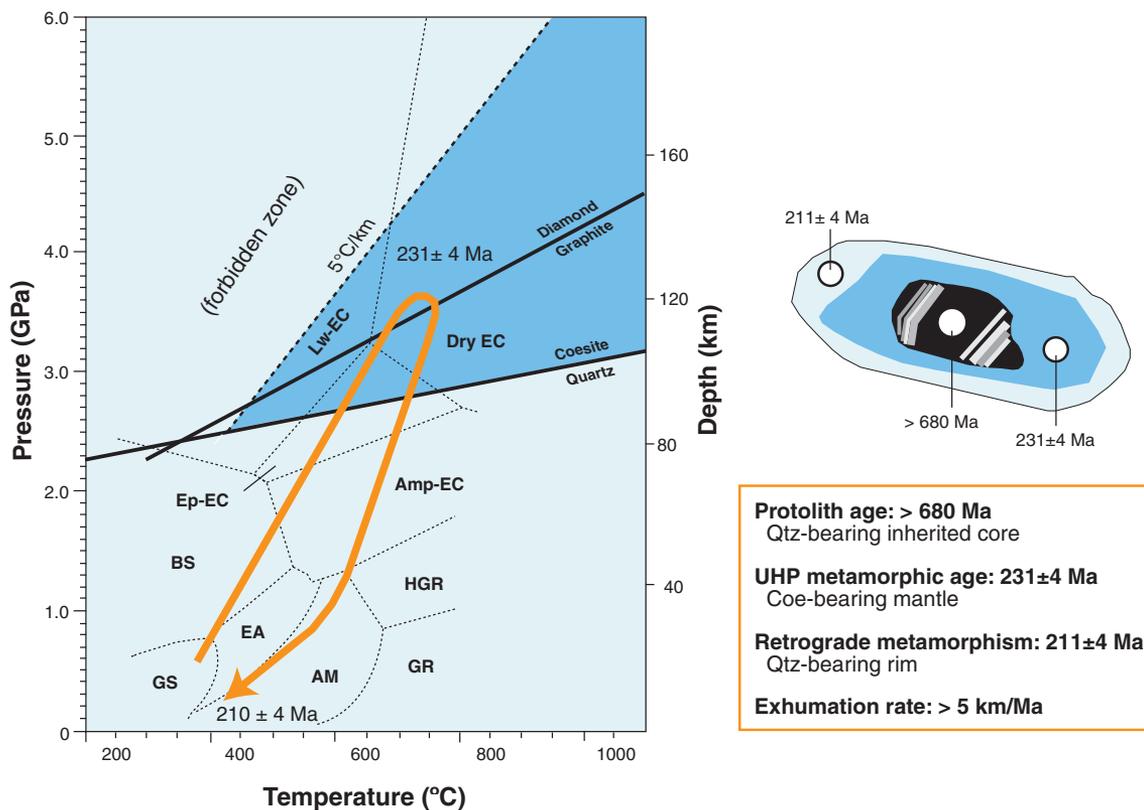
Figure 8

Schematic P-T-time path for Sulu UHP rocks based on mineral parageneses, P-T estimates of various rocks, and SHRIMP U-Pb dating of zoned zircons (Zhang et al. 2004).

in the SW part of the terrane (Lee & Cho 1995, 2003; Lee et al. 2000, 2003; Oh et al. 2005, 2006; Seo et al. 2005; Kim et al. 2006). Zircons from banded gneiss yielded a TIMS U-Pb age of 2.16 Ga (Kim et al. 1999). Ion microprobe U-Pb zircon ages from various granitic rocks and orthogneisses display zircon values ranging 2900–713 Ma (Lee et al. 2000, 2003; Zhai et al. 2005). In contrast, monazite U-Th-total Pb ages indicate an approximately 255–240 Ma regional metamorphic event (Suzuki & Adachi 1994, Cho et al. 1996). Kim et al. (2000) also reported a 226 Ma Rb-Sr muscovite age from mylonitic gneiss in the Gyeonggi massif and interpreted it to represent postcollisional, extensional ductile shear. Recently, Oh et al. (2005) described a relict eclogitic mineral assemblage consisting of Cpx (Jd = ~22%) + Grt + Rt + Ab in a mafic granulite; they estimated conditions of metamorphism as 1.7–2.1 GPa and 835–860°C for the HP mineral assemblage, and 0.7–1.1 GPa and 830–850°C for a later, low-P granulite-facies stage. Kim et al. (2006) reported zircon ion microprobe U-Pb ages of ~800 Ma cores and ~230 Ma rims from their retrograde eclogite, although the analytical data are mostly discordant.

Figure 9

General geologic-tectonic map of the central/southern Korean Peninsula, nonmetamorphosed
Cretaceous and Cenozoic units shown in gray (after Cluzel et al. 1991, Yin & Nie 1993, Oh
2006).

The Ogcheon belt is a NE-SW-trending polymetamorphic belt. It is made up
chiefly of Neoproterozoic to Paleozoic low-grade metasedimentary rock, metafel-
sic to intermediate metavolcanic rock, and scarce marble (Cluzel et al. 1990, Min
& Cho 1998, Chough et al. 2000, Oh et al. 2004, Cho & Kim 2005). Rare
staurolite-kyanite-grade pelitic schists occur in the NW part of the terrane. The
Ogcheon belt exhibits Paleozoic stratigraphy very similar to that of the North China

craton (Ishiwatari & Tsujimori 2003), hence may not be analogous to the Dabie-Sulu belt. Conventional U-Pb dating of zircon from metatrachyte yielded an U-Pb upper intercept of 756 Ma (protolith age) and a lower intercept of 160 Ma (Lee et al. 1998). Cho & Kim (2005) also reported a zircon ion microprobe U-Pb age of 742 Ma from metafelsic tuff, and confirmed a Neoproterozoic rifting event at ~750 Ma. Cheong et al. (2003) proposed that the Ogcheon belt underwent a peak metamorphic event at ~285 Ma, based on Pb-Pb whole-rock ages of slate and uraninite electron-microprobe Th-U total Pb chemical ages. This Early Permian metamorphic culmination is supported by a zircon ion microprobe U-Pb age of ~290 Ma (Cho et al. 2004). Cho & Kim (2005) proposed a revised, three-stage metamorphic evolution for the Ogcheon belt: Permian amphibolite-facies metamorphism (P = 0.4–0.9 GPa, T = 490–630°C), Triassic greenschist-facies metamorphism (P = 0.1–0.3 GPa, T = 350–500°C), and Jura-Cretaceous contact metamorphism around granitoids. This history of recrystallization is compatible with structural development of the Ogcheon belt as a Neoproterozoic intracontinental rift zone that evolved into a Permo-Triassic fold-thrust belt (Cluzel et al. 1990, Cho & Kim 2005).

The Yeongnam massif lies to the SE of the Honam shear zone, and consists of gneisses, minor amphibolites, and metasedimentary rocks. Metamorphic grade ranges from lower-amphibolite to lower-granulite facies, reaching 750–800°C and 0.4–0.6 GPa in migmatitic gneisses (Kim & Cho 2003). TIMS U-Pb ages for granitic gneisses range from 1.9 to 2.1 Ga (Cheong et al. 2000). Apparently, Precambrian crustal evolution of the Yeongnam massif was characterized by the formation of protocrust at ~2.9–2.5 Ga, followed by felsic magmatic episodes at ~2.1–1.9 Ga. A correlation of this lithotectonic entity with the Yangtze, or Cathaysia (?) block is plausible but uncertain (Lee et al. 1998).

GEOLOGIC SKETCH OF THE EAST ASIAN PACIFIC RIM

Southwestern Japan

The Japanese archipelago is an active Pacific-type accretionary orogenic system with oceanward growth since Early Paleozoic time, as supported by considerable field-geologic and biostratigraphic data (Isozaki 1996, 1997; Maruyama 1997; Maruyama et al. 1997; Ishiwatari & Tsujimori 2003). Geologic relationships are illustrated in **Figure 10**. The growth of SW Japan is characterized by a series of orogen-parallel accretionary complexes containing syn- or postorogenic calc-alkaline volcanic rocks and plutons; each accretionary complex is characterized by an oceanic plate stratigraphy, and widespread granitic magmatism accompanied low-P metamorphism (Isozaki 1996). The overall structure is a stack of north-rooting, subhorizontal nappes, with older sheets normally occupying upper structural positions. The nappes were gently folded in Cretaceous time to form synform-antiform structures. Several stages of exhumation of HP metamorphic rocks have been documented, e.g., 450–400 Ma (Kurosegawa-Oeyama), 330–280 Ma (Renge), 220–170 Ma (Suo), and 90–60 Ma (Sambagawa). Paleozoic terranes are sporadically exposed in the Hida and Chugoku mountains, as well as in Kyushu.
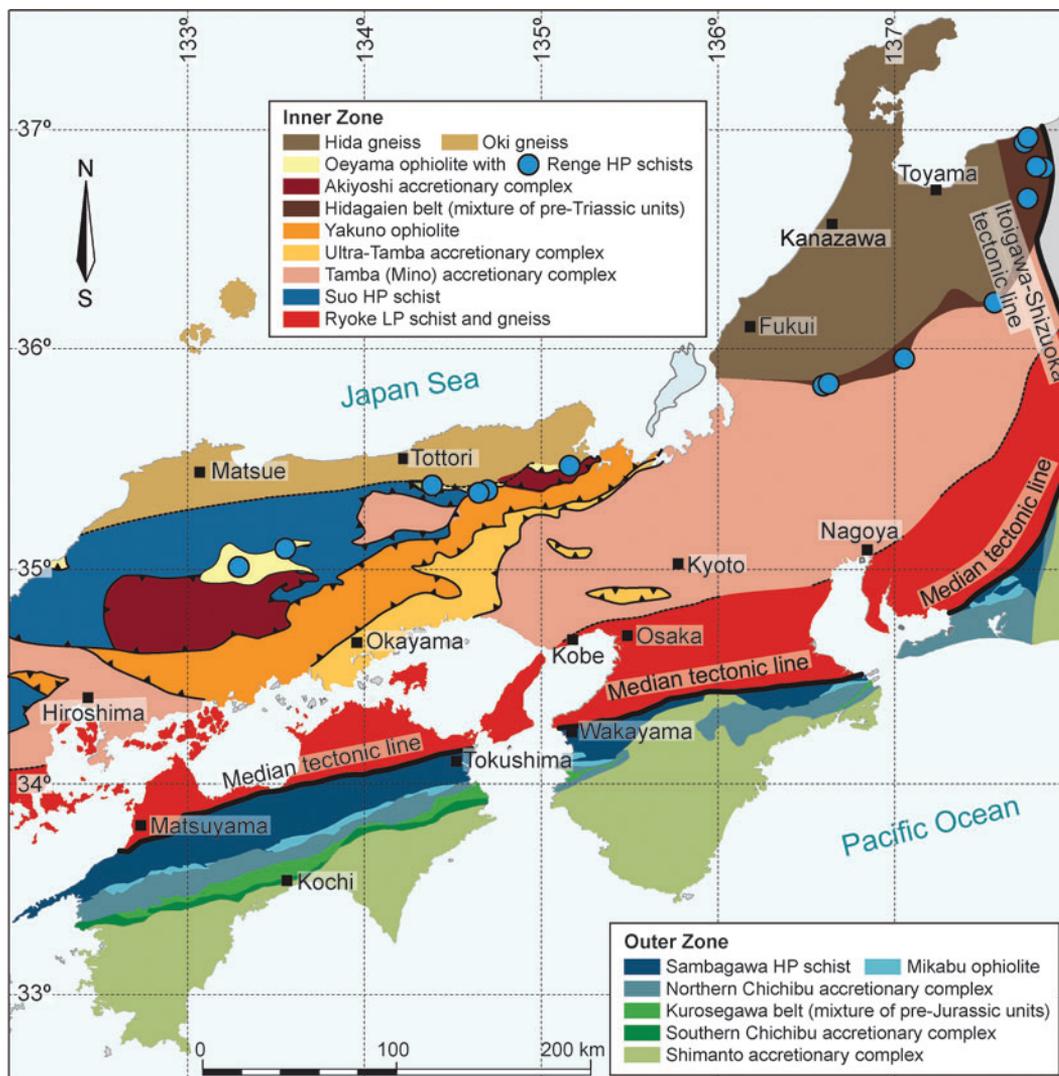
Figure 10

General geologic-tectonic map of SW Japan (after Maruyama et al. 1997, Ishiwatari &
Tsujimori 2003).

In the Hida Mountains, an eastern portion of Southwestern Japan, pre-Jurassic
metamorphic rocks occur as two petrotectonic units, the Hida belt and the Hida-
gaien (Hida Marginal) belt. These basement terranes are overlain unconformably
by Lower Jurassic to Lower Cretaceous shallow-marine and nonmarine sedimen-
tary rocks. The Hida belt apparently was thrust southward as a large-scale nappe
onto the Hidagaien belt (Komatsu 1990). The Hida consists mainly of polymetamor-
phosed orthogneiss, paragneiss, marble, amphibolite, and Fe-Al-rich pelitic schist

(Hiroi 1981, 1983; Suzuki et al. 1989; Arakawa et al. 2000). Zircon ion microprobe U-Pb geochronology for the Hida paragneiss gave a concordant detrital age of 1.84 Ga, whereas zoned zircons record three different ages, 1.69 Ga, 440 Ma, and 250 Ma (Y. Sano et al. 2000). Microprobe Th-U-total Pb chemical ages of zircon in the paragneisses yield 230–250 Ma for sillimanite-grade amphibolite-facies metamorphism (Suzuki & Adachi 1994). K-Ar and Rb-Sr mineral ages of both metamorphic rocks and remobilized Jurassic granitic intrusions cluster at ~180 Ma (Ohta & Itaya 1989). In the Hida gneiss terrane, a typical Barrovian-type staurolite-bearing pelitic-schist unit, termed the Unazuki belt, represents a possible eastern extension of the Ogcheon terrane (Hiroi 1983) and the Sulu-Dabie suture zone (Isozaki 1997, Maruyama 1997).

In contrast, the Hidagaien belt is a composite tectonic unit that lies structurally between the Hida belt and the outboard Jurassic Tamba-Mino accretionary complex (Komatsu 1990). The Hidagaien terrane consists mainly of fragments of various pre-Jurassic rocks that are most widely developed in the Chugoku Mountains; serpentinites containing blocks of Late Paleozoic schists and Middle Ordovician to Upper Triassic unmetamorphosed clastic rocks are the most characteristic components (Banno 1958; Tazawa 2001; Kurihara & Sashida 2000; Tsujimori 2002, 2004; Tsukada 2003; Nozaka 2005). Metasomatic zircon in jadeitite within serpentinite gave a U-Pb ion microprobe age of ~500 Ma (Kunugiza et al. 2004). HP schists of the Hidagaien belt are termed the Renge metamorphic rocks (Nishimura 1998, Tsujimori et al. 2000); they record chiefly greenschist-amphibolite-facies metamorphism, but locally preserve blueschist-eclogite-facies assemblages. P-T conditions of the latter were estimated as >1.8 GPa and 550–600°C (Tsujimori 2002). Phengitic white micas from the Renge epidote-glaucophane eclogites and garnet amphibolites yield K-Ar and Ar-Ar ages of approximately 347–283 Ma, regardless of metamorphic grade (Shibata & Nozawa 1968, Kunugiza et al. 2004). However, a Triassic K-Ar age was reported recently from a paragonite-bearing garnet-epidote-amphibolite (Tsujimori et al. 2006).

In the Chugoku Mountains, tectonically superposed, almost EW-trending Paleozoic ophiolites and accretionary complexes occupy the highest structural positions (Ishiwatari & Tsujimori 2003). Pre-Triassic rocks occur as six petrotectonic units: (*a*) the Oki belt, (*b*) the Oeyama belt, (*c*) the Akiyoshi belt, (*d*) the Maizuru belt, (*e*) the Ultra-Tamba belt, and (*f*) the Suo belt. The Oki belt consists of low-P pelitic and felsic gneisses ± minor marble and amphibolite. Microprobe Th-U-total Pb ages of metamorphic monazite and zircon in gneisses yield ~250 Ma for the amphibolite-facies metamorphism (Suzuki & Adachi 1994), whereas conventional TIMS zircon U-Pb ages are ~1.9 Ga (Yamashita & Yanagi 1994). This gneissic terrane is petrologically similar to the Hida belt. The Early Paleozoic Oeyama belt consists mainly of serpentinized harzburgite with minor gabbroic rocks (Arai 1980, Tsujimori & Liou 2004); Sm-Nd ages for gabbroic intrusions are ~560 Ma, suggesting a Cambrian ophiolite sequence. Jadeite-inclusion-containing zircon in a jadeitite vein in serpentinite yielded a U-Pb SHRIMP age of ~470 Ma (Tsujimori et al. 2005). Two different HP metamorphic rock types are associated with the Oeyama belt as tectonic blocks: epidote-amphibolite facies metagabbroic rocks with 470–400 Ma hornblende K-Ar ages (Nishimura & Shibata 1989, Tsujimori & Liou 2004) and

blueschist-facies pelitic and mafic schists with phengite K-Ar ages of 330–280 Ma (Nishimura 1998, Tsujimori & Itaya 1999). The younger HP rocks are regarded as fragments of the Late Paleozoic Renge blueschist belt, tectonically underlying the Oeyama belt (Tsujimori 1998). The Akiyoshi belt is a Permian accretionary complex consisting mainly of a thick limestone-greenstone complex associated with pelagic to hemipelagic sediments; limestone contains Early Carboniferous to Middle Permian fossils (Kanmera et al. 1990), and greenstone exhibits an N-MORB geochemical affinity (S. Sano et al. 2000). The Maizuru belt is a Late Permian ophiolitic unit capped by sedimentary cover; ophiolitic metabasalt-metagabbro-metaperidotite complexes in this belt are termed the Yakuno ophiolite (Ishiwatari 1985, Ichiyama & Ishiwatari 2004). Metagabbroic hornblende has yielded K-Ar ages of ~280–240 Ma (Shibata & Nozawa 1968), and zircon from plagiogranite provided U-Pb ages of ~280 Ma (Herzig et al. 1997). The Ultra-Tamba belt is a Late Permian accretionary complex lying structurally beneath the Maizuru belt; it consists mainly of pelagic to hemipelagic sediments with minor greenstones (Ishiga 1990). The Suo belt is HP metamorphic belt consisting dominantly of pumpellyite-actinolite facies to greenschist/epidote-blueschist transitional facies rocks (Nishimura 1998). Phengitic micas have yielded K-Ar ages of ~220 Ma in the east and ~190 Ma in the west, whereas U-Pb zircon geochronology suggest ~1.9–2.0 Ga detrital ages for the metasediments and ~230 Ma for the subduction-zone metamorphism (Miyamoto & Yanagi 1996). All these Paleozoic rocks occur as a nappe pile with older units in structurally higher positions, except for the uncertain position of the Oki belt.

Minor tracts of Renge blueschist (340–280 Ma K-Ar ages) crop out in north and central Kyushu (Nishimura 1998). Also, Permo-Triassic gneiss and granulite of the Higo metamorphic complex occur in central Kyushu (Obata et al. 1994; Osanai et al. 1998, 2006). Conventional U-Pb zircon geochronology has yielded Neoproterozoic (~2.2–1.8 Ga) detrital ages as well as Early Paleozoic (~550–450 Ma, and ~380 Ma) and Permo-Triassic (~260–230 Ma) metamorphic ages.

Sikhote-Alin (Far East Russia)

Figure 11 shows that the geology of the Sikhote-Alin Mountains is made up of two principal units, the Khanka and Sikhote-Alin lithotectonic terranes. The former consists of Precambrian continental basement covered by thick Cambrian calcareous sediments and post-Silurian nonmarine strata; it may be part of a larger continental entity including the Bureya and Jiamusi blocks to the north (Khanchuk et al. 1996; Khanchuk 2001). The Sikhote-Alin terrane mainly consists of Paleozoic and Mesozoic accretionary complexes that were intruded by Cretaceous granites and covered by Cretaceous-Tertiary volcanic rocks (Kemkin & Khanchuk 1994, Kojima et al. 2000).

The Sikhote-Alin terrane contains minor epidote-blueschist localities (Kovalenko & Khanchuk 1991, Ishiwatari & Tsujimori 2003). Blueschists occur as windows and thin thrust sheets beneath an Early Paleozoic gabbro-tonalite-diorite complex. HP pelitic schists have yielded phengite K-Ar ages of 250–230 Ma. Rare mafic gneiss ± marble and coarse-grained garnet amphibolite are associated with the blueschist unit. Although a Precambrian (~2500 Ma) Rb-Sr isochron age was reported from
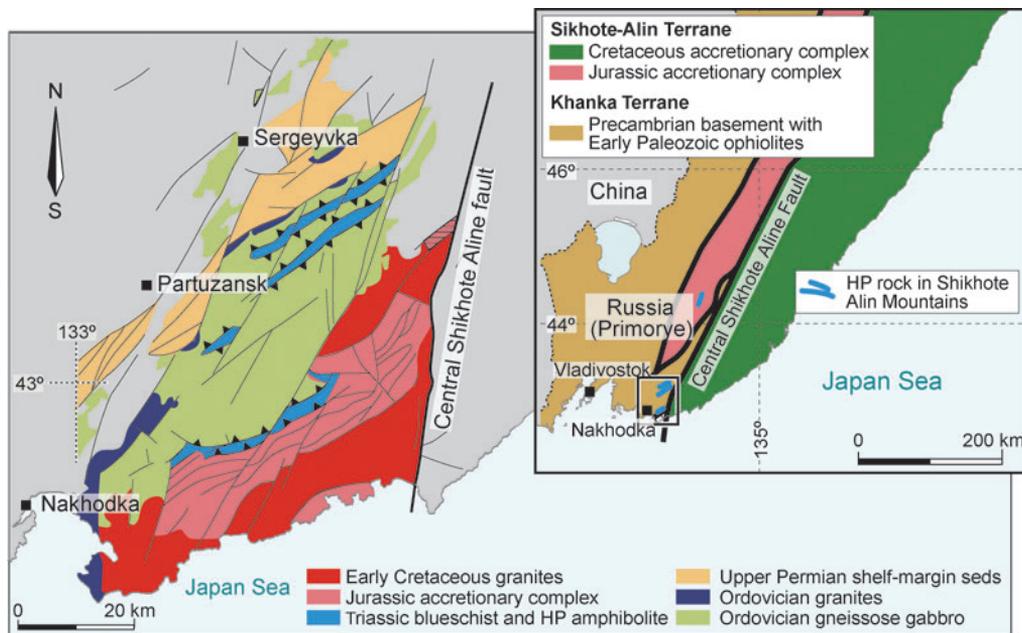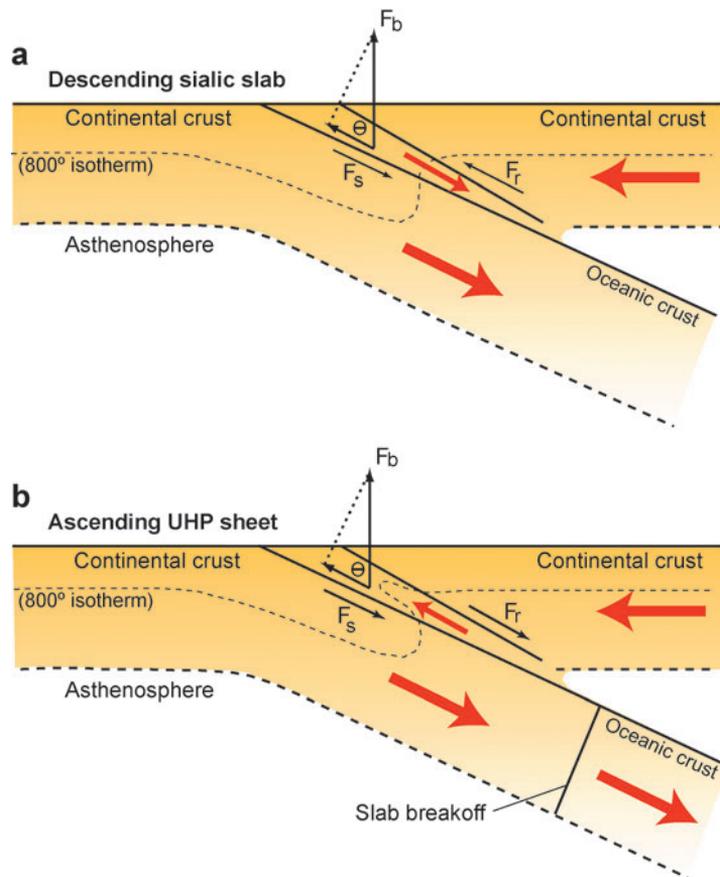
Figure 11

General geologic-tectonic map of Sikhote-Alin, Russian Far East (after Khanchuk et al. 1996, Khanchuk 2001).

spatially associated garnet-hornblende gneiss, hornblende K-Ar ages are ~250 Ma, contemporaneous with the HP complex.

EXHUMATION OF HP-UHP SUBDUCTION COMPLEXES

In general, the thermal history of a decompressing rock mass is a function of its thickness, the rate of ascent, and the temperature structure of the medium through which it ascends (e.g., Root et al. 2005). Relatively thin slices exchange heat more effectively than thicker units. If a thin HP or UHP body ascends infinitely slowly through a typical, cool subduction-zone thermal regime, the P-T trajectory can simply be the reverse of that during compression, provided that conduction-mediated thermal reequilibration takes place. If it rises moderately slowly, it will carry some deep-seated heat along with it, and will follow a retrograde P-T path at a slightly elevated temperature (for a given pressure) compared with the prograde path. However, if a thin HP-UHP body ascends slowly through a zone of much hotter rocks—say, through interior portions of the mantle wedge—it may become hot enough that mineralogic evidence of HP or UHP metamorphism is obliterated. Most well-characterized HP terranes faithfully track the prograde P-T trajectory on exhumation and retrogression, attending moderately slow decompression. In contrast, others rise rapidly, and thus exhibit near-isothermal decompression to midcrustal conditions.

Figure 12

Schematic convergent lithospheric plate-boundary diagram for ongoing subduction (after Ernst et al. 1997). Lithosphere is shaded (crust-mantle boundary not indicated) and asthenosphere is uncolored. (*a*) Deep burial and thermal structure of subducted continental lithosphere. (*b*) Later decompression cooling of a rising slice of the low-density sialic material. Relative motions of plates and slices indicated by arrows (the subducting plate actually is sinking and rolling back; Hamilton 1995). During ascent of the HP and/or UHP terrane (thickness exaggerated), cooling of the upper margin of the sheet takes place where it is juxtaposed against the lower temperature mantle wedge; cooling along the lower margin of the sheet takes place where it is juxtaposed against the lower temperature, subduction-refrigerated lithosphere. Exhumation of low-density slices requires erosive denudation and/or gravitational collapse and a sialic root at depth. The resolution of forces acting on the sialic slab in stages (*a*) and (*b*) are discussed in the text.

Schematic relations shown in **Figure 12** apply to the underflow and exhumation of HP and UHP buoyant sheets. Descent of sialic material occurs only if shear forces caused by underflow (F_s) exceed the combined effects of buoyancy (F_b) and frictional resistance along the hanging wall of the subduction channel (F_r). Here, $F_s > F_b \sin \theta + F_r$. Decoupling and ascent of a slice of the low-density crustal material takes

place where buoyancy is greater than the combined effects of shearing along its footwall and resistance to movement along its upper, hanging wall surface. In this case, $F_b \sin \theta > F_s + F_r$. The mantle wedge guides exhumation, and the rising nappe is emplaced oceanward from the site of metamorphism. Where the angle of subduction decreases, buoyancy lessens during underflow and exhumation. For an HP-UHP subduction complex to be returned to shallow depths and partly preserved, the rising rock mass must overcome frictional resistance to sliding, so it must be thick enough for buoyancy-driven ascent, yet thin enough that heat is efficiently removed by conduction across the bounding upper normal and lower reverse faults. Such structural relationships have been mapped in many resurrected subduction terranes, such as the Himalayas (Searle 1996, Searle et al. 2001, Kaneko et al. 2003), the Franciscan Complex (Ernst 1970, Suppe 1972, Platt 1986), the Western Alps (Henry 1990, Compagnoni et al. 1995, Michard et al. 1995), the Sambagawa belt (Kawachi 1968, Ernst et al. 1970, Banno & Sakai 1989), and the Kokchetav Massif (Kaneko et al. 2000, Ishikawa et al. 2000, Ota et al. 2000, Maruyama & Parkinson 2000). Nappes have also been described from the Western Gneiss Region of Norway (Harley & Carswell 1995; Krogh & Carswell 1995; Terry et al. 2000a,b) and the Dabie–Sulu belt (Liou et al. 1996; Hacker et al. 1995, 1996, 2000; Webb et al. 1999).

Retrogressed UHP complexes, although less dense than anhydrous mantle, become neutrally buoyant and stall at approximately middle levels of the continental crust (Walsh & Hacker 2004). Further exhumation of such slabs may be the product of contractional tectonism (Maruyama et al. 1994, 1996) or low-density crustal underplating—in either case combined with isostatically compensated regional exhumation and erosional decapitation (Platt 1986, 1987, 1993). Or, if oceanic plate breakoff occurs, a decrease in aggregate density of the subducting continental lithosphere would result in shallowing of the increasingly buoyant downgoing slab, and might be responsible for the late doming noted in many exhumed convergent plate junction regimes (Ernst et al. 1997, O'Brien 2001, O'Brien et al. 2001). Yet another unloading mechanism involves the antithetic faulting typical of some contractional orogens, where double vergence characterizes end stages of the ascent of low-density crust (Ring & Brandon 1994, 1999).

PERMO-TRIASSIC PLATE-TECTONIC EVOLUTION OF EAST ASIA

Accretion, deformation, and metamorphism of the Tongbai-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin orogenic belt took place during the approximate interval 320–210 Ma, reflecting convergence between one or more paleo-Pacific plates and the nonsubducted East Asian lithosphere. The polarity of subduction reflects underflow of the dominantly oceanic crust-capped paleo-Pacific lithosphere beneath the continental margin. The general northward increases in degrees of penetrative deformation, HP and UHP metamorphic intensities, and recovered depths of recrystallization reflect the direction of descent of the oceanic lithosphere. In general, nappes are subhorizontal or are south-vergent and thrust faults root to the north, in accord with the subduction-accretion kinematic event. The amalgamated suture

zone is marked by an inferred earlier stage of oceanic consumption and a later stage of approach and collision between the Sino-Korean and Yangtze cratons on the SW at 220–245 Ma; to the NE, the orogen is characterized by the multiple events involving accretion of outboard oceanic arcs + microcontinental fragments against the East Asian margin at ∼320–210 Ma. Subducted Proterozoic-Paleozoic continental plus or minus oceanic crustal complexes were subjected to UHP metamorphism at moderately elevated temperatures on the SW, and HP, low-temperature recrystallization on the NE.

The Dabie-Sulu sector of the orogen constitutes the most deeply subducted, now recovered UHP complex. Exhumed slices of the South China craton tectonically separated from the downgoing oceanic lithosphere at 220–245 Ma, and propelled upward by buoyancy, ascended to midcrustal levels from depths exceeding 90–140 km, where they cooled rapidly. Jurassic and later doming and gravitational collapse exposed portions of such HP-UHP complexes at the surface. The western extension of the terrane in the Hong'an-Tongbai block contains only HP eclogitic rocks as well as lower-pressure, lower-temperature blueschists, reflecting less-extreme exhumation of the Yangtze-Sino-Korean collisional suture zone.

Judging by the rather high-temperature/moderate-pressure overprinting exhibited by exhumed, ∼250 Ma metamorphic complexes of the Korean Peninsula, early-collided portions of the South China craton remained sequestered at great depth for a sufficient length of time that thermal reequilibration occurred. Farther to the east in SW Japan, underflow and the episodic arrival and accretion of scraps of exotic oceanic and sialic materials took place attending paleo-Pacific subduction over the approximate time interval 320–210 Ma (Renge and Suo blueschist belts, respectively). At the end of Permian time, low-temperature ophiolitic rocks of the Sikhote-Alin HP belt were also sutured against the East Asian margin in the Russian Far East.

Thus, leading up to the Permo-Triassic accretionary events, the eastern edge of cratonal Asia—from the Tongbai area on the west to Sikhote-Alin on the NE—was a convergent margin. Reflecting underflow of paleo-Pacific oceanic lithosphere, this consuming plate junction collided with continental blocks in east-central China and as far to the east as the central Korean Peninsula. Progressively more ophiolitic arcs and sialic scraps were sutured to the growing margin in SW Japan and in the Russian Far East. HP-UHP metamorphism accompanied the accretion of these lithotectonic terranes, and episodic exhumation over portions of the interval from 320 to 210 Ma accounted for the oceanward growth of East Asian continental crust.

Subsequently, this originally curvilinear orogen was segmented and displaced by major faults such as the Huwan mylonitic line, the Tan-lu fault, the Honam shear zone, and the Itoigawa-Shizuoka tectonic line, and by minor breaks as well. Moreover, Cenozoic backarc spreading opened marginal basins such as the Japan Sea, separating SW Japan from the Sikhote-Alin and Imjingang-Gyeonggi complexes (e.g., Ernst & Liou 1995); possibly earlier extension produced the Yellow Sea, rifting the Dabie-Sulu belt from the Korean Peninsula (e.g., see Oh 2006). Nonetheless, this now complicated suture zone remains sufficiently intact to attest to the Permo-Triassic accretion of East Asia (see **Figure 4**).

ACKNOWLEDGMENTS

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