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Orogeny and metallogenesis along the margin of eastern Asia: Permo-Triassic subduction-zone metamorphism, crustal accretion, and exhumation

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ABSTRACT

Long-sustained, chiefly transpressive plate motion at ~305-210 Ma generated the Tongbo-Hong'an-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin terrane amalgam running from east-central China through central Korea and southwest Japan to the Russian Far East. This contractional orogen attests to roughly northwest transpressive underflow of oceanic lithosphere and collision between the Sino-Korean and Yangtze cratons along the southwest portion of the suture zone, and the arrival and docking of a collage of oceanic arcs and microcontinental blocks against the Asian cratonal backstop on the northeast. Subducted units underwent high- and ultrahigh-pressure (HP and UHP) metamorphism at low to moderate temperatures. Slices of sialic crust episodically disengaged from the sinking, largely oceanic crust-capped plate, and driven chiefly by buoyancy forces, ascended rapidly to mid-crustal levels from depths exceeding 90-140 km after continental collision in east-central China; oceanic terranes rose from depths of ~30-50 km after accretion of exotic crust in southwest Japan. Rising HP-UHP complexes achieved neutral buoyancy at 10-20 km depths, and ascent stalled; later compressional doming, underplating, gravitational collapse, and/or erosion exposed parts of the HP-UHP metamorphic terranes. In some respects, Taiwan and Indonesia represent modern plate-tectonic analogues of the Permo-Triassic accretionary margin of East Asia.

Ophiolitic Cu-Zn-Pb-S ore bodies, particularly numerous in southwest Japan, formed as submarine hydrothermal vent deposits adjacent to oceanic spreading centers prior to terrane suturing; deep-sea Mn ± Ba cherts and Cr-bearing serpentinized peridotites occur in the shallowest and deepest sections of the offloaded oceanic plate, respectively. During Permo-Triassic underflow of basaltic crust, economic concentrations of rutile in Ti- and Fe-rich eclogites formed in some parts of the orogen. Much later, during Cretaceous underflow of oceanic lithosphere, rising subduction-zone aqueous solutions or hydrothermal fluids derived from crystallizing granitic intrusions evidently contained base and precious metals, and/or leached them from pre-existing basement terranes, and formed major ore bodies, especially in the pluton-invaded Tongbo-Hong'an-Dabie-Sulu belt; a range of important mineral deposits thus occurs in rocks of the Permo-Triassic suture zone, but are products of this much later metallogenesis. Few non-oceanic East Asian ore bodies apparently formed as a direct result of the Permo-Triassic lithospheric underflow, reflecting the fact that transpression and continental collision involved only minor high-T devolatilization in the magmagenic zone, thus generated only small volumes of granitoid plutons.

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CONTRASTING TYPES OF SUBDUCTION ZONES

Circum-Pacific and Alpine convergent plate junctions

Two principal transpressive to convergent plate-tectonic end-member types, circum-Pacific and Alpine, generally are recognized (Bally, 1981; Ernst, 2005). Head-on convergence is restricted to specific regions along curvilinear consumptive plate boundaries, unless they describe arcs of great circles, reflecting the spherical-sector nature of globe-encircling lithospheric plates (Irwin, 1972; Coney et al., 1980; Jones, 1983; Howell, ed., 1985). Consequently, many sutured terrane assemblies are produced by oblique convergence or by strike-slip (transpression or transform) motion. Thus Alpine- and Pacific-type orogens represent end-members of a more complex continuum of actualistic plate-tectonic configurations.

Circum-Pacific high-pressure (HP) metamorphic belts, such as the Franciscan Complex of western California (Ernst et al., 1970), are typified by massive amounts of quartzofeldspathic detritus supplied to the subduction realm during the sustained underflow of thousands of kilometers of oceanic lithosphere. Metamorphic phase assemblages reflect very low temperatures of recrystallization at moderate pressures, producing blueschist- and low-rank eclogite-facies mineral assemblages. Due to their poorly consolidated nature, such accretionary complexes typically decouple from the descending oceanic plate at maximum depths of ~30-50 km, and buoyantly ascend to upper crustal levels (Ernst, 1970). Essentially end-member Circum-Pacific-type convergent plate boundaries have evolved in situations where vast expanses of oceanic lithosphere are consumed without volumetrically important sialic terranes entering the subduction zone, as typifies the Late Mesozoic-Cenozoic histories of the eastern, northwest, and southwest borders of the circum-Pacific realm (Engebretson et al., 1985; Stock and Molnar, 1988). This plate-tectonic situation gives rise to an outboard, active-margin accretionary wedge as a largely sedimentary trench complex, an intervening, longitudinal forearc basin, and an inboard, roughly contemporaneous calcalkaline volcanic-plutonic arc (e.g., Kusky et al., 1997). The trench section is typified by a relatively narrow, low-T, low-heat-flow belt, and the broad magmatic arc is characterized by high temperatures and an elevated thermal flux (Miyashiro, 1961, 1967). The former is deposited on oceanic crust, whereas the latter is constructed on pre-existing basement of the continental margin, island arc, or older oceanic crust.

In contrast to circum-Pacific HP metamorphic belts, Alpine high-pressure – ultrahigh-pressure (HP-UHP) orogens occupy transpressive to convergent plate junctions involving consumption of an intervening ocean basin (i.e., an oceanic plate) followed by insertion of an island arc or microcontinental salient into the suture zone. The subducted terrane may descend to considerable depth, carried down by the spatially associated high-density ocean lithosphere. The leading edge of the downgoing continental crust, with or without a passive-margin sedimentary platform, is sutured against an accretionary complex forming at the margin of the stable, nonsubducted mantle-wedge plate. Accompanying impaction, the thickness of the continental crust increases by amalgamation and contraction. Major mountain belts formed along collisional sutures are characterized by a conspicuous lack of calcalkaline igneous activity coeval with the suturing event. Typical examples include the Urals, Alps, and Himalayas (Hamilton, 1970; Dal Piaz et al., 1972; Ernst, 1973; Molnar et al., 1987; Burchfiel et al., 1989; Searle, 1996; Searle et al., 2001). During underflow, crustal sections may reach depths exceeding 90-140 km, as indicated by the neoblastic crystallization of minerals stable only at ultrahigh pressures, such as coesite or diamond, K-bearing pyroxenes, and/or Si-excess garnets ± pyroxenes (Liou et al., 1998). In these largely sialic complexes, scattered UHP phases may be preserved in strong, tough, refractory zircon, pyroxene, and garnet – minerals typified by great tensile strengths and low rates of intracrystalline diffusion. Armoring of UHP relics allows maintenance of high confining pressures and provides spatial isolation from catalytic intergranular aqueous fluids that promote back reaction on later surfaceward ascent.

During underflow and exhumation, ductilely deformed recumbent folds and thrust sheets form in both circum-Pacific- and Alpine-style subduction channels (Ernst et al., 1997; Koons et al., 2003; Hacker et al., 2004; Terry and Robinson, 2004); such imbricate nappe piles are typical of most exposed HP and UHP complexes. Ascent to shallow crustal levels may take place by: tectonic extrusion (Maruyama et al., 1994, 1996; Searle et al., 2003; Mihalynuk et al., 2004); corner flow constricted by the mantle wedge backstop (Cowan and Silling, 1978; Cloos and Shreve, 1988a, b; Cloos, 1993); underplating and extensional or erosional collapse (Platt, 1986, 1987, 1993; Ring and Brandon, 1994, 1999); and/or buoyant ascent (Ernst, 1970, 1988; England and Holland, 1979; Hacker, 1996; Hacker et al., 2000, 2004). An old, cool, sinking plate may cause oceanward trench retreat more rapidly than advance of the nonsubducted plate, resulting in back-arc spreading and seaward transportation of the forearc (Molnar and Atwater, 1978; Seno, 1985; Busby-Spera et al., 1990; Hamilton, 1995); rollback settings are tensional, so compression and extrusion of subducted sialic sections cannot explain the exhumation. Corner flow requires buoyancy or tectonic contraction to produce the return flow of subducted sialic material. Extension and erosion aid in unroofing HP-UHP terranes after they reach mid-crustal levels, but these processes do not generate the well-known major pressure discontinuities that mark thrust contacts between deeply subducted and nonsubducted crust (Ernst, 1970; Ernst et al., 1970; Suppe, 1972). On the other hand, buoyancy coupled with erosional removal provides a plausible mechanism accounting for the regurgitation of low-density crustal slices along the subduction channel. Geologic relationships, scale models (Chemenda et al., 1995, 1996, 2000; Fig. 1), and numerical simulations (Beaumont et al., 1996, 1999; Pysklywec et al., 2002; Fig. 2), illustrate this process (see volumes edited by: Parkinson et al., 2002; Carswell and Compagnoni, 2003; Malpas et al., 2004).

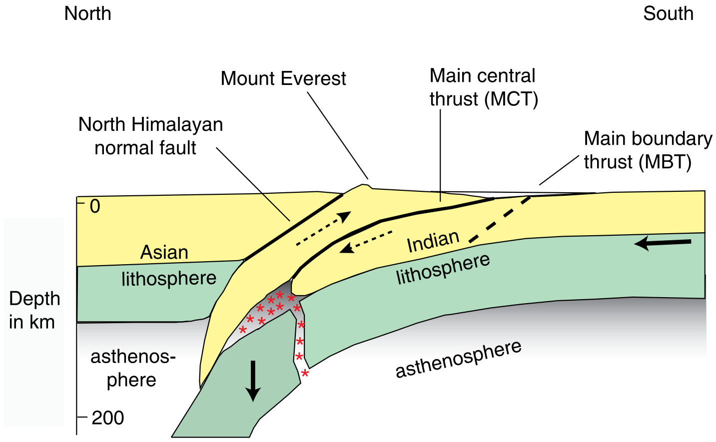


Figure 1 (above). Simplified tectonic evolution of an Alpine-type collisional mountain belt and associated tectonic features, based on scale-model experiments conducted by Chemenda et al. (1995, 1996, 2000). Continental crust is shown in yellow, mantle lithosphere in light green, asthenosphere in pale gray, and decompression mafic melt by red asterisks. The delamination of mantle lithosphere (vertical black arrow) reflects gravitational instability and transpression-subduction underthrusting. The Tongbo-Hong'an-Dabie-Sulu-Gyeonggi sector of the East Asian Permo-Triassic orogen apparently was subjected to plate convergence similar to that depicted here.

Modern transitional convergent plate junctions

Convergent-transpressive plate-tectonic regimes transitional between Alpine and circum-Pacific subduction types are common. The Indonesian island arc (Hamilton, 1979; Charlton, 1991; Maruyama et al., 1996; Snyder et al., 1996) is an instructive case. The strongly curved eastern part of the collisional suture zone between Timor and Seram marks the site of underflow of old, cool continental crust of the Australian plate, whereas farther west along the Sumba-Java segment of the convergent boundary, oceanic crust-capped lithosphere is descending beneath Indonesia. Simplified regional relationships are shown in Figure 3. HP blueschists exposed in the strongly curved eastern suture zone reflect decoupling and ascent of subducted, largely sialic material. The driving force for ascent reflects rupturing and accelerated sinking of the oceanic lithosphere, and a decrease in shear stress along the base of the buoyant, ductile crust as it warms within the upper mantle. Slab breakoff in this area was documented seismically by Osada and Abe (1981),

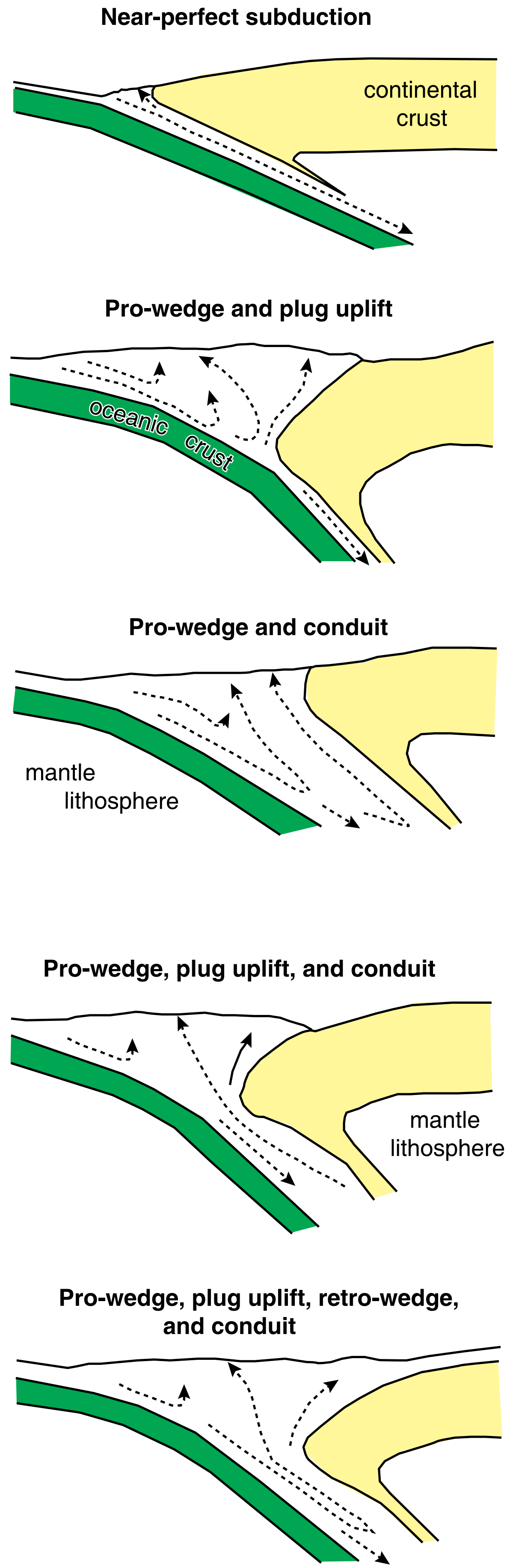


Figure 2 (right). Schematic dynamic architecture of circum-Pacific-type subduction orogens, generalized from numerical modelling by Beaumont et al. (1996, 1999) and Pysklywec et al. (2002). Several accretion-exhumation scenarios are shown. Oceanic crust is shown in dark green and continental crust in yellow. Exhumation paths are a function of many input variables, such as convergence rate, adherence to the downgoing plate, frictional resistance, temperature structure, and viscosity of the imbricated mélange. The Imjingang-Renge-Suo-Sikhote-Alin section of the East Asian Permo-Triassic orogen underwent more heterogeneous accretion than shown here, including the docking of exotic oceanic and microcontinental terranes, but relations are similar to those illustrated.

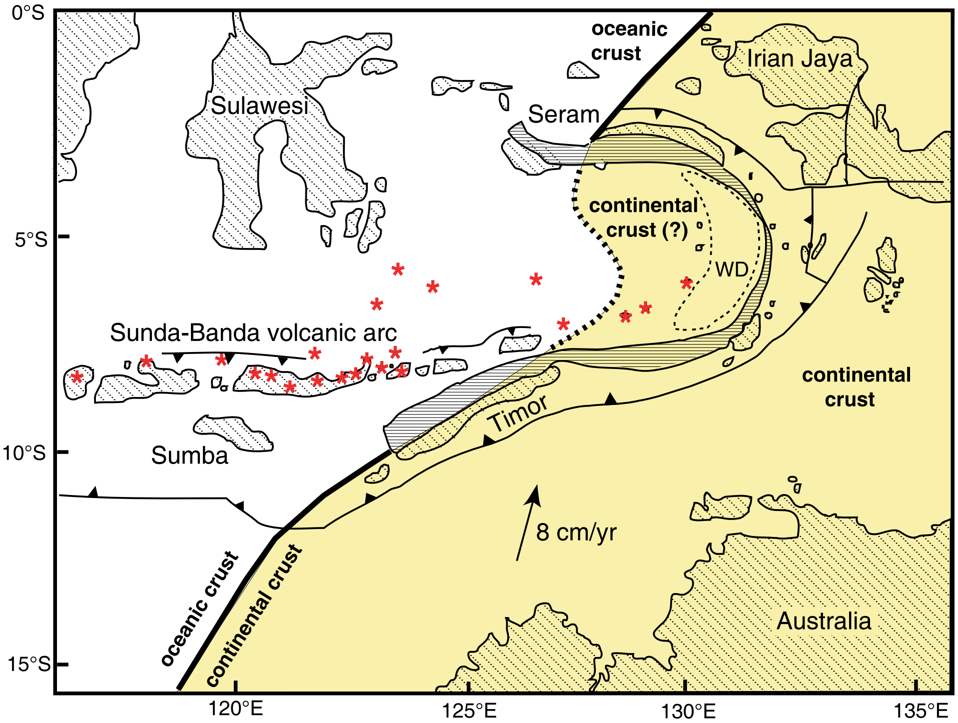


Figure 3. Current ongoing crustal collision and exhumation of a transitional Alpine-circum-Pacific-type blueschist belt, after Osada and Abe (1981), Charlton (1991), and Maruyama et al. (1996). The transpressive-convergent plate-tectonic junction (barbs on stable, nonsubducted plate) and exhumed HP belt (shaded pattern) are indicated. Australian continental crust is sinking beneath the Timor-Seram segment of the Indonesian suture zone. The most active part of the Sunda-Banda volcanic arc (red asterisks) lies above descending oceanic—not continental—lithosphere of the Australian plate. WD = Weber Deep

Milsom and Audley-Charles (1986), and Widiyantoro and van der Hilst (1996). Loss of the dense, leading, oceanic section of the Australian plate may be responsible for exhumation of the light sialic crust. Significantly, ductile, relatively buoyant continental crust is sandwiched between dense, relatively rigid mantle peridotite making up both hanging wall and footwall, so ascent of the ~5 km thick slice of crustal material is confined within the tectonic boundaries of the active subduction channel acting as a stress guide (Cloos, 1993).

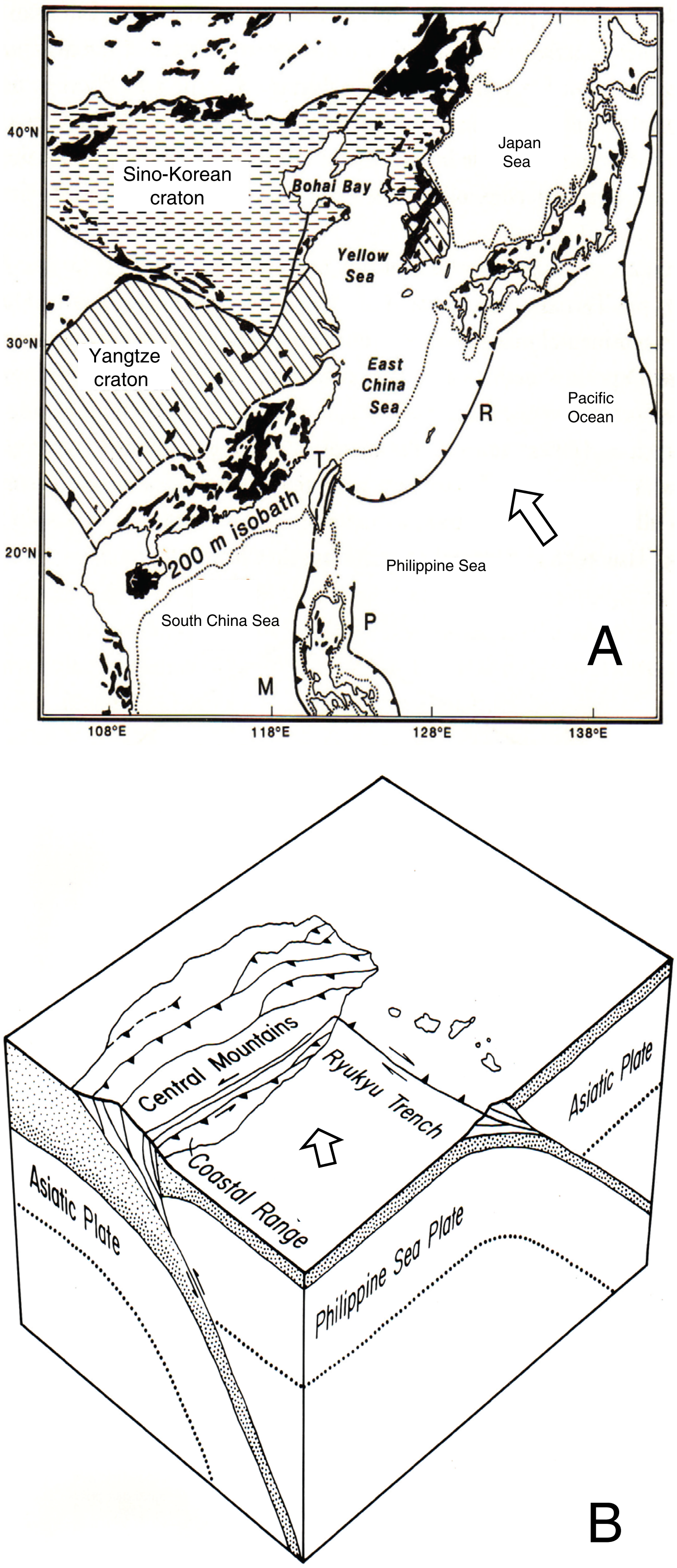
The role played by subducting, amphibole-rich oceanic crust in contrast to micaceous continental crust along this modern plate junction in generating hydrous calcalkaline arc magmas reflects the fact that hornblende devolatilizes at pressures above ~2.3 GPa whereas white micas are stable to pressures in excess of 4.0 GPa (Ernst, 1999). As indicated in Figure 3, the Banda inner volcanic arc is extremely active west of Timor where oceanic lithosphere sinks beneath Indonesia; andesitic volcanism diminishes eastward where Australian continental lithosphere is underthrusting the Asian plate and is absent in the eastern, strongly curved part of the archipelago.

Further east, where the Australian plate is impinging on the southwest edge of the Pacific plate, young UHP rocks crop out in eastern Papua New Guinea; SHRIMP U-Pb data for zircons from coesite-bearing eclogite yield a crystallization age of 7.9 Ma, the youngest such rocks yet discovered. These UHP eclogites were exhumed at plate tectonic rates of ~10-25 mm/yr (Baldwin et al., 2004; Monteleone et al., 2007).

Taiwan, another complex convergent junction, lies along the eastern edge of the Asian continental plate. The Taiwan region is dynamically unstable, and is evolving rapidly (Bowin et al., 1978; Hamilton, 1979; Biq, 1981; Suppe, 1984; Byrne and Liu, eds., 2002; Teng and Lin, 2004). Spatial relations are shown schematically in Figure 4. On the north, Asian sialic crust is descending beneath the oceanic lithosphere of the advancing Philippine Sea plate and its western edge, the Coastal Range of eastern Taiwan; to the south along the Luzon Arc, eastward underflow of the South China Sea is causing increasing insertion of Asian continental crust into the subduction zone. Young (8-14 Ma) blueschists occur as tectonic blocks in the eastern Central Mountain Range of Taiwan, reflecting this subduction of Asian lithosphere beneath the Luzon Arc (Liou et al., 1975; Jahn et al., 1981; Lo and Yui, 1996). The Philippine Trench, where the Philippine Sea plate is sinking westward beneath the Luzon Arc, appears to be propagating northward as eastward descent of the South China Sea terminates; ultimately this should result in the stranding of the Philippine Islands and the Taiwanese Coast Range along the eastern margin of Asia.

Metamorphic belts marking convergent plate junctions

The strength, ductility, and integrity of subducted material, extent of deep-seated devolatilization, and rate of recrystallization strongly influence the nature of the resultant HP and UHP metamorphic belts (Ernst et al., 1998). Low temperatures and high pressures are generated by the lithospheric underflow of rocks (which are poor thermal conductors), resulting in clockwise prograde-retrograde P-T paths. Taiwan (Fig. 5) presents diagrammatic examples of compression-decompression metamorphic trajectories for circum-Pacific- and Alpine-type transpressive subduction-zone orogens.



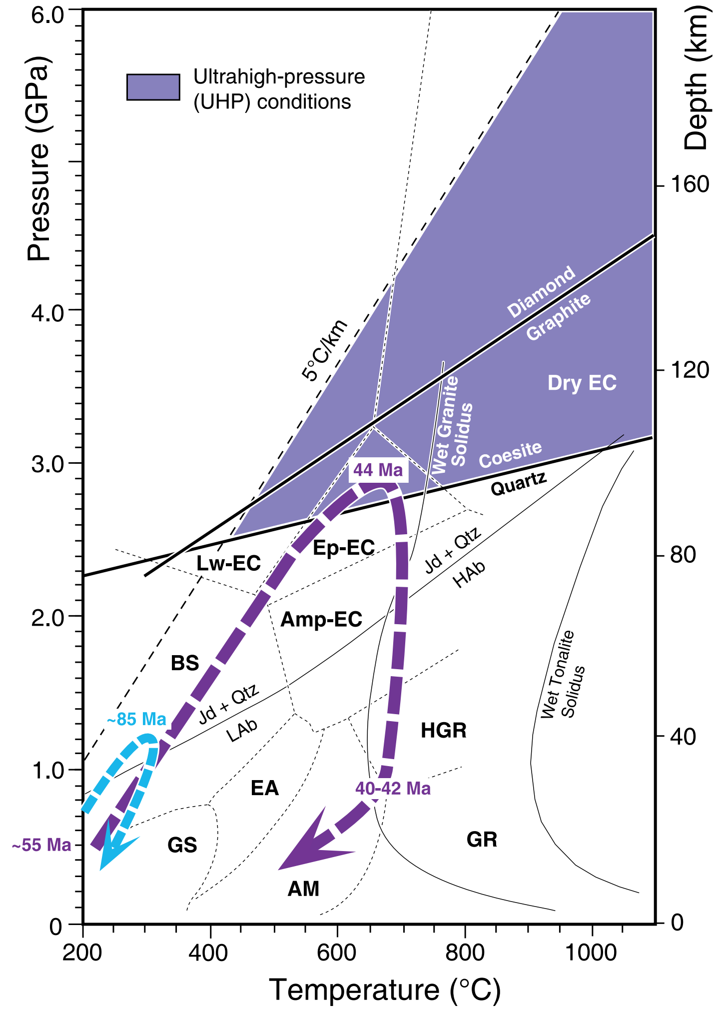


Figure 5 **(above)**. Pressure-temperature history of subduction and exhumation to mid-crustal levels of: (1) continental collision conditions (thick-dashed purple curve)–typical UHP imbricate thrust sheets, such as those exposed in the Kaghan Valley, western Himalayan syntaxis, after O'Brien et al. (2001), Parrish et al. (2003), and Kaneko et al. (2003); and (2) oceanic plate underflow conditions (thin-dashed blue curve)–diagrammatically illustrated for the Late Cretaceous Diablo Range portion of the eastern Franciscan HP belt (Ernst, 1993; Dalla Torre et al., 1996). Mineral abbreviations: Jd = jadeite; Qtz = quartz; LAb = low albite; and HAb = high albite. Metamorphic-facies abbreviations: AM = amphibolite; Amp-EC = amphibolite-eclogite; BS = blueschist; EA = epidote amphibolite; EC = eclogite; Ep-EC = epidote-eclogite; GR = sillimanite-granulite; GS = greenschist; HGR = kyanite-granulite; and Lw-EC = lawsonite-eclogite.

Figure 4. Plate-tectonic environment of Taiwan. **(A)** Regional location of Taiwan (T) along the continental margin of East Asia at the intersection of the Ryukyu (R) and Manila (M) trenches, largely after Hamilton (1979). The Philippine Trench (P) apparently is propagating northward and eventually will transfer the Philippine Islands and the Coastal Range of Taiwan to the leading edge of the Asian plate. Granitic rocks are shown in black. **(B)** Local plate-tectonic setting of Taiwan, after Ernst (1983) See also Byrne and Liu, eds., (2002). The transpressive-convergent plate junction coinciding with the Ryukyu Trench is a relatively stable, long-lived feature. In contrast, the present eastward underflow of buoyant Asian continental crust beneath the Philippine Sea lithospheric plate and the Coastal Range is gravitationally unstable, and imbricate sialic slices of low-density materials are moving back up the subduction zone attending contraction of the Taiwanese continental crust.

ARCHITECTURE OF THE PERMO-TRIASSIC EAST ASIAN COLLISIONAL BELT

We now summarize in simplified form the metamorphic lithologic assemblages and structural architecture of the Tongbo-Hong'an-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin orogen, and provide our interpretation of the Permo-Triassic petrotectonic evolution of East Asia. The UHP Dabie and Sulu continental collisional terranes represent the most deeply subducted sectors of this transpressive belt, and have been well studied; the HP Renge-Suo ophiolitic assembly also has been well investigated. The suture zones exposed in central Korea and in the Russian Far East have been examined somewhat less thoroughly, so these sectors will be described more briefly. Nevertheless, the available metamorphic and structural data provides important constraints on the petrotectonic development of this HP-UHP belt.

Figure 6 presents a simplified tectonic map of eastern Asia. In east-central China, the EW-trending Tongbo-Hong'an-Dabie-Sulu belt exhibits a gradation from weakly developed blueschist-greenschist facies metamorphism in the south, to amphibolitized HP eclogitic gneiss and metamafic layers and pods, and further north to UHP units ± garnet peridotite lenses (Liou et al., 1996). Protoliths range in age from Middle and Late Proterozoic granitic gneisses through bimodal igneous rocks, platform carbonates, and turbidites, including Vendian-Lower Paleozoic peraluminous sedimentary and volcanic rocks. Triassic (240-220 Ma) HP-UHP mineral parageneses developed on the leading edge of the Yangtze (South China) craton passive margin (Hacker et al., 2000, 2004). On the north, the Dabie-Sulu belt is pervasively invaded by Cretaceous granitoids. Younger northeast-trending faults that parallel the major left-lateral Tan-lu fault divide the collisional orogen into discrete blocks. The metamorphic grade of exhumed litho-

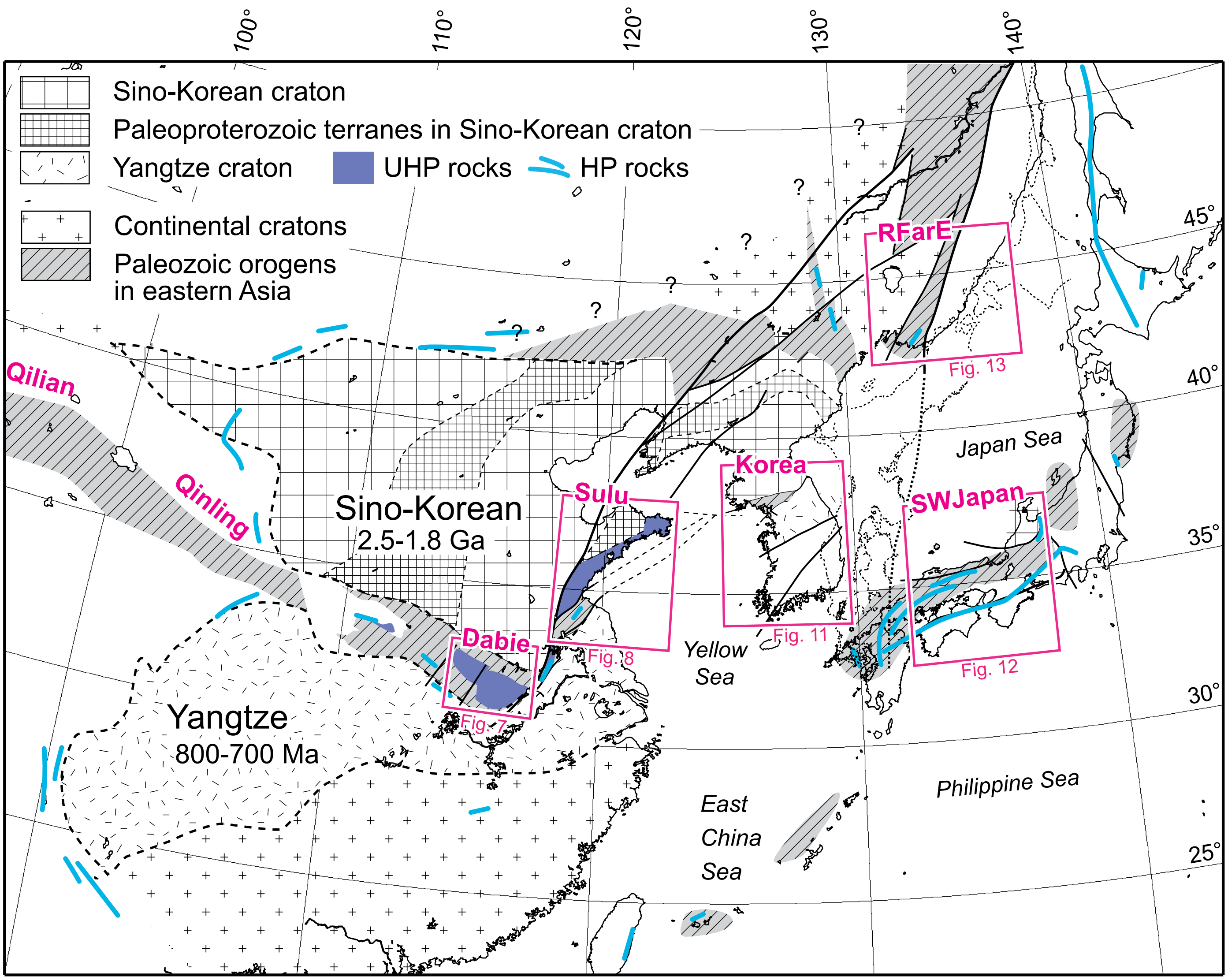


Figure 6. Generalized tectonic map of eastern Asia showing the Tongbo-Hong'an-Dabie-Sulu Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin orogen sandwiched between the Yangtze and Sino-Korean cratons along the Permo-Triassic continental margin. The Qilian and Qinling belts are Early Paleozoic orogens. Transpressive-convergent suture zones are decorated with HP and UHP petrotectonic assemblages. See text for map sources and discussion.

logic units varies from block to block, reflecting differential unroofing. The UHP sector is best exposed in Sulu and Dabie, whereas the HP belt crops out widely in Hong'an and Tongbo. The non-subducted, Late Archean-Early Proterozoic Sino-Korean (North China) craton lies directly north of the convergent plate junction, and acting as the backstop, was unaffected by the Triassic HP-UHP event.

The central and southern Korean Peninsula comprises four major geologic belts displaying the effects of Permo-Triassic HP metamorphism. From south to north, the South China-correlative lithologic sequence and times of origin are the Proterozoic Yeongnam cratonal massif, the Neoproterozoic-Early Mesozoic Ogcheon belt, the Archean-Proterozoic Gyeonggi microcontinental massif, and the Late Proterozoic-Middle Paleozoic Imjingang belt. The Imjingang HP belt ± the Gyeonggi massif apparently occupies the convergent zone, to the north of which lies the Late Archean and younger Nagrim massif which is part of the stable, nonsubducted, North China cratonal backstop. Imjingang HP metamorphism took place at ~253-249 Ma (Ree et al., 1996; Cho et al., 2007). Mafic eclogites that recrystallized at ~230 ± 30 Ma have been reported from the southwest Gyeonggi block (Kim et al., 2006; Oh and Kusky, 2007). In contrast to east-central China, the upper amphibolite grade of the Gyeonggi massif is almost invariant, and does not increase toward the plate boundary juxtaposing the South and North China cratons.

The Yangtze craton of east-central China and the South China-type blocks of the Korean Peninsula are not present in southwest Japan. Instead, a series of accretionary prisms, transpressive complexes, and oceanic crustal slices episodically arrived at the margin of the East Asian continental backstop from mid-Paleozoic to Triassic time (Tsujimori, 2002; Tsujimori and Liou, 2005; Tsujimori et al., 2006). The crust grew seaward, with ages of collisional recrystallization and docking of exotic terranes against the continental North China craton margin generally decreasing toward the descending paleo-Pacific oceanic plate. The Renge and Suo HP blueschist-eclogite terranes were subducted, metamorphosed, and accreted to the East Asian margin at ~305 and 210 ± 25 Ma, respectively. Typical of exhumed transpression-subduction complexes, the intensity of recrystallization increases toward the stable continental margin (i.e., toward the Hida and Oki belts, floored by Archean-Proterozoic basement of Sino-Korean affinity).

We theorize a northward continuation of the Renge-Suo terrane into the Paleozoic-Early Mesozoic accretionary complexes of Sikhote-Alin (Zonenshain et al., 1990; Khanchuk et al., 1996). The presence of low-T blueschists in these exhumed subduction-zone rocks reflect HP metamorphic conditions (Ishiwatari and Tsujimori, 2003). Similar to other segments of the orogen, this weakly recrystallized belt was sutured against the landward Khanka terrane (Sino-Korean cratonal backstop) by Triassic time.

Non-involvement of the North China craton during Permo-Triassic deformation and HP-UHP recrystallization, and northward increase in recovered transpression-subduction depths of exhumed slices, suggest that the approaching edge of the Yangtze craton and intervening oceanic lithosphere descended beneath the East Asian margin prior to offloading of material from the downgoing plate, then ascended to mid-crustal levels. The curvilinear Permo-Triassic transpressive-convergent suture zone was segmented and offset by later differential plate motions. In the southwest sector of the orogen in east-central China, this included post-Triassic sinistral slip on the Tan-lu fault (Yin and Nie, 1993). Miocene and younger rifting and sea-floor spreading opened the Sea of Japan, displacing the Japanese arc, including the Renge-Suo complex, ~400 km southeast from its projected western extension across the Korean Peninsula, as well as from its inferred northern arm in Sikhote-Alin (Otofuji et al., 1991; Ernst and Liou, 1995; Yun et al., 2007).

PERMO-TRIASSIC OROGENY IN EAST-CENTRAL CHINA

Tongbo block

The Dabie orogen passes west-northwest through adjacent Hong'an and Tongbo areas to the Qinling Range on the north and west, and yet more remote Qilian Mountains farther west (Fig. 6). Once correlated with the Dabie-Sulu belt, the Qinling-Qilian terranes contain HP-UHP units metamorphosed at ~500-450 Ma, and collided with the North China block long before Permo-Triassic HP-UHP recrystallization of the orogenic belt on the southeast (Hacker et al., 2004; Ratschbacher et al., 2006; Mattinson et al., 2006; Zhang et al., 2007a). The EW-trending, 5-10 km wide Huwan mylonite shear zone marks the contact between the inboard Qinling belt on the northwest and the more recently accreted Tongbo-Hong'an-Dabie complex on the southeast. Consisting of Late Proterozoic basement recrystallized at ~240 Ma to high-pressure mafic eclogitic lenses and felsic gneisses on the north, the Tongbo belt grades southward to less intensely deformed, weakly recrystallized platform strata and massive greenstone-blueschist lithologies. Feebly metamorphosed HP rocks are also present to the west-southwest directly north of Wudang Mountain (Ernst et al., 1991).

Hong'an-Dabie block

The Hong'an-Dabie HP-UHP terrane consists of several fault-bounded metamorphic units. Passing southward, these are: the Foziling low-grade metaflysch series draped over the Sino-Korean cratonal edge; the northern Dabie high-T gneiss-migmatite complex; the central Dabie UHP eclogite belt; the south-central Dabie HP eclogite belt; the southern Dabie epidote-amphibolite belt; and the southernmost Dabie blueschist-greenschist belt (Fig. 7). In the northern Dabie, widespread post-collisional Late Mesozoic granitic plutons contain xenoliths of granitic gneiss and mafic ± ultramafic rocks, and have

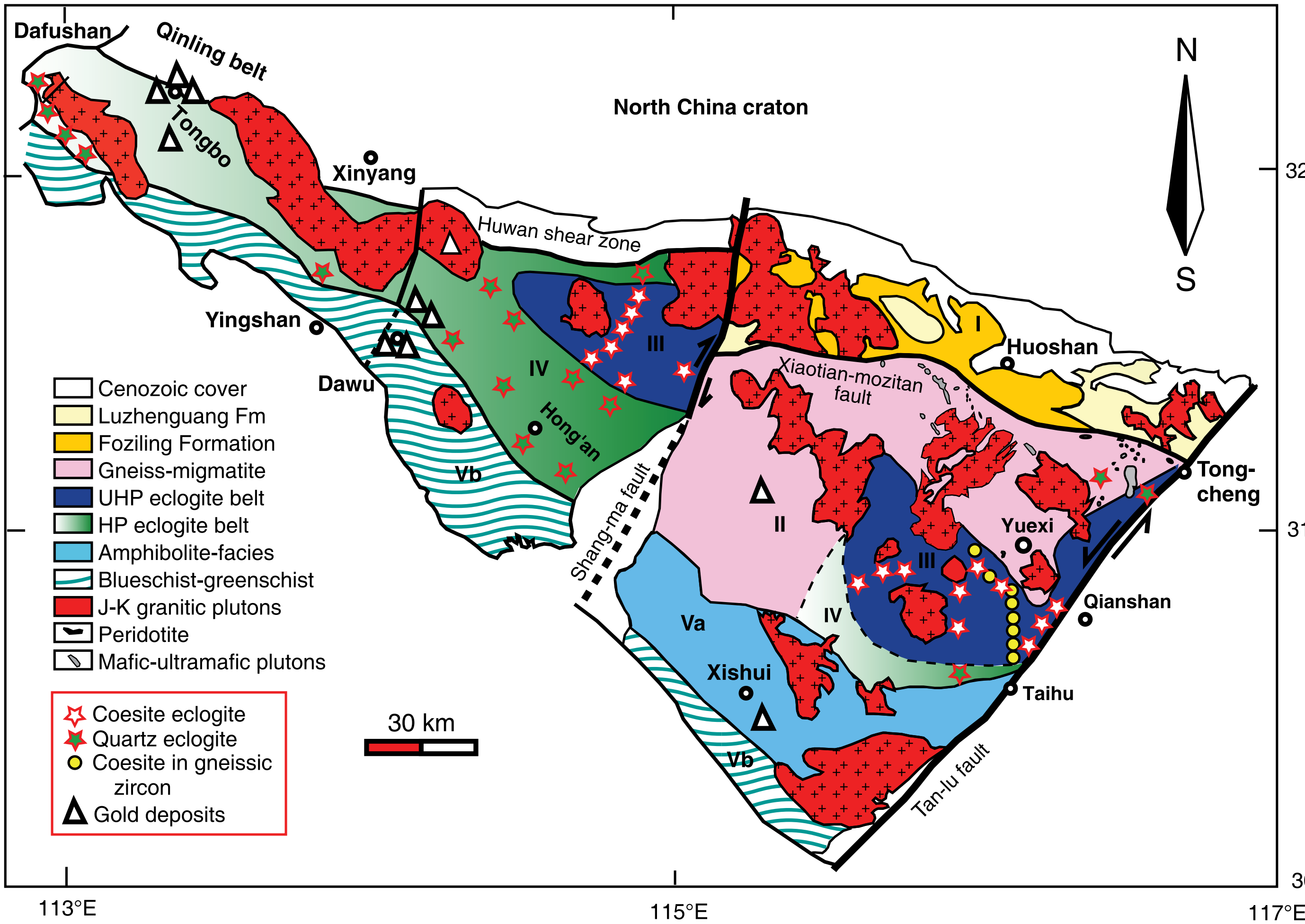


Figure 7. Generalized geologic map of the Tongbo-Hong'an-Dabie Mountains, showing metamorphic units and locations of eclogite and of coesite inclusions in zircons extracted from gneisses (modified after Zhang et al., 2007b). Gold ore deposits are also shown (see Xu et al., 1995). Most promising rutile ore deposits occur in the area characterized by HP and UHP eclogites.

significantly modified earlier HP-UHP structures and phase assemblages (Jahn et al., 1999; Hacker et al., 2000, 2004; Z. Zhao, 2005). The feebly recrystallized flysch is separated from the northern Dabie unit by the Xiaotian-Mozitan fault, and is overlain by Jura-Cretaceous shallow-water sedimentary and volcanic rocks.

The northern Dabie high-T metamorphic complex consists of upper amphibolite-granulite- to migmatitic-facies gneisses (Zhang et al., 1996), and is a part of the Yangtze craton (Hacker et al., 2000; Bryant et al., 2004). Ion microprobe U-Pb ages of zircons from orthogneisses indicate two stages of granite emplacement at 749 ± 18 and 127 ± 4 Ma. Minor eclogite lenses have been reported from both peridotite and gneiss (Wei et al., 1998; S. Xu et al., 2000; Y. Liu et al., 2001); however, the mafic-ultramafic pods enclosed in peridotite are actually garnet clinopyroxenite. S. Xu et al. (2005) described microdiamond inclusions in eclogitic garnet; zircons containing microdiamond inclusions from high T/P gneiss yield SHRIMP U-Pb age of 218 ± 3 Ma, whereas zircon rims give the time of an Early Cretaceous migmatization overprint at 126 ± 5 Ma (Y. Liu et al., 2007). Eclogite inclusions in gneiss have been extensively retrogressed to amphibolite, retaining only minor relict garnet and rutile; omphacite is totally replaced by a symplectite of fine-grained plagioclase and amphibole. True omphacite-bearing eclogite and coesite-bearing granitic gneiss of 226 Ma have only been found as float (Wei et al., 1998; Wan et al., 2005). Post-collisional mafic-ultramafic intrusives including gabbro ± diorite are common in the northern Dabie terrane. The Raobazhai peridotite consists mainly of Cr-spinel harzburgite and dunite with minor garnet pyroxenite, and records an early mantle crystallization at ~2.2 GPa, >1100 °C (Zhang et al., 1996); it also contains relict Triassic UHP supersilicic omphacite (Tsai et al., 2000; Tsai and Liou, 2000).

The central Dabie is the classic terrane where inclusions of coesite (Wang et al., 1989; Okay et al., 1989) and microdiamond (S. Xu et al., 1992) occur in eclogitic garnet. Recently, coesite inclusions have been documented in omphacite, kyanite, zoisite, zircon, and dolomite from mafic eclogitic lenses in gneiss and marble (Zhang et al., 1995a; Zhang and Liou, 1996; Liou et al., 1998; Cong et al., 1995; Carswell and Zhang, 1999). The country rock gneisses also contain

UHP relics. Garnet peridotites, pyroxenites, and associated eclogites at Bixiling and Maowu are mafic-ultramafic cumulate layers or lenses, interpreted as crust-hosted UHP metaperidotites (Zhang et al., 1995b; Liou and Zhang, 1998; Jahn et al., 2003a).

Although present to the west in Tongbo, and to the east in the Dabie complex, the HP eclogite belt is most widely developed in Hong'an; here eclogites lack inclusions of coesite and formed under physical conditions less extreme than those of the UHP belt. The central and south-central Dabie and Hong'an terranes share comparable lithologies and structures, so evidently represent parts of a crustal continuum (e.g., Eide and Liou, 2000). The amphibolite-blueschist unit is juxtaposed against the more northerly HP eclogite belt, possibly along a normal fault. In the southern Dabie, a coherent sequence of epidote-amphibolite-facies rocks, including felsic gneiss, pelitic schist, and amphibolite, lies directly north of the blueschist-facies unit. These HP amphibolites differ from the northern Dabie high-T amphibolites in the common occurrence of rutile, garnet and epidote and lack of clinopyroxene. On the south, high-pressure amphibolites grade into transitional blueschist-greenschist-facies rocks.

Sulu block

Similar to Dabie-Hong'an, the Sulu terrane consists of fault-bounded UHP and HP belts on the northern edge of the Yangtze craton; the rocks are unconformably overlain by Jurassic clastic strata and Cretaceous volcanosedimentary cover, and are intruded by post-orogenic, Late Mesozoic granites (Fig. 8). The Sulu belt is bounded by the Yantai-Qingdao-Wulian fault on the northwest against the Sino-Korean craton, and the Jiashan-Xiangshui fault on the south. The UHP belt consists mainly of amphibolite-facies gneisses, with minor garnet peridotite, eclogite, amphibolite, quartzite and marble. Small blocks and lenses of garnet peridotite and serpentinite are scattered throughout the terrane. Coesite and quartz pseudomorphs after coesite occur as inclusions in garnet, omphacite, kyanite and epidote, and as an intergranular phase in eclogite (Hirajima et al., 1990; Zhang et al., 1995b; Liou and Zhang, 1996; Zhang and Liou, 1997). The HP belt lies southeast of the UHP belt, and consists of quartz-mica-kyanite schist, quartzite, marble, and rare blueschist (Zhang et al., 1995b, 2002a). Based on a systematic age difference between the time of UHP metamorphism of the Dabie and Sulu belts (240-216 versus 229-207 Ma, respectively), Leech

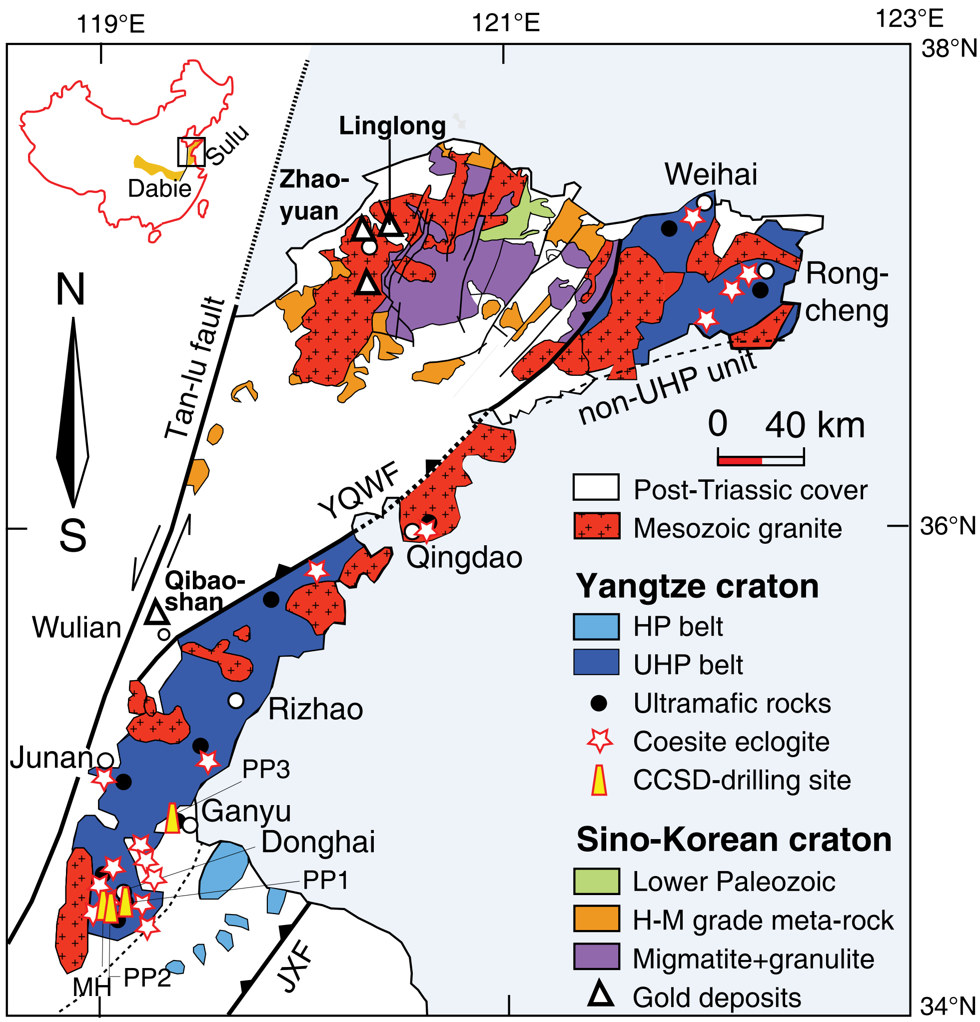


Figure 8. Generalized geologic map of the Shandong Peninsula, showing major metamorphic units, the distribution of eclogites, the CCSD sites (after Zhang and Liou, 1998; R. Y. Zhang et al., 2006), and locations of gold ore deposits (after X. Y. Zhang et al., 2001; Du et al., 2003). Rutile ore deposits occupy the general area of HP and UHP eclogites. YQWF, Yantai-Qingdao-Wulian fault; JXF, Jiashan-Xiangshui fault; H-M, high- and medium-grade metamorphic rocks.

et al. (2006) suggested that these terranes – both segments of the leading edge of the South China craton – were subducted separately rather than being part of a single block.

In order to measure the structure and thickness of the Sulu UHP slab, and to clarify the tectonic evolution of the collisional orogen, the Chinese Continental Scientific Drilling (CCSD) project was initiated in 1998. Three pre-pilot holes (PP1 = 432 m; PP2 = 1008 m; PP3 = 705 m) and a 5 km main hole (CCSD-MH) were drilled at Donghai, in the southern Sulu terrane (Fig. 8). The project had a recovery rate exceeding 80% for para- and orthogneiss, garnet peridotite, and eclogite samples; many cores, particularly those of garnet peridotite, are continuous and quite fresh. The 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

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 and Wang, 1995; Cong, ed. 1996; Zhang and Liou, 1996, 1998; Zhang et al., 1995a, b, 2000, 2003a; Liou et al., 1996) and geochronologic (Li et al., 1993; Bryant et al., 2004; X. Liu et al., 2004; Hacker et al., 2000, 2006; F. Liu et al., 2001, 2002, 2004; Jahn et al., 2003a, b) data demonstrate that the UHP rocks have been exhumed from depths exceeding 90-140 km between 240 and 220 Ma by a combination of normal-sense shear from beneath the hanging wall of the Sino-Korean craton, southeast thrusting onto the footwall of the Yangtze craton, orogen-parallel eastward extrusion, and subvertical flattening and horizontal extension. Important characteristics of Hong'an-Dabie-Sulu UHP rocks include: (1) occurrence of widespread coesite and HP hydrous phases such as talc, epidote, nyböite and phengite in eclogite (Hirajima and Nakamura, 2003; Rumble et al., 2003) and OH-rich topaz in kyanite-bearing quartzite (Zhang et al., 2002a); (2) the world-record lowest $\delta^{18}O$ values (-15‰ for rutile) for mineral separates from eclogites and metasedimentary rocks (for reviews, see Zheng et al., 2003; Rumble et al., 2003); (3) world-record highest bulk-rock ε_{Nd} values of about +170 to +260 for Weihai eclogites (Jahn et al., 1996, 2003a); (4) widespread garnet peridotites of mantle origin (Zhang et al., 2000, 2004); (5) abundant exsolution textures in UHP minerals from garnet peridotites and eclogites (Hacker et al., 1997; Zhang and Liou, 1998, 1999; Zhang et al., 2000; Zhang and Liou, 2003; Chen and Xu, 2005); and (6) thin clinoenstatite lamellae in peridotitic orthoenstatite (Zhang et al., 2002b, 2003a).

Retention of extraordinary $\delta^{18}O$ and ε_{Nd} values in these rocks indicates that open-system conditions involving a pervasive aqueous fluid did not attend the UHP metamorphism. Closed system recrystallization and the virtual absence of free H_2O prevented re-equilibration of the oxygen isotopes, and temperatures were too low to reset Nd isotopes during the roundtrip transpression-subduction and exhumation of the supracrustal rocks (Rumble et al., 2003; Jahn et al., 2003a). This conclusion helps to explain preservation of protolith structures such as pillows and unconformities (Dong et al., 2002; Oberhänsli et al., 2002), primary igneous textures, and relict igneous minerals such as biotite, plagioclase, and orthopyroxene (Hirajima et al., 1990; Zhang and Liou, 1997).

Inclusions in zircon and P-T-timing of Hong'an-Dabie-Sulu metamorphism

Quartzofeldspathic gneisses are ubiquitous in the Dabie-Sulu belt; most lack evidence of UHP metamorphism. However, geologic relationships suggest that lithologic contacts of some eclogite pods within gneisses have retained structural coherence through subduction, metamorphism, and exhumation, thus are not exotic. Moreover, rare indicators of UHP conditions have been reported from the country rocks. Coesite micro-inclusions occur in zircons from felsic gneiss (Sobolev et al., 1994; Tabata et al., 1998; Ye et al., 2000a, b; J. Liu et al., 2001; F. Liu et al., 2001, 2002, 2004) and marble (Liu et al., 2006), in dolomite and garnet from calc-silicate rocks and dolomite-bearing eclogite (Schertl and Okay, 1994; Zhang and Liou, 1996), and in 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 resultant thermobarometric computations (Carswell et al., 1997, 2000) have demonstrated that these lithologies were subjected to P-T conditions similar to the spatially associated coesite eclogites and garnet peridotites.

During subsolidus growth, zoned zircon domains may include and preserve inclusions of phases in P-T equilibrium with the matrix mineral assemblage. Zircons from Dabie-Sulu UHP outcrops and core samples (eclogite and amphibolite studied by F. Liu et al., 2004; Z. M. Zhang et al., 2006; para- and orthogneisses investigated by Ye et al., 2000b; J. Liu et al., 2001; F. Liu et al., 2001, 2002, 2004; marble examined by Liu et al., 2006) retain low-P mineral-bearing relict cores, UHP coesite-bearing mantles, and low-P quartz + plagioclase-bearing rims. Figure 9 illustrates such mineralogic features. Ion microprobe U-Pb analyses of these zoned zircons have identified three discrete age groups, shown schematically in Figure 10: latest Proterozoic protolith ages (> 680 Ma) in inherited cores; a culminating UHP metamorphic event in coesite-bearing mantles at 240-220 Ma; and amphibolite-facies overprinting in quartz-bearing rims at 210 ± 10 Ma. Such studies demonstrate that supracrustal and mafic-ultramafic rocks were subjected to in situ UHP metamorphism. Using a variety of thermochronologic methods, Webb et al. (2006) and Hacker et al. (2006) showed that exhumation of this UHP terrane to mid-crustal levels was completed by ~205 Ma.

Dabie-Sulu garnet peridotites: Further constraints on Dabie-Sulu petrotectonic development

Integrated chemical-mineralogic-geochronologic studies of ultramafic bodies provide information regarding mantle

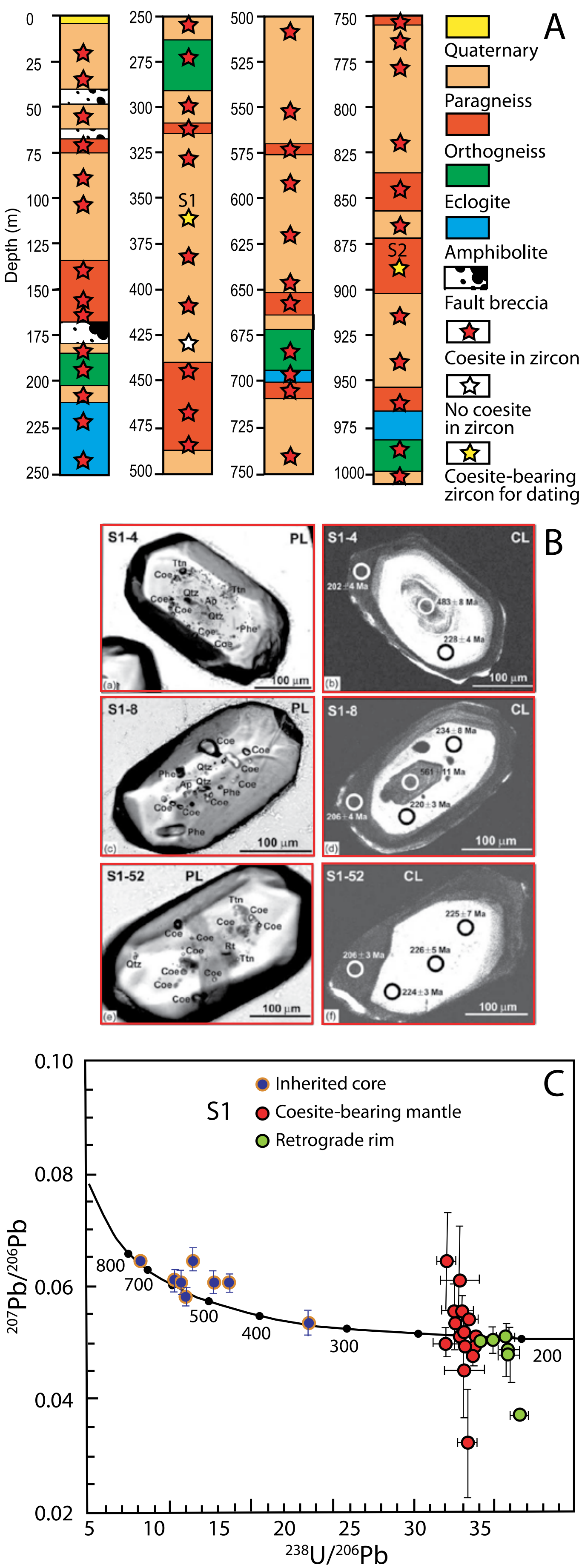


Figure 9 (left). (A) Lithologic column of PP2 core showing core locations of zircon separates containing coesite inclusions. (B) Zircons from mafic eclogites and felsic gneisses shown in plain light (PL) and in cathodoluminescence (CL); images after F. Liu et al. (2004). (C) Tera-Wasserburg diagram for ion microprobe U-Pb zircon ages of paragneiss S1 from a bore-hole depth of 362 m (Zhang et al., 2007b).

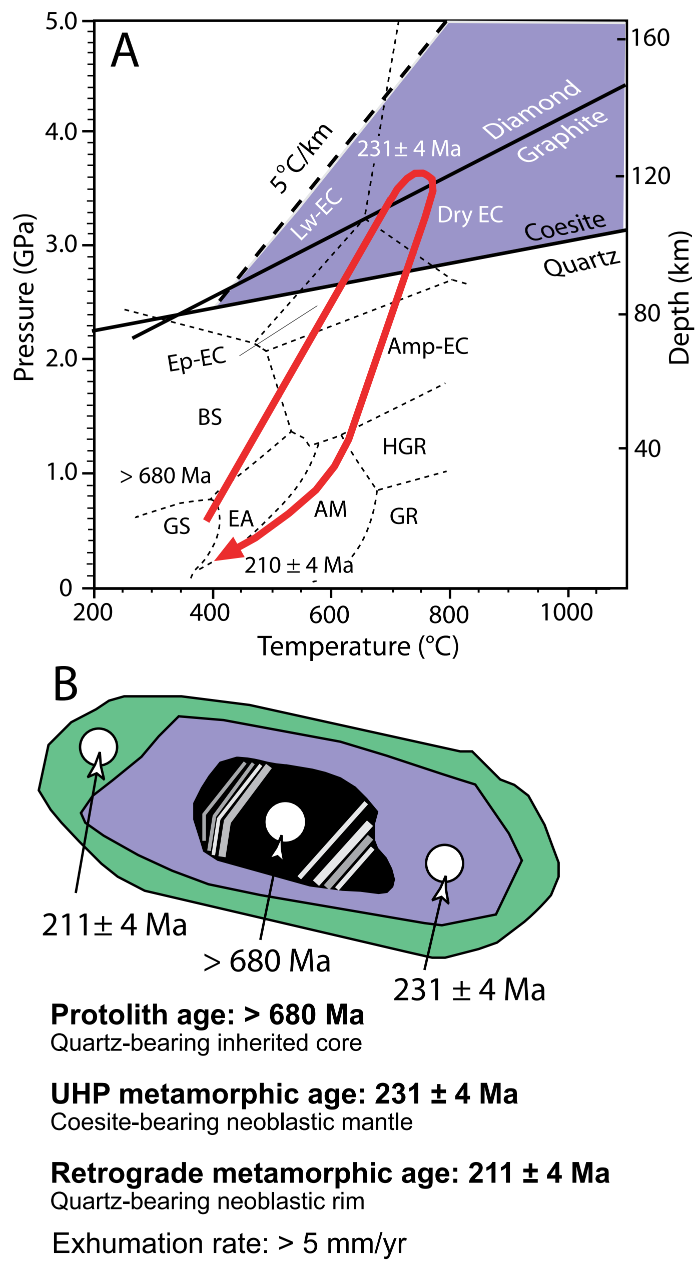


Figure 10 (above). (A) Schematic P-T-time path (red) for Sulu UHP rocks based on mineral parageneses and thermobarometry for various rock types, and (B) ion microprobe U-Pb dating of zoned zircon crystals (Zhang et al., 2004). Metamorphic-facies abbreviations are defined in Figure 5.

processes, and on compositions and evolution of the lithosphere beneath and/or overlying a transpressive subduction zone. Garnetiferous ultramafic rocks occur as minor, widely scattered lenses in the Dabie-Sulu UHP terrane (Zhang et al., 1994, 2000). Although most natural exposures are weathered, fresh samples from quarries and along the coast have been intensively studied (Yang et al., 1993; Zhang et al., 1994, 1995a, 2000, 2003a, 2004, 2005a, 2007a; Zhang and Liou, 2003; Liou and Zhang, 1998; Yang et al., 2007; Liou et al., 2007). The drilling project recovered many garnet lherzolite, harzburgite, wehrlite, and dunite core samples, with an aggregate thickness of ~700 m from three bore holes, CCSD-MH, PP1, and PP3. Dabie-Sulu garnet peridotites are classified as mantle-derived, Type-A, and crust-hosted mafic-ultramafic cumulates, Type-B. Both types underwent transpression-subduction-zone UHP metamorphism and metasomatism at so-called "forbidden zone" P-T conditions (<5 °C/km), with computed pressures up to ~6.7 GPa. Peridotite thermobarometry yields substantially higher computed pressures than the minimum P values required by mineral assemblages of associated eclogites. Thus the peridotite lithologies must reflect: (a) ascent and insertion of more deep-seated ultramafics into the UHP terrane; (b) overestimated pressures of peridotite origin; or (c) underestimated pressures of eclogite formation.

Studies of micro-inclusions and exsolution lamellae have revealed several features that apparently formed at much higher P-T conditions than those determined using the Grt-Opx geobarometer (Liou et al., 1998). These include a silicon-bearing spinel solid solution Fe_3O_4-$(Fe, Mg)_2SiO_4$ (Zhang et al., 1999), and inferred pre-existing majoritic garnet – now consisting of intergrown rutile, clinopyroxene and apatite lamellae – in eclogite and garnet pyroxenite lenses in peridotite (Ye et al., 2000b; Zhang et al., 2003b). Moreover, coarse-grained Cpx from a Rizhao garnet clinopyroxenite contains up to 25 volume % exsolved garnet and 4 volume % ilmenite; judging from petrologic and experimental studies, the precursor of this intergrowth was a relict very-high-pressure phase, probably majoritic garnet in which $(Mg, Fe)^{2+}Ti^{4+} \rightarrow 2Al^{3+}$, $Mg^{2+}Si^{4+} \rightarrow 2Al^{3+}$, and $Na^{+}Ti^{4+} \rightarrow Ca^{2+}Al^{3+}$ (Zhang and Liou, 2003; Zhang et al., 2003b).

Intergrowths of ortho- and clinoenstatite lamellae are common in garnet peridotite CCSD samples from PP1 and the main hole, as well as from the Xugou peridotite. Clinopyroxene lamellae in Opx may have formed by inversion from orthoenstatite or by a displacive transformation from very-high-pressure clinoenstatite during decompression (Zhang et al., 2002b). Experiments at 900 °C indicate that Opx converts to very-high-pressure clinoenstatite above about 8 GPa, corresponding to a mantle depth of ~300 km (Pacalo and Gasparik, 1990; Ulmer and Stalder, 2001). The recent report of very-high-pressure Cpx in a Dabie crystal cumulate metamorphosed to garnet peridotite (X. Liu et al., 2007) is important, because it requires the mantle material to have been inserted into a continental section of rocks, then carried to much greater depths than indicated by the minimum-P values recorded in the spatially associated mafic and felsic UHP rocks. Apparently the entire crustal assemblage descended to a depth of ~300 km before exhumation.

Reflecting low Zr and Si contents, zircon is extremely rare in ultramafic rocks, so dating peridotites is very difficult. Nevertheless, trace amounts of zircon have been reported from mineral separates and thin sections of CCSD peridotites, as well as from several outcrops. Morphologies and inclusions suggest that these zircons grew attending metamorphism and metasomatism. Ion microprobe U-Pb dating of zircons from the Weihai Type-B peridotite (Fig. 8) and from the PP1 core Type-A peridotite yielded identical UHP metamorphic ages of 221 ± 12 Ma (J. S. Yang et al., 2003) and 221 ± 3 Ma (Zhang et al., 2005b). Similar 230 ± 10 Ma ages were obtained for several other garnet peridotites and their included eclogite lenses, such as the Rongcheng body (R. Zhao et al., 2005, 2006).

PERMO-TRIASSIC OROGENY IN THE KOREAN PENINSULA

As shown in Figure 11, the Korean Peninsula consists of five principal lithotectonic belts (Metcalf, 2006). From northwest to southeast, these are the Nagrim massif, the Imjingang belt, the Gyeonggi massif, the Ogcheon belt and the Yeongnam massif. The Nagrim massif is part of North China craton; it includes Late Archean to Paleoproterozoic gneisses as well as younger meta-igneous and metasedimentary rocks. In North Korea, Cambro-Ordovician and Permo-Carboniferous strata overlie the Precambrian basement. The Nagrim backstop was not significantly affected by the Permo-Triassic contractional HP accretionary event discussed in this paper. We regard the four belts to the south as possessing Yangtze cratonal affinities, but this correlation is still debated (Cluzel et al., 1991; Yin and Nie, 1993; Chough et al., 2000).

The Imjingang belt is an EW-trending, Barrovian-style metamorphic terrane consisting chiefly of metasedimentary and metavolcaniclastic sequences and minor marble (Cho et al., 1995, 2007; Ree et al., 1996). Cho et al. (2005) reported a U-Pb ion microprobe age of 253 ± 2 Ma for zircon growth attending metamorphism of garnet amphibolite at 0.85-1.15 GPa, 660-780 °C, and a Neoproterozoic U-Pb age of 861 Ma from relict igneous zircon in an amphibolite. Based on radiometric data and mineral parageneses, Cho et al. (2007) interpreted the Imjingang belt and the Gyeonggi massif ± the Ogcheon belt (described below) as having collided with the North China craton during Permo-Triassic time, resulting in crustal thickening; deep-seated eclogitic units that formed under transpression-subduction-zone P-T conditions subsequently decompressed during exhumation at ~230-220 Ma.

The Gyeonggi polymetamorphosed granulitic gneiss complex lies between the Imjingang belt to the north and the Ogcheon belt the south. Based on discovery of relict eclogite in the southwest part of the Gyeonggi massif, and on recognition that the grade of metamorphism increases southward in the Imjingang belt, and northward in the Ogcheon belt, Oh and

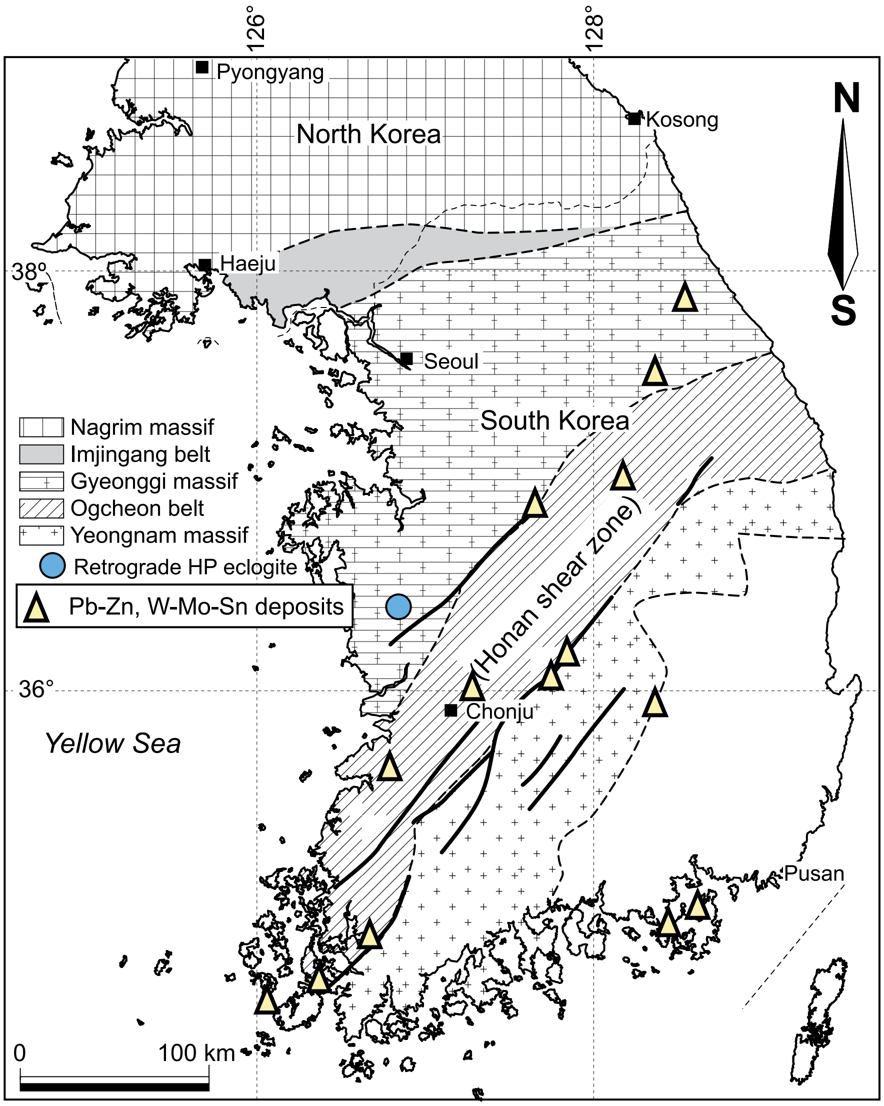


Figure 11. Generalized geologic map of the central and southern Korean Peninsula, with non-metamorphosed Cretaceous and Cenozoic units unpatterned (after Cluzel et al., 1991; Yin and Nie, 1993; Oh, 2006). Ore-deposit types and locations are from Kim (1971) and Choi et al. (2005).

Kusky (2007) postulated that the HP Gyeonggi gneiss complex is the eastern limb of the Dabie-Sulu terrane. Its southern boundary with the Ogcheon belt is occupied by a mylonitic alkalic metagranitoid (Lee et al., 2003). The Gyeonggi massif consists of Archean-Proterozoic sialic basement and a Paleo-Mesoproterozoic supracrustal series, with minor serpentinized peridotite in its southwestern part (Lee and Cho, 1995, 2003; Lee et al., 2000, 2003; Seo et al., 2005; Oh et al., 2005; Oh, 2006; Kim et al., 2006). Zircons from banded gneiss yielded a U-Pb age of 2.16 Ga (Kim et al., 1999). Ion microprobe U-Pb ages of zircons from several granitic rocks and felsic orthogneisses display zircon ages ranging from 2900-713 Ma (Lee et al., 2000, 2003; Zhai et al., 2005). In contrast, monazite chemical U-Th-total Pb ages attest to an ~255-240 Ma regional metamorphic event (Cho et al., 1996; Suzuki and Adachi, 1994); Kim et al. (2000) reported a 226 Ma Rb-Sr muscovite age from a Gyeonggi mylonitic gneiss, and interpreted it as a manifestation of post-collisional, extensional ductile shear. Oh et al. (2005) described the relict eclogitic mineral assemblage, and estimated HP metamorphic P-T conditions as 1.7-2.1 GPa, 835-860 °C, and 0.7-1.1 GPa, 830-850 °C for a later, low-P granulite-facies stage. Kim et al. (2006) obtained zircon U-Pb ion microprobe ~800 Ma core ages and ~230 Ma rim ages from this retrograded eclogite. All these data support correlation of the Gyeonggi massif with the South China craton (Jeon et al., 2007).

The northeast-trending, polymetamorphic Ogcheon belt consists of Neoproterozoic-Paleozoic low-grade metasedimentary strata, metafelsic and intermediate metavolcanic rocks, and rare marble (Cluzel et al., 1990; Min and Cho, 1998; Chough et al., 2000; Oh et al., 2004; Cho and Kim, 2005). Rare medium-grade pelitic schists occur in the northwest part of the terrane. This belt displays a Paleozoic stratigraphic section similar to that of the North China craton (Ishiwatari and Tsujimori, 2003), but lies south of the Yangtze-affinity Gyeonggi gneiss complex, so probably represents an extension of the Dabie-Sulu belt. U-Pb dating of zircon from metatrachyte yielded a U-Pb upper intercept protolith age of 756 Ma and a lower intercept of 160 Ma (Lee et al., 1998). Cho and 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) suggested that Ogcheon belt peak metamorphism occurred at ~285 Ma, based on Pb-Pb whole-rock ages of slate, and uraninite electron-microprobe Th-U total Pb chemical ages; an Early Permian metamorphic peak is also supported by a zircon ion microprobe U-Pb age of ~290 Ma (Cho et al., 2004). Cho and Kim (2005) proposed a three-stage evolution for the Ogcheon belt: Permian amphibolite-facies metamorphism (P= 0.4-0.9 GPa, T= 490-630 °C); Triassic regional greenschist-facies overprinting (P= 0.1-0.3 GPa, T= 350-500 °C); and Jura-Cretaceous contact metamorphism around later granitoid plutons. This paragenetic history reflects Ogcheon tectonic development as a Late Proterozoic intracontinental rift zone that evolved into a Permo-Triassic fold-and-thrust belt (Cluzel et al., 1990).

The Yeongnam massif is situated southeast of the Honam shear zone, and consists of gneisses and minor amphibolites and metasedimentary rocks. Metamorphic grade is lower amphibolite to lower granulite facies, reaching 750-800 °C and 0.4-0.6 GPa in migmatitic gneisses (Kim and Cho, 2003). U-Pb ages for the granitic gneisses range from 1.9 to 2.1 Ga (Cheong et al., 2000). Kim and Cho suggested that Precambrian crustal evolution of the Yeongnam massif reflects the formation of protocrust at ~2.9-2.5 Ga, followed by felsic magmatic episodes at ~2.1-1.9 Ga. Correlation of this lithotectonic entity with the Yangtze (or Cathaysia) block seems most plausible (Lee et al., 1998).

PERMO-TRIASSIC OROGENY IN WESTERN JAPAN

Southwestern Japan

The Japanese island arc is an active circum-Pacific-type orogen exhibiting oceanward growth since mid-Paleozoic time, as documented by abundant structural, biostratigraphic, and geochronologic data (Isozaki, 1996, 1997; Maruyama, 1997; Maruyama et al., 1997; Ishiwatari and Tsujimori, 2003). Regional geologic relations are shown in Figure 12. The accretion of southwest Japan has involved the progressive suturing of a collage of subparallel HP collisional belts, subsequently invaded and overlain by post-orogenic calcalkaline plutonic and volcanic rocks; each complex has an oceanic plate stratigraphy, and later granitic magmatism generated a low-P contact metamorphic overprint (Isozaki, 1996). Several intervals of exhumation of HP metamorphic rocks are well known: 450-400 Ma (Kurosegawa-Oeyama); 305-280 Ma (Renge); 210-170 Ma (Suo); and 90-60 Ma (Sanbagawa). The gross architecture is a stack of subhorizontal nappes, with older sheets occupying the upper structural positions. The nappes were folded during Cretaceous time, forming broad synforms and antiforms. Paleozoic-Triassic transpressive terranes are exposed sporadically throughout western Honshu, as well as in Kyushu.

In the Hida Mountains of southwest Japan, pre-Jurassic metamorphic rocks occur as two petrotectonic units, the Hida belt (part of the Sino-Korean cratonal backstop), and the Hidagaien (Hida Marginal) belt. These basement terranes are overlain unconformably by Lower Jurassic – Lower Cretaceous shallow-water and non-marine strata. The Hida belt was thrust southward as a giant nappe over the Hidagaien belt (Komatsu, 1990). Hida lithologies are mainly polymetamorphosed orthogneiss, paragneiss, marble, amphibolite, and Fe-Al-rich pelitic schist (Hiroi, 1981, 1983; Suzuki et al., 1989; Arakawa et al., 2000). Ion microprobe U-Pb age data for zircons from a Hida paragneiss gave a detrital age of 1.84 Ga, whereas zoned crystals record three later thermal events at 1.69 Ga, 440 Ma, and 250 Ma (Y. Sano et al., 2000). Microprobe Th-U-total Pb chemical ages of zircon in sillimanite-grade amphibolite-facies paragneisses yielded 250-230 Ma ages (Suzuki and Adachi, 1994). K-Ar and Rb-Sr mineral ages of both metamorphic rocks and remobilized Jurassic granitic intrusions cluster at ~180 Ma (Ohta and Itaya, 1989). In the Unazuki belt of the Hida gneiss terrane, a typical Barrovian staurolite-bearing pelitic-schist may represent an eastern extension of the Ogcheon (Hiroi, 1983), and Sulu-Dabie belts (Isozaki, 1997; Maruyama, 1997).

In contrast, the Hidagaien belt is a composite tectonic unit that lies structurally below the inboard Hida belt and above the outboard Jurassic Tamba-Mino accretionary complex (Komatsu, 1990). It consists mainly of slices of various pre-Jurassic rocks; serpentinites containing blocks of Late Paleozoic schist and Middle Ordovician to Upper Triassic unmetamorphosed clastic rocks are typical (Banno, 1958; Nakamizu et al., 1989; Tazawa, 2001, Kurihara and Sashida, 2000; Tsujimori, 2002, 2004; Tsukada, 2003; Nozaka, 2005). Metasomatic zircon in jadeitite within a serpentinite body gave a U-Pb ion microprobe age of ~500 Ma (Kunugiza et al., 2004). HP Renge schists of the Hidagaien belt record mainly greenschist-amphibolite-facies metamorphism but locally preserve blueschist-eclogite assemblages (Nishimura, 1998; Tsujimori et al., 2000). Metamorphic conditions of the latter were estimated as >1.8 GPa and 550-600 °C (Tsujimori, 2002). Phengitic micas from HP Renge epidote-glaucophane eclogites and garnet amphibolites yielded K-Ar and Ar-Ar ages of ~347-283 Ma, regardless of metamorphic grade (Shibata and Nozawa, 1968; Kunugiza et al., 2004). However, a Triassic K-Ar date – possibly thermally reset – was reported from a paragonite-bearing garnet-epidote-amphibolite (Tsujimori et al., 2006).

In western Honshu, tectonically imbricated, EW-trending Paleozoic ophiolites and accretionary stacks occupy the highest structural sites (Ishiwatari and Tsujimori, 2003). Pre-Triassic rocks occur as six distinct petrotectonic belts: the Oki, Oeyama, Akiyoshi belt, Maizuru belt (the Yakuno ophiolite), Ultra-Tamba, and Suo units. The Oki terrane consists of low-P pelitic and quartzofeldspathic gneisses ± minor marble and amphibolite. Microprobe Th-U-total Pb chemical ages of neoblastic monazite and zircon in gneiss gave ~250 Ma for the amphibolite-facies metamorphism (Suzuki and Adachi, 1994), whereas thermal ionization zircon U-Pb ages are ~1.9 Ga (Yamashita and Yanagi, 1994). This gneissic terrane has North China cratonal affinities and is similar petrologically to

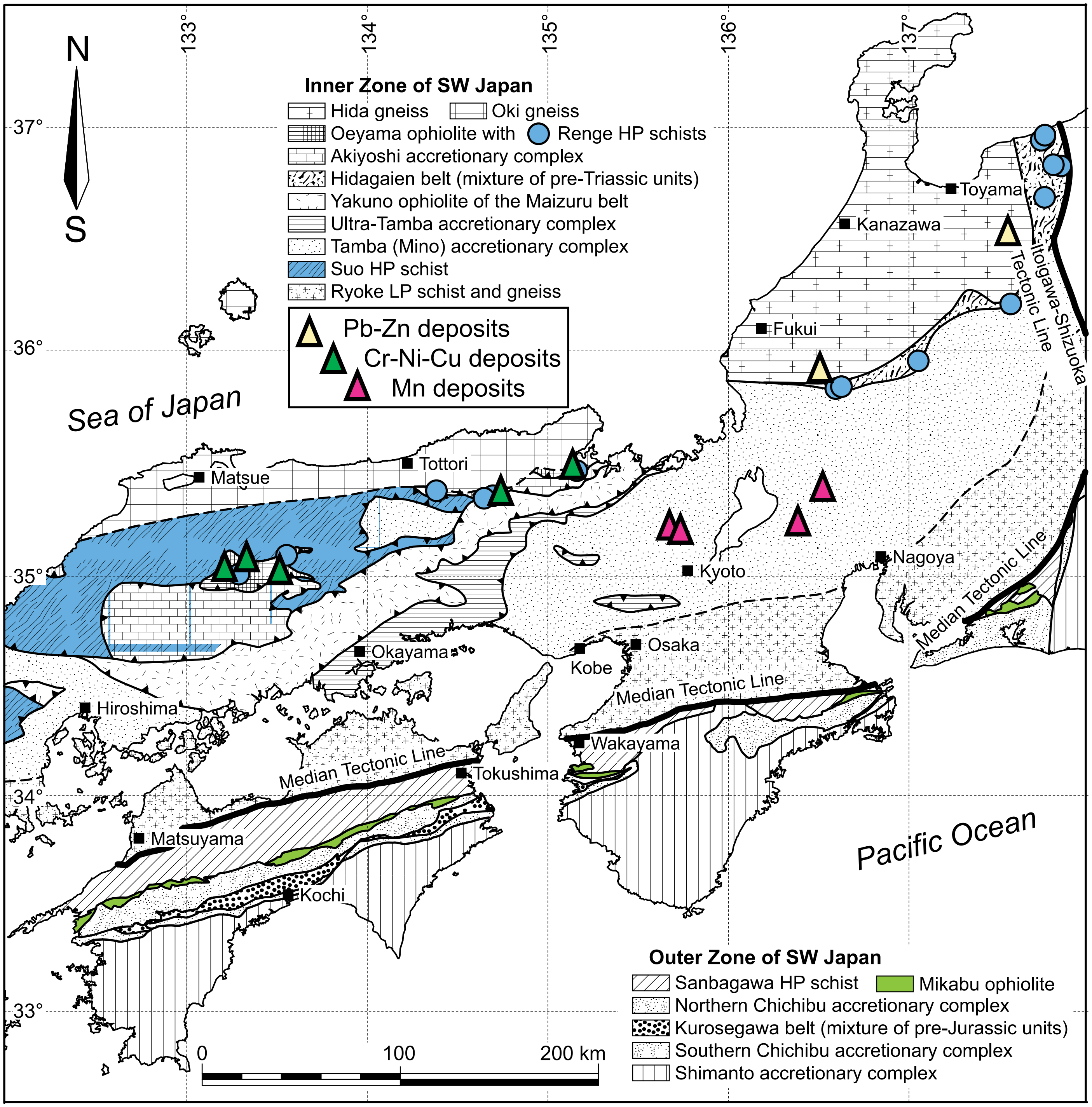


Figure 12. Generalized geologic map of southwestern Japan (after Maruyama et al., 1997; Ishiwatari and Tsujimori, 2003). Ore-deposit types and locations are from Ichikawa et al. (1990), Sato and Kase (1996), and Watanabe et al. (1998).

the Hida belt. The Early Paleozoic Oeyama belt is made up mainly of serpentinized harzburgites ± minor gabbros (Arai, 1980; Tsujimori and Liou, 2004); Sm-Nd ages for the mafic intrusions are ~560 Ma, suggesting an Early Cambrian ophiolite sequence. A jadeite vein in serpentinite gave a U-Pb ion microprobe age of ~470 Ma (Tsujimori et al., 2005). Two contrasting HP metamorphic rock types occur as tectonic blocks in the Oeyama belt: epidote-amphibolite-facies metagabbros with 470-400 Ma hornblende K-Ar ages (Nishimura and Shibata, 1989; Tsujimori and Liou, 2004); and blueschist-facies pelitic and mafic schists with 305-280 Ma phengite K-Ar ages (Nishimura, 1998; Tsujimori and Itaya, 1999). The younger HP rocks may be fragments of the Late Paleozoic Renge terrane, tectonically underlying the Oeyama belt (Tsujimori, 1998). The Akiyoshi Permian accretionary complex consists of a thick limestone-greenstone complex ± pelagic-hemipelagic sediments; carbonate strata contain Early Carboniferous to Middle Permian fossils (Kanmera et al., 1990), and the greenstone has N-MORB geochemical affinities (S. Sano et al., 2000). The Maizuru ophiolitic belt is a Late Permian unit capped by sedimentary cover; the metabasalt-metagabbro-metaperidotite complexes are termed the Yakuno ophiolite (Ishiwatari, 1985; Ichiyama and Ishiwatari, 2004). Hornblende from metagabbro yielded K-Ar ages of ~280-240 Ma (Shibata and Nozawa, 1968), and zircon from oceanic plagiogranite gave U-Pb ~280 Ma ages (Herzig et al., 1997). The Ultra-Tamba belt is a Late Permian accretionary complex lying beneath the Maizuru belt; it consists mainly of pelagic-hemipelagic sediments ± minor greenstones (Ishiga, 1990). The Suo metamorphic belt is made up mainly of low-grade HP units; pumpellyite-actinolite facies to greenschist and epidote-blueschist facies rocks dominate (Nishimura, 1998). Phengitic micas yielded K-Ar ages of ~220 Ma in the eastern area and ~190 Ma in the west. Detrital zircon U-Pb data suggest a ~1.9-2.0 Ga depositional age for the metasedimentary rocks and ~230 Ma for the transpression-subduction-zone metamorphism (Miyamoto and Yanagi, 1996). Except for the uncertain position of the Oki belt, all these Paleozoic units constitute a giant nappe pile with the older sheets occupying structurally higher sites.

Southwest of the area of Figure 12, small tracts of Renge blueschist crop out in northern and central Kyushu (Kabashima et al., 1995; Nishimura, 1998). The HP rocks possess 340-280 Ma K-Ar ages. In addition, Permo-Triassic gneiss and granulite of the Higo metamorphic complex are present in central Kyushu (Obata et al., 1994; Osanai et al., 1998, 2006); U-Pb zircon geochronology yielded Neoproterozoic (~2.2-1.8 Ga) detrital ages as well as Early Paleozoic (~550-450 Ma), Middle Paleozoic (~380 Ma), and Permo-Triassic (~260-230 Ma) ages.

Central Japan

Small tracts of Permo-Triassic HP schists occur in the southern Kitakami Mountains (Maekawa, 1988). A 300 Ma phengite K-Ar age (Kawano and Ueda, 1965) and 239-225 Ma hornblende K-Ar ages (Kanisawa et al., 1992) from garnet-epidote amphibolites suggest that blueschist-facies metamorphism in central Japan was coeval with formation of the Renge and Suo blueschists in southwestern Japan. The HP schist unit contains older amphibolite blocks characterized by hornblende K-Ar ages of 479 and 524 Ma.

PERMO-TRIASSIC OROGENY IN THE RUSSIAN FAR EAST

Figure 13 presents the general geology of the Sikhote-Alin region; it consists of two distinctly different lithologic

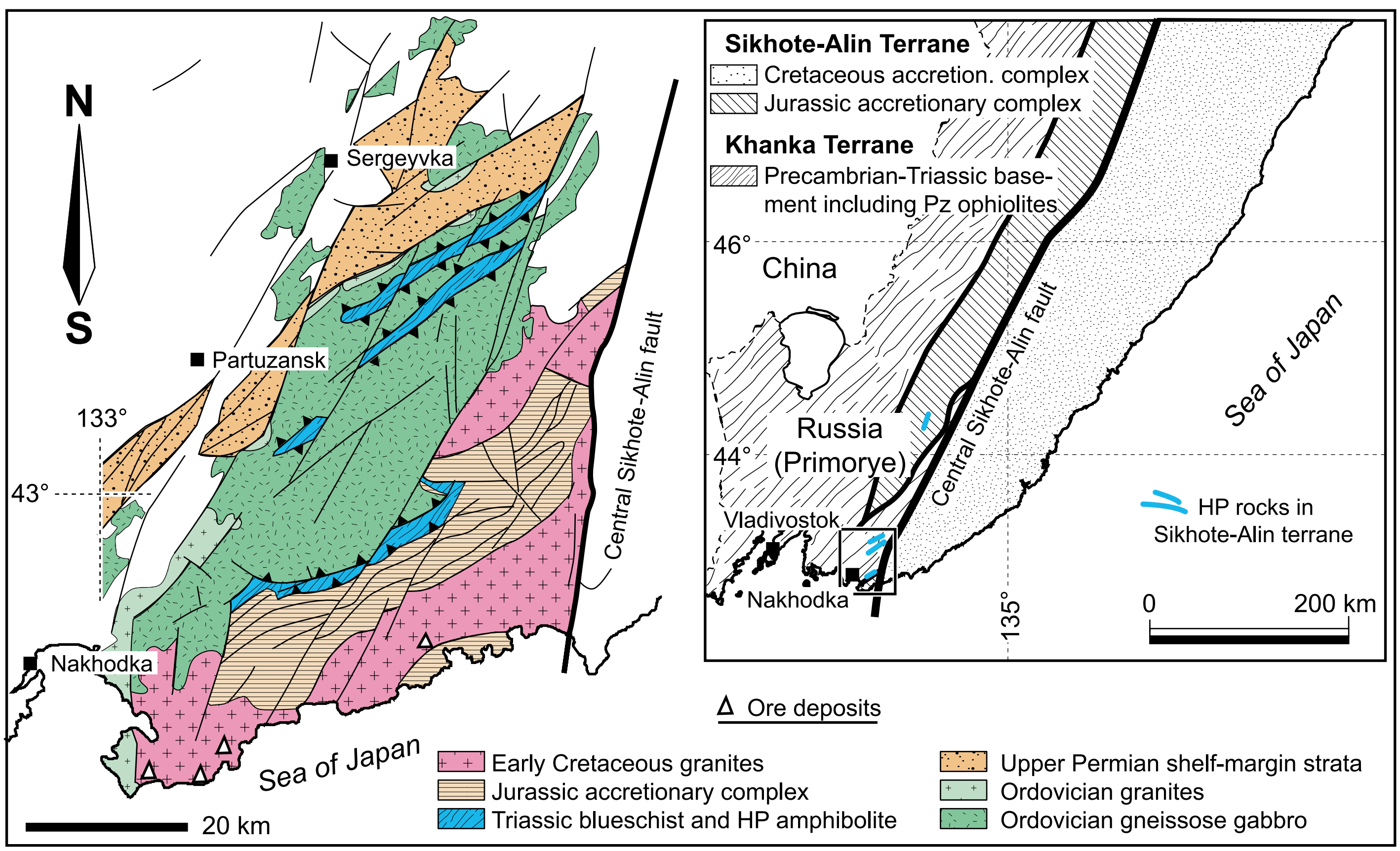


Figure 13. Generalized geologic map of Sikhote-Alin, Russian Far East (after Khanchuk et al., 1996; Khanchuk, 2001). The Permo-Triassic HP rocks of the Sikhote-Alin terrane are exposed in windows beneath the Khanka nappe complex. Ore-deposit types and locations are from Kazachenko et al. (1979, 2006).

units, the Khanka and Sikhote-Alin terranes. The former may be part of a much larger continental entity, the Sino-Korean craton, including the Bureya and Jiamusi blocks to the north (Khanchuk et al., 1996; Khanchuk, 2001); the Khanka terrane consists of Precambrian sialic basement overlain by thick Cambrian calcareous strata and post-Silurian continental sedimentary strata. The Sikhote-Alin terrane is made up of Paleozoic and Mesozoic accretionary complexes intruded by Cretaceous granites and is covered by Cretaceous-Tertiary volcanic rocks (Kemkin and Khanchuk, 1994; Kojima et al., 2000). The Sikhote-Alin belt includes minor schist localities (Kovalenko and Khanchuk, 1991; Ishiwatari and Tsujimori, 2003). Epidote-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. A Precambrian ~2.5 Ga Rb-Sr isochron age was reported from spatially associated garnet-hornblende gneiss, but hornblende K-Ar ages are ~250 Ma, coeval with the time of metamorphism of the HP complex.

TECTONIC REGURGITATION OF HP-UHP SUBDUCTION COMPLEXES

The P-T evolution of a decompressing rock mass is a composite function of its past tectonic history, aggregate heat capacity and thermal conductivity, thickness, rate of ascent, and temperature and thermal properties of the medium through which it passes (e.g., Root et al., 2005). Thin sheets, possessing a large surface-to-volume ratio, exchange heat by conduction more efficiently than do thick, relatively equidimensional masses. If a thin HP or UHP slab rises infinitely slowly along a cool subduction channel (the thermal gradient being maintained dynamically by lithospheric plate descent), the P-T trajectory will retrace the prograde path, provided conduction-mediated refrigeration takes place. If it rises rapidly, the slice will carry most of its heat along with it, and will follow a retrograde path at an elevated temperature for a given pressure compared with the prograde trajectory. However, in situations where a thin HP-UHP body ascends through a zone of much hotter rocks, such as the interior of the overlying mantle wedge, it may become hot enough that mineralogic evidence of high- or ultrahigh-pressure metamorphism is destroyed. Many well-documented HP terranes do track the prograde P-T path on exhumation, indicating moderately slow decompression. Some UHP terranes show similar retrograde P-T trajectories, whereas others exhibit the effects of rapid, near-isothermal decompression to mid-crustal P-T conditions.

Figure 14 shows forces acting on subduction and exhumation of low-density sheets. Descent of buoyant material at a dip angle of θ occurs if shear forces caused by underflow (F_s) exceed the combined effects of buoyancy (F_b) and frictional resistance (F_r) along the hanging wall of the subduction channel. Here, $F_s > F_b \sin\theta + F_r$. Decoupling and ascent of a slice of

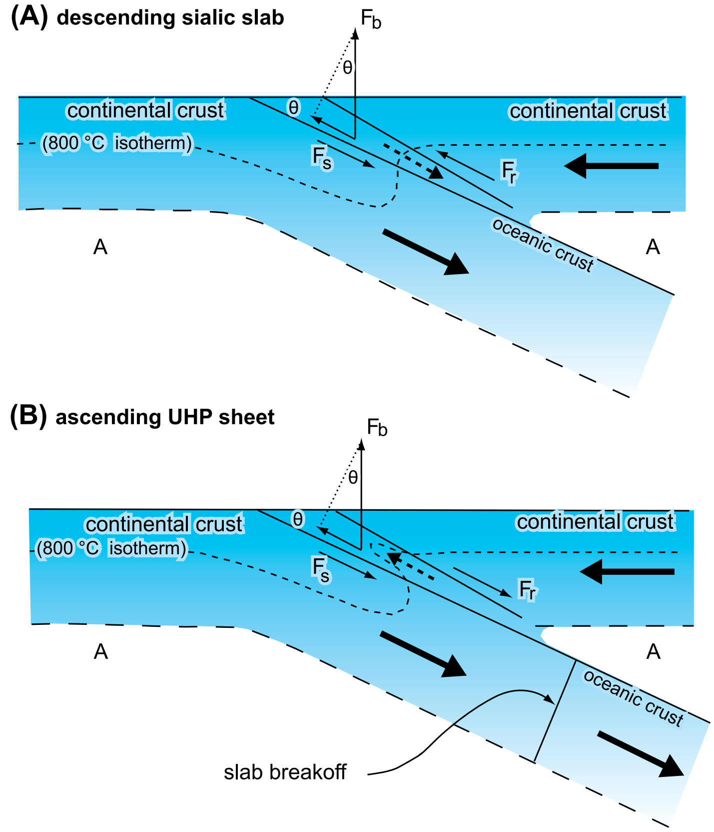


Fig. 14. Schematic convergent lithospheric plate-boundary diagram for active plate descent, after Ernst and Peacock (1996). Only the subduction component of transpressive underflow is diagrammed. Lithosphere is shaded blue (crust-mantle boundary not shown); asthenosphere (A) is uncolored. (a) Deep burial and thermal structure of a downgoing sheet of continental material. (b) Later decompression cooling of a rising slice of low-density sialic material. Relative motions of plates and slices are indicated by arrows (the plate actually is sinking and rolling backward; Hamilton, 1995). During ascent of the HP and/or UHP slab (thickness exaggerated for clarity), cooling of the upper margin of the sheet takes place where it is in contact with the low-temperature hanging wall (the mantle wedge); cooling along the lower margin of the slab takes place where it is juxtaposed against the low-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 buoyant slab in stages (a) and (b) are discussed in the text.

low-density material can take place in cases where buoyancy exceeds the aggregate effects of shearing along the subduction channel footwall and resistance to movement along the hanging wall. For this situation, $F_b \sin\theta > F_s + F_r$. The mantle wedge guides the exhumation path, and the rising sheet is emplaced outboard from the deep-seated realm of HP-UHP metamorphism. As subduction angle decreases, the effective buoyancy lessens during both underflow and exhumation. For subducted complexes to be returned to shallow depths, the rising mass must overcome frictional resistance to sliding, so must be thick enough for buoyancy-driven ascent, yet thin enough that heat is effectively conducted across the bounding upper (normal) and lower (reverse) faults. Such petrotectonic features have been mapped in many exhumed subduction terranes, e.g., the Himalayas (Burchfiel et al., 1989; Searle, 1996; Searle et al., 2001; Kaneko et al., 2003); the Franciscan Complex (Ernst, 1970; Suppe, 1972; Platt, 1986; Jayko et al., 1987); the Western Alps (Henry, 1990; Compagnoni et al., 1995; Michard et al., 1995); the Sanbagawa belt (Kawachi, 1968; Ernst et al., 1970; Banno and Sakai, 1989); the Kokchetav Massif (Kaneko et al., 2000; Ishikawa et al., 2000; Ota et al., 2000; Maruyama and Parkinson, 2000); the Western Gneiss Region of Norway (Harley and Carswell, 1995; Krogh and 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).

Although less dense than dry mantle, most back-reacted UHP complexes reach neutral buoyancy and stall at middle levels of the continental crust (Walsh and Hacker, 2004). Further exhumation may result from contraction (Maruyama et al., 1994, 1996) or low-density sialic underplating, in either case combined with isostatically compensated regional uplift and erosion (Platt, 1986, 1987, 1993). Also, if plate breakoff occurs, a decrease in aggregate density of the sinking lithosphere would result in shallowing of the buoyant downgoing slab, and might account for the late doming noted in some exhumed subduction-zone complexes (Ernst et al., 1997; O'Brien, 2001; O'Brien et al., 2001). Another unloading mechanism is the antithetic faulting typical of some contractional orogens, where double vergence characterizes end stages of ascent of low-density crust (Dal Piaz et al., 1972; Ring and Brandon, 1994, 1999). Finally, rapid uplift of diapiric masses of sialic crust seems to be occurring along convergent plate boundaries where curvilinear arcs intersect at pronounced cusps. Such uplifts have been termed tectonic aneurysms (Zeitler et al., 2001; Koons et al., 2002), and may be another way in which some UHP terranes are exposed (Ernst, 2007).

MINERAL DEPOSITS OF THE PERMO-TRIASSIC EAST ASIAN OROGEN

General statement

Only minor metallogenesis appears to have been related to the ~305-210 Ma transpression-subduction of oceanic lithosphere that terminated in the continental collision and contractional suturing of the Yangtze and Sino-Korean cratons in east-central China and the Korean Peninsula, and in the accretionary stranding of oceanic crust, deep-sea sedimentary rocks, and distal turbidites in southwest Japan and the Russian Far East (Fig. 6). Ophiolitic copper-zinc-lead sulfide deposits sequestered in uppermost levels of the oceanic crust formed offshore mainly as submarine hydrothermal deposits around oceanic spreading centers, prior to landward transport and tectonic stranding (e.g., Sato and Kase, 1996; Dilek and Ernst, 2008). Such base-metal deposits are interlayered with hemipelagic sedimentary units that overlie submarine basaltic flows and flow breccias; some flow-top strata are rich in Mn. Although ophiolitic sequences are abundant in southwest Japan and northeast Russia, mafic complexes are rare in the continental collisional zones of east-central China and central Korea. Economic concentrations of TiO_2 occur, but are confined to Ti- and Fe-rich eclogites that were annealed during transpression-subduction of mafic units scattered throughout the East Asian orogen; the most economically attractive rutile deposits are coarse-grained units metamorphosed under HP and especially UHP conditions (e.g., Gao et al., 2007). In addition, thin layers and podiform chromite deposits typify a few of the harzburgitic underpinnings of the oceanic lithosphere where tectonically inserted into the continental crustal margin and later exposed (Dilek and Ernst, 2008).

Post-collisional aqueous fluids derived from solidifying Late Mesozoic granitic intrusions evidently contained base and precious metals that were derived from the granitic magmas or mobilized from pre-existing basement terranes. In any case, the metals were deposited in the general vicinity of the plutons, especially in the Tongbo-Hong'an-Dabie-Sulu belt. Thus, a range of important economic mineral deposits formed regionally in rocks of the Permo-Triassic suture zone in east-central China, but are actually products of a later, apparently unrelated metallogenic event. Few East Asian mineral deposits can be shown to have formed as a result of the Permo-Triassic convergent suturing, reflecting the fact that the ~305-210 Ma transpressive event generated insignificant volumes of intermediate and felsic plutons.

Many ore-forming processes seem to be related to evolution of high-T fluids derived under the deep-seated conditions where intermediate and felsic magmas are generated, such as along convergent margins (Goldfarb et al., 2001; Groves et al., 2005). Head-on subduction results in the wholesale devolatilization of a downgoing, hydrated oceanic plate (Ernst, 1990), promoting H_2O-induced partial melting of transformed oceanic crust ± the overlying mantle wedge (DePaolo, 1981; Drummond and Defant, 1990; Hawkesworth et al., 1993; Clift et al., 2001; Hickey-Vargas et al., 2002). Calc-alkaline plutons and hydrothermal fluids rising from magmagenic depths (80-120 km) into the zone of fracture of the upper-level, quartzofeldspathic crust, interact with the wall rocks and on cooling and decompression, produce various types of deposits.

The absence of major ore deposition coeval with the Permo-Triassic continental collision in east-central China and the central Korean Peninsula may reflect the transpression-subduction of relatively dry, mica-rich sialic protoliths: a paucity of aqueous fluid evolution and circulation would inhibit the generation of coeval magmatic activity (Ernst, 1999) as well as the subsolidus hydrothermal leaching of precious and base metals from other potential source rocks. Lack of an aqueous fluid during HP-UHP metamorphism also would reduce retrograde reaction rates, so the scattered preservation and surface exposure of such deep-seated metamorphic belts is further evidence of relatively dry conditions attending lithospheric plate descent (Ernst et al., 1998; Liou et al., 1998). The near absence of H_2O and closed-system recrystallization in which UHP mineralogic relics persisted in the Dabie-Sulu belt is also supported by the pre-existing formation and preservation of unusually low $\delta^{18}O$ values in analyzed garnet, rutile, and omphacite from coesite eclogites (Yui et al., 1995; Baker et al., 1997; Rumble, 1998; Zheng et al., 2003), as well as the wildly anomalous bulk-rock ε_{Nd} values ranging from +170 to +260 in some Weihai eclogites (Jahn et al., 1996, 2003a). Finally, lack of an aqueous phase during and after UHP recrystallization is suggested by laboratory rate studies of the conversion of coesite to quartz which indicate that, at moderate temperatures, even H_2O contents of 400-500 ppm in SiO_2 are sufficient to cause transformation to the low-P polymorph on decompression (Mosenfelder and Bohlen, 1997; Mosenfelder et al., 2005). Thus, closed-system chemical behavior and lack of isotopic re-equilibration supports the idea that much of the western portion of the East Asian Permo-Triassic orogen was dry: underflow failed to release important amounts of volatiles to the overlying crust.

In the richly ophiolitic belts of southwest Japan and the Russian Far East, recovered transpression-subduction depths are relatively shallow – considerably less than those typical of the magmagenic zone. So although these oceanic terrane assemblies have been subjected to devolatilization and low-temperature fluid circulation, and have undergone HP metamorphism, high-T aqueous fluids and contemporaneous cal-calkaline plutons did not invade the belt, accounting for the general absence of coeval island-arc-type base and precious metal deposits.

Table 1 presents a very simple genetic scheme regarding the plate-tectonic setting of precious and base metal deposits, but one that may be roughly applicable to rocks of the Tongbo-Hong'an-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin belt. An exhaustive compilation of lode and placer deposits for the entire region of northeastern Asia was presented by Rodionov et al. (2003). However, except for a few mineral deposits occurring on the Sino-Korean craton of northeast China well to the north of the plate junction with the Yangtze craton, economic deposits of Permo-Triassic age are absent from the Rodionov et al. compendium. We suspect that, except for oceanic spreading-center and sea-floor metallogenesis, most continental-margin ore deposits sequestered in the upper levels of a plutonic-volcanic arc have originated due to subduction-zone dewatering at magmagenic depths, followed by ascent of hot aqueous solutions and/or calcalkaline melts into the fractured upper crust. Where continental collision subjected refractory mica-rich sialic crust to HP-UHP conditions, dry conditions would prevail (as in the Dabie-Sulu orogen), effectively extinguishing arc magma production and the formation of spatially associated ore deposits.

Permo-Triassic metallogenesis in east-central China

The southeast margin of the Sino-Korean craton juxtaposed against the northern border of the Yangtze craton is the site of a number of mineral commodity concentrations spatially related to Jura–Cretaceous granitic plutons and associated skarns (Zaw et al., 2007; Chen et al., 2007). These include the world-class Sulu district gold deposits in Shandong Peninsula (Mu, 2006), and the Hong'an-Dabie belt Au + Cu ± Ag ores in Anhui and Hubei provinces. The Shandong Au and Au + Cu deposits occur mainly west of the Yantai-Qingdao-Wulian fault (Fig. 8). The Qibaoshan gold-cuprite deposit northwest of Wulian City occupies subvolcanic, cryptoexplosive breccia pipes (Zhang et al., 2001). Several Au deposits are present in the Zhaoyuan area. Most ore bodies are enclosed in granitic or dioritic rocks or in wall-rock contact zones; economic deposits are controlled by northeast- and north-northeast-trending faults that are subparallel and kinetically related to left-lateral slip along the Tan-lu fault (Du et al., 2003). The Linglong area is the largest district (8 x 12 km), and includes three super-large and two large ore deposits. To date, gold reserves of ~400 tons has been proven at Linglong (Du et al., 2003). The Au contents of four other ore deposits in this district range from three to several hundred g/ton (Lu et al., 2000; Peng et al., 2000; Li et al., 1998).

In the Dabie Mountains, approximately ten mesothermal gold ± silver deposits of economic value are known, sited mainly around Xishui, Dawu, and Tongbo (Fig. 7). Ore bodies chiefly transect Late Mesozoic granitic and contact metamorphic rocks as fault-controlled veins or dikes. The formation of Au ± Ag ore bodies took place during late-stage uplift of the North China-South China collisional suture zone. Minerals associated with the Au ore include pyrite, quartz, chalcopyrite, galena, and sphalerite (Xu et al., 1995). In contrast, HP-UHP metamorphic units of the Tongbo-Hong'an belt appear to be nearly devoid of high-tonnage precious-metal deposits.

Base-metal sulfide ores in the rare, tectonically stranded slices of oceanic crust are uncommon in east-central China. Rutile-rich mafic eclogites constitute an economic source of TiO_2, especially in the UHP part of the Dabie-Sulu orogen. These rutile concentrations reflect nearly complete expulsion of Ti from the coexisting garnet and clinopyroxene at great depth (e.g., Tropper and Manning, 2005), and its segregation as a separate TiO_2 phase (Z. M. Zhang et al., 2006). Rutile as a

TABLE 1. ORE DEPOSITS AND PLATE TECTONICS

motions	plate-tectonic regimes	aqueous fluids	magmas	ore deposits
divergent or transtensional	spreading ridge	high-T	diabase	Cu-Pb-Zn, Mn
divergent or transtensional	extensional crust	high-T	gabbro	PGE, Cr + Ni
lateral	transform fault	none	none	none
convergent or transpressional	shallow subduction	abundant low-T	none	Hg?, Ti
convergent or transpressional	deep subduction	rare to abundant high-T	calc-alkaline, I + S type	precious + base metals

principle ore mineral occurs as inclusions in garnet and omphacite, as intergranular crystals in the eclogite matrix, and as veinlets in both Dabie and Sulu ultrahigh-pressure eclogites. Three large rutile deposits were identified in the Sulu belt (Fig. 8). Aggregate ore reserves of rutile are 3 x 10^6 tons; Maobei, the largest deposit, contains more than 10^6 tons. Rutile-rich eclogites (2-5 volume %, some up to 8-10 volume %) recovered from the CCSD-MH are more than 1000 m in thickness at depths less than 2000 m; the grain size of the rutile ranges mostly from 0.2 to 0.6 mm, with some prisms up to 3-4 mm (Wang et al., 2006). In the Tongbo Mountains Dapushan deposit, rutile occurs mainly in garnet amphibolite (Fig. 7). Here, the ore is present in a ring complex consisting of a core of troctolite, surrounded by garnet amphibolite and amphibolite; the latter contains important amounts of rutile, up to 2.3 volume %. Six ore bodies have been identified and a reserve of more than 5.6 million tons of TiO_2 has been estimated. About 1.8 million tons of rutile and 24.4 million tons of garnet are recoverable employing simple open pit mining (Zhou et al., 1996).

In the Sulu HP belt, phosphorus deposits occur as apatite lenses and layers (tens to >1000 m long and several to 35 m thick) in Precambrian metasedimentary rocks. Average P_2O_5 contents in several of the medium-sized stratified ore bodies range from 5.52 to 17.95 wt%; the highest P_2O_5 content in the deposits range up to 32.2 wt% (Yu et al., 2006).

Permo-Triassic metallogenesis in the central and southern Korean Peninsula

Ore parageneses similar to those described for the Hong'an-Dabie-Sulu belt typify the Gyeonggi and Yeongnam massifs and intervening Okcheon belt in the Korean Peninsula (Kim, 1971; Choi et al., 2005). Jura-Cretaceous granitic plutons appear to have been responsible for the mobilization from preexisting source terranes, cooling, and formation of geochemical culminations of gold and silver, as well as abundant economic concentrations of Pb + Zn, and scattered, lesser amounts of W + Mo + Sn. These northeast-trending deposits parallel the areal disposition of the post-collisional granitoid intrusives (Fig. 11). Ophiolitic rocks are uncommon in Korea, hence oceanic-type mineral deposits are as scarce as in east-central China.

Permo-Triassic metallogenesis in southwestern and central Japan

Paleozoic ophiolitic terranes are stacked along the inner, Sea of Japan side of Japan in Kyushu and in western and central Honshu (Fig. 12). These accreted oceanic terranes host base-metal and minor precious-metal sulfide ore bodies, especially stratified cupriferous pyrite ores and Cu ± Zn veins spatially associated with massive submarine basalts, pillow lavas, and breccias, and with more felsic submarine tuffs (Ichikawa et al., 1990; Sato and Kase, 1996; Watanabe et al., 1998). Permo-Triassic deep-water metasedimentary rocks containing important concentrations of Mn ± Ba ± Fe are interlayered with coeval bedded cherts. Economic concentrations of podiform chromite are present locally in serpentinized dunite and in harzburgite – the mantle lithospheric underpinnings of the oceanic crust. In the Hida belt, lead-zinc replacement ores occur in layers of marble intercalated with migmatitic gneiss; metamorphism of the gneiss took place at 234 Ma, based on ion microprobe U-Pb ages of zircons (Sakoda et al., 2006). The Late Cretaceous granitic rocks of southwest Japan appear to be nearly barren of significant precious- and base-metal deposits except for widespread skarn and vein deposits (Ishihara, 1978; Ishihara and Sasaki, 2002).

Permo-Triassic metallogenesis in Sikhote-Alin, Russian Far East

Accretionary complexes of southern Sikhote-Alin attest to successive docking of oceanic crust and overlying distal turbidites that grade upward to coarse-grained proximal olistostromes (Fig. 13). The underplating and eastward crustal growth of the continental margin took place in discrete pulses during Late Paleozoic, Early Mesozoic, and mid-Mesozoic time (Kemkin and Kemkina, 2000). Manganiferous cherts spatially related to the oceanic crust contain significant concentrations of gold, silver, and platinum group elements (PGE), as well as base metals (Kazachenko et al., 1979, 2006). However, mineral deposits coeval with accretion-assembly of most of this terrane are not well known (Nokleberg et al., eds., 2003). Gold deposits of the northeast Sikhote-Alin belt appear to have formed during the Late Cretaceous-Paleogene invasion of the terrane by relatively oxidized granitoids (Sato et al., 2002).

PERMO-TRIASSIC ACCRETION ALONG THE EAST ASIAN MARGIN

The accretion, deformation, and HP-UHP recrystallization of the Tongbo-Hong'an-Dabie-Sulu-Imjingang-Gyeonggi-Renge-Suo-Sikhote-Alin belt occurred during the interval ~305-210 Ma, attending transpression and underflow of one or more paleo-Pacific plates beneath the non-subducted lithospheric backstop of East Asia. Approximately northwest polarity of subduction (present coordinates) resulted in an overall northward increase in the degree of penetrative deformation, progressive HP and UHP metamorphic intensity, and recovered depth of underflow. Most folds are overturned to the south, and thrust faults root to the north, reflecting the subduction component of transpressive accretion. The amalgamated suture zone attests to an inferred earlier stage of oceanic plate consumption at ~305-245 Ma, and a later stage of collision between the Sino-Korean and Yangtze cratons on the southwest at 245-220 Ma; to the northeast, the orogen is characterized by multiple events involving the docking of outboard oceanic arcs and microcontinental fragments against the East Asian margin over the time span ~305-210 Ma. Recovered pre-Mesozoic continental and oceanic crustal complexes underwent transpression-subduction-zone metamorphism – UHP at moderate to elevated temperatures on the southwest, and HP at low temperatures on the northeast.

The Dabie-Sulu sector of the orogen constitutes the most deeply subducted, now exhumed UHP complex. Tectonic slices of the South China craton episodically disengaged from the downgoing oceanic lithosphere at 245-220 Ma and, propelled upward by buoyancy, rapidly ascended from depths exceeding 90-140 km to mid-crustal levels where they then cooled. Jurassic and later doming and gravitational collapse exposed portions of these HP-UHP terranes at the surface. The western extension of the belt in the Hong'an-Tongbo area contains HP eclogitic rocks and lower pressure, low-T blueschists, indicating less extensive exhumation of this section of the Yangtze-Sino-Korean collisional zone.

Judging by the high-temperature, moderate-pressure overprinting exhibited by exhumed, ~250 Ma metamorphic complexes in the Korean Peninsula, early-collided blocks of the South China craton remained at great depth long enough for thermal re-equilibration to be established. Farther to the east in southwest Japan, underflow and the episodic arrival and accretion of scraps of far-traveled oceanic and microcontinental fragments took place attending paleo-Pacific transpression-subduction over the interval ~305-210 Ma (Renge and Suo blueschist belts, respectively). In the Russian Far East, low-temperature ophiolitic rocks of the Sikhote-Alin HP belt were also sutured against the eastern margin of Asia at the end of the Permian.

During Permo-Triassic time, the eastern edge of cratonal Asia, from the Tongbo Mountains on the west to Sikhote-Alin on the northeast, was an accretionary margin. Reflecting underflow of paleo-Pacific oceanic plates beneath the North China craton, this transpressive plate junction was the site of collision of sialic blocks in east-central China and apparently also in central Korea. Eastward, mostly ophiolitic arcs and microcontinental scraps were stranded along the growing margin in southwest Japan and Sikhote-Alin. HP-UHP metamorphism accompanied underflow and oceanward accretion of these lithotectonic terranes, followed by piecemeal exhumation. Subsequently, the original curvilinear orogen was segmented, with individual blocks displaced by major transverse faults, including the Huwan mylonitic line, the Tan-lu fault, the Honam shear zone, and the Itoigawa-Shizuoka tectonic line, as well as by minor structural breaks. Cenozoic backarc spreading opened marginal basins such as the Japan Sea, separating southwest Japan from the Sikhote-Alin and the Imjingang-Gyeonggi terranes (Ernst and Liou, 1995); possibly, earlier extension may have produced the Yellow Sea, rifting the Dabie-Sulu belt from the Korean Peninsula (Oh, 2006). In spite of subsequent dislocations, this complex curvilinear orogen remains sufficiently intact to mark the Permo-Triassic accretionary growth of the East Asian margin.

Important economic base-metal deposits in the Permo-Triassic suture zone of East Asia are hosted in ophiolitic assemblages. Strata-bound copper sulfide ores precipitated as submarine hydrothermal vent deposits in and adjacent to oceanic fracture zones and spreading centers; deep-sea manganiferous chert layers and Cr-bearing lenses in serpentinized peridotites are sequestered in the uppermost and lowermost parts of the oceanic lithosphere, respectively. Attending seafloor spreading, ophiolites were transported toward – and tectonically emplaced along – the evolving continental margin. During transpression-subduction of the basaltic crust, economic concentrations of rutile crystallized in HP-UHP mafic eclogites; most readily extractable TiO_2 ores are located in the western, UHP metamorphic sections of the belt. Somewhat later, mainly Cretaceous granitic plutons remobilized base and precious metals from pre-existing source terranes, and on cooling, produced economically significant skarn-, disseminated-, and vein-type ore deposits distributed throughout the invaded and thermally overprinted portions of the ~305-210 Ma transpression-subduction complex. Most of the latter deposits owe their ultimate origin to deep- seated devolatilization of oceanic lithosphere at magmagenic depths.

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