Geological Society of America
Special Paper 403
2006

Polyphase subduction and exhumation of the Sulu high-pressure–ultrahigh-pressure metamorphic terrane

Zhiqin Xu
Lingsen Zeng
Fulai Liu
Jingsui Yang
Zeming Zhang
Key Laboratory for Continental Dynamics, Ministry of Land and Resources, Institute of Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China
M. McWilliams
J.G. Liou
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115, USA

ABSTRACT

Four structural-metamorphic zones separated by ductile shear zones comprise the Sulu high- to ultrahigh-pressure metamorphic terrane. From south to north, they are the southern high-pressure zone (0.2–0.4 GPa, 350–400 ºC), the central very high-pressure zone (1.5–2.5 GPa, 500–600 ºC), the northern ultrahigh-pressure (UHP) zone (>2.8 GPa, 650–800 ºC) dominated by paragneiss, and the northern UHP zone dominated by granitic gneiss. Exhumation was associated with retrograde amphibolite- to greenschist-facies metamorphism and oblique southeastward ductile extrusion within the subduction channel. Geologic observations and seismic reflection profiles suggest an eroded asymmetric antiformal slab intruded by numerous Mesozoic granitic plutons. Zircon U/Pb ages indicate that peak metamorphism in the UHP zone occurred at 240–220 Ma, and $^{40}Ar/^{39}Ar$ thermochronology documents later exhumation at 220–200 Ma. In contrast, in the high-pressure zone, peak metamorphism and exhumation ages are older than 253 Ma and 253–240 Ma, respectively, by the same mineral. Together with previous results, these new data suggest that subduction and exhumation of different parts of the Yangtze slab occurred at different times, depending upon vertical variations in the physical properties of the subducted continental crust.

Keywords: polyphase structural deformation, Sulu, high-pressure, ultrahigh-pressure, UHP slices.

INTRODUCTION

The Dabie-Sulu high-pressure–ultrahigh-pressure (UHP) metamorphic terrane of eastern China was created by Triassic collision between the Sino-Korean and Yangtze cratons (Li et al., 1989, 1996, 2000a, 2000b; Ames et al., 1993; Liou et al., 1998; Hacker et al., 1998). It is the largest and one of the best-preserved UHP terranes in the world. Much of the Sulu high-pressure and UHP terrane is Yangtze continental crust that was subducted to >100 km and then exhumed (Cong and Wang, 1999; Liou et al., 2000). Because these UHP rocks preserve important information about continental subduction processes,

Xu, Z., Zeng, L., Liu, F., Yang, J., Zhang, Z., McWilliams, M., and Liou, J.G., 2006, Polyphase subduction and exhumation of the Sulu high-pressure–ultrahigh-pressure metamorphic terrane, *in* Hacker, B.R., McClelland, W.C., and Liou, J.G., eds., Ultrahigh-pressure metamorphism: Deep continental subduction: Geological Society of America Special Paper 403, p. 93–113, doi: 10.1130/2006.2403(05). For permission to copy, contact editing@geosociety.org.

they have been extensively studied (Ernst et al., 1997; Ernst, 2001; Chopin, 2003, and references therein). Published work has characterized the petrology, geochemistry, structural geology, and geochronology of these extraordinary UHP rocks, but most work has focused on the Hong'an and Dabie blocks. In contrast, the high-pressure and UHP rocks of the Sulu terrane are poorly exposed and less well known.

To better characterize the structure of the Sulu UHP eclogite terrane and its associated country rocks, we mapped the Lianyungang area at 1:250,000 scale and conducted detailed structural studies of rocks from the Sulu area, as well as the Chinese Continental Scientific Drilling (CCSD) drill cores. By combining large- and small-scale structural analyses with radiometric ages, we have attempted to (1) better define the structures in the Sulu high-pressure and UHP metamorphic slice, (2) determine the nature and mechanism of its deformation, (3) constrain the timing of subduction and exhumation, and (4) develop a tectonic model to explain the tectonic evolution of Sulu high-pressure and UHP rocks.

GEOLOGICAL SETTING AND TECTONIC FRAMEWORK

The Sulu high-pressure–ultrahigh-pressure metamorphic terrane extends NE-SW for ~750 km and is 180 km wide (Fig. 1). It is bounded on the north by the Wulian-Yantai fault and the Laiyang Cretaceous basin, and on the south by the Xiangshui fault and the North Jiangsu basin. Field observations and petrologic data suggest that the Sulu terrane is composed primarily of three parallel metamorphic zones: the southern Sulu high-pressure zone (0.2–0.4 GPa, 350–400 ºC), the central Sulu very high-pressure zone (1.5–2.5 GPa, 500–600 ºC), and the northern Sulu UHP zone (2.8 GPa, 650–800 ºC) (Xu et al., 2004). Detailed field mapping and recent seismic reflection experiments from Taoyuan to Lianshui (Fig. 2) have allowed us to identify a number of imbricated slices that are separated by ductile shear zones in each metamorphic zone. The CCSD main hole is located in the southern part of the UHP zone (Fig. 1). Petrology and structural data from the CCSD main hole have confirmed the overall structure for the Sulu high-pressure–UHP belt, as suggested in the seismic reflection profile.

Southern Sulu High-Pressure Zone (I)

The southern Sulu high-pressure zone is composed of glaucophane- and kyanite-bearing paragneiss, quartzite, and marble. The occurrences of glaucophane in the Yangji drill core (Zhang et al., 1991) and winchite, barroisite, and aragonite in Yuntaishan and Liandao (Qiu et al., 2002) define the range of the southern Sulu high-pressure slice. The protoliths for these high-pressure rocks are sedimentary with minor basic volcanic rocks. Textures and thermobarometric studies suggest early blueschist-facies metamorphism at 0.70–0.85 GPa and 300–360 °C, followed by greenschist-facies retrogression at 350–410 °C and 0.2–0.4 GPa (Qiu et al., 2002). From top to bottom, zone I is subdivided by ductile shear zones DF1, DF2, and DF3 into four imbricated slices: Guannan (Ia), Guanyun (Ib), Yuntaishan (Ic), and West Yuntaishan (Id), with a NE-SW–trending foliation that dips 20–35°SE, and a SE-plunging stretching lineation. The shear zones that separate these slices are 300 to 500 m thick (Xu et al., 2004) (Fig. 3).

Central Sulu Very High-Pressure Zone (II)

Zone II (Hanshan) is 5–12 km wide and is located to the north of the high-pressure zone. It was recognized recently by the presence of OH-topaz in kyanite quartzites from Hanshan. Its upper part is composed of kyanite-chlorite quartzite, kyanite-bearing phengite–quartz schist, and kyanite-bearing albite–quartz schist, and its lower part is marble, phosphatic marble, and phosphorite. Metamorphic mineral assemblages Toz + Ky + Qtz, Ky + Ms + Qtz + Ap, Ky + Qtz + Ab, and Grt + Bt + Ab + Qtz are common (mineral abbreviations are from Kretz, 1983, unless we specify otherwise). Petrologic studies show that zone II rocks experienced peak very high-pressure metamorphism, which was later overprinted by blueschist-facies retrogression. OH-topaz in kyanite quartzite from Hanshan indicates peak metamorphic conditions of 500–600 °C and 1.5–2.5 GPa, respectively (Zhang et al., 2002), substantially higher than zone I. The upper part of zone II is separated from the overlying West Yuntaishan slice Id by DF4, a 500-m-wide ductile shear zone in mylonitic granitoids that dips 15–20°SE. The lower part of zone II is strongly sheared and overlies the UHP zone along ductile shear zone DF5 (Fig. 2).

Northern Sulu UHP Zone (III and IV)

The northern Sulu UHP metamorphic zone is defined by the widespread occurrence of coesite within garnets and clinopyroxenes in eclogites, as well as micro-inclusions within zircons from gneisses and eclogites (Liu et al., 2002, 2004a). It covers an area bounded on the south by the DF5 shear zone, on the north by the Wulian-Yantai fault, and on the west by the Tan-Lu fault (Fig. 1). Within this zone, paragneiss (25%) and granitic gneiss (70%) are the dominant country rocks, enclosing blocks and lenses of eclogite and garnet peridotite. Based on the dominant rocks that host the eclogites and garnet peridotites, this zone is subdivided by ductile shear zone DF9 into UHP zone III and UHP zone IV. UHP zone III is composed of dominantly supracrustal rocks and UHP zone IV of granitic gneisses, both with minor eclogite and peridotite lenses and layers.

Northern Sulu UHP Zone III

Zone III consists mainly of UHP supracrustal rocks intercalated with eclogitic and ultramafic lenses. The supracrustal rocks include coesite-bearing paragneiss, kyanite quartzite,

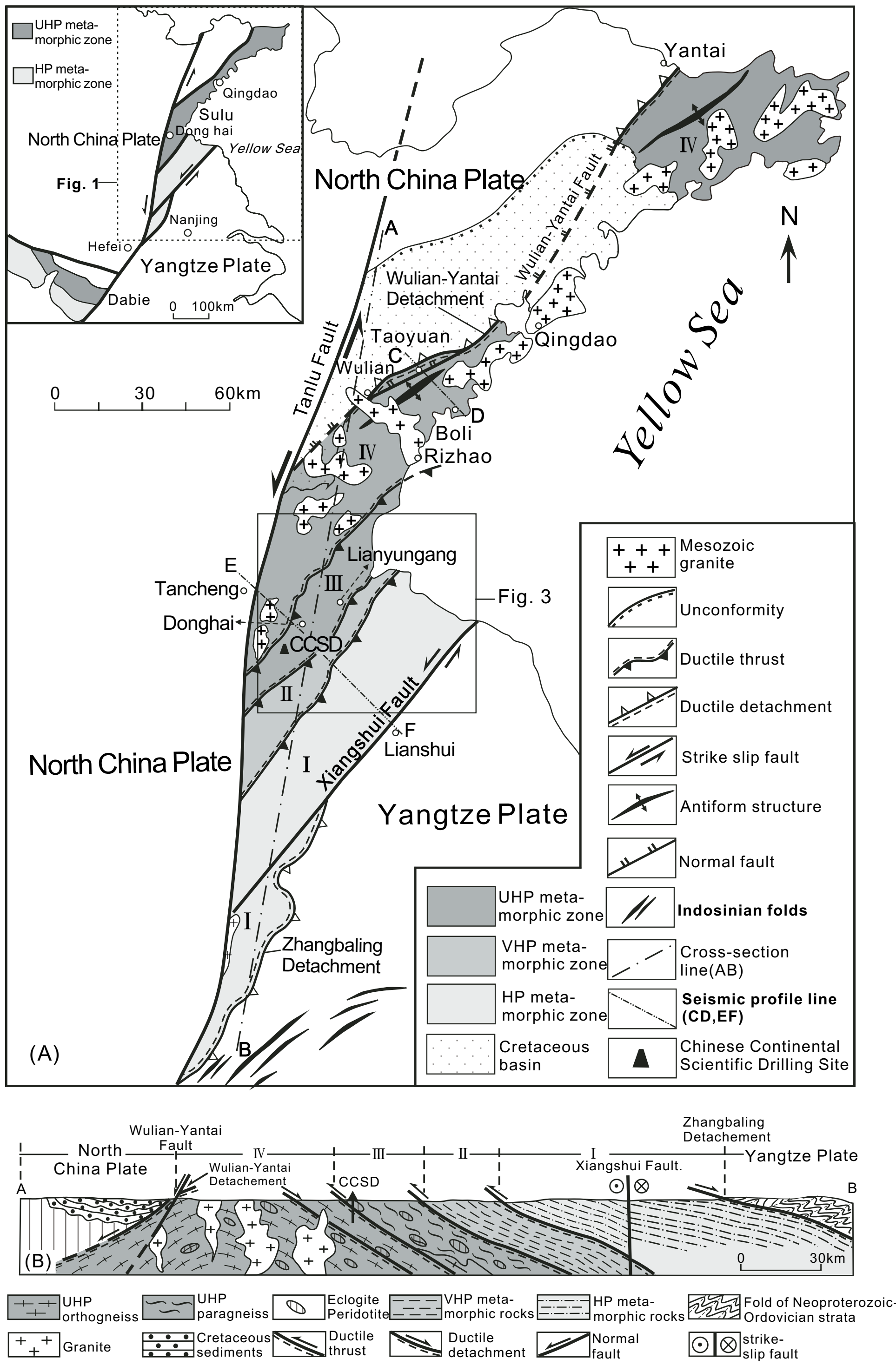

Figure 1. Tectonic sketch map (A) and a cross section (B) of the Sulu high-pressure–ultrahigh-pressure (HP-UHP) metamorphic terrane, showing: (1) high-pressure zone I, very high-pressure (VHP) zone II, and UHP (III and VI) zones separated by ductile shear zones; and (2) overall structure along the cross-section line A–B in (A). CCSD—location of the Chinese Continental Scientific Drilling Project site. Two seismic reflection profiles along lines C–D and E–F, respectively, are used to construct a continuous seismic reflection profile across the Sulu UHP belt as shown in Figure 2.

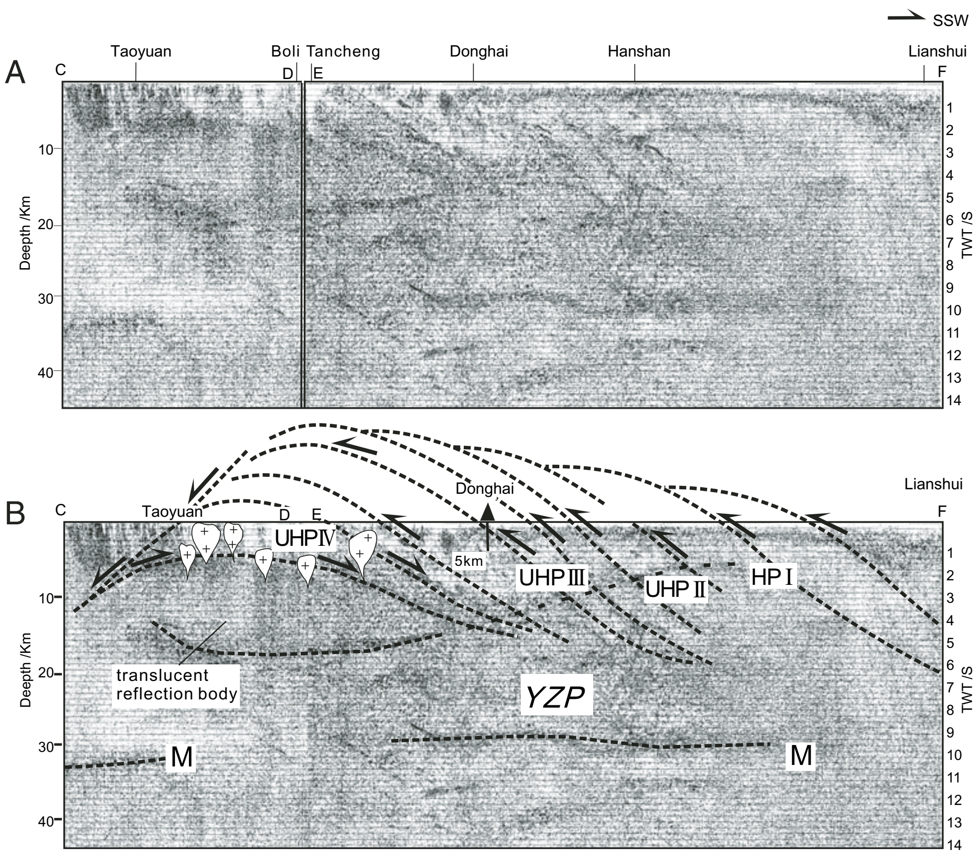

Figure 2. Original seismic reflection profile (A) (after Yang et al., 2004) with an updated interpretation (B) across the Sulu high-pressure–ultrahigh-pressure (UHP) terrane showing an eroded antiform structure in which the UHP zone IV is situated in the core and UHP zone III, very high-pressure (VHP) zone II, and high-pressure (HP) zone I are in the envelope. M—Moho, YZP—Yangtze craton; TWT—two-way traveltime.

jadeite quartzite, mica schist, and amphibolite. OH-topaz in kyanite quartzite at Hushan indicates metamorphic conditions of ~650 °C and 2.8–3.0 GPa (Zhang et al., 2002). The middle and upper parts of the supracrustal rocks south of Donghai are coesite- or aegirine-bearing gneiss. From SE to NW, the Lianyungang (IIIa), Maobei (IIIb), Donghai (IIIc) and Shilianghe (IIId) slices are separated by ductile shear zones DF6, DF7, and DF8, respectively (Fig. 2). In these shear zones, mylonites, mylonitic rocks, and type-A folds are abundant. These tectonic slices and their intervening shear zones have SE-dipping foliations and SE-plunging stretching lineations, similar to those in the high-pressure zone.

Peak metamorphic assemblages and textures related to the UHP metamorphism were strongly overprinted by retrogression during exhumation. Mineral assemblages diagnostic of UHP metamorphism within the paragneiss, such as Coe + Grt + Omp + Phe + Rt and Coe + Grt + Jd + Phe, are only preserved as inclusions in zircons (Liu et al., 2002, 2004a), where Coe, Omp, and Phe are coesite, omphacite, and phengite, respectively. Based on these mineral assemblages, we identify three main retrograde stages:

(1) Early exhumation: Grt + Coe + Rt + H_2O = Ttn + Ep + Qtz, at 750–850 °C and 2.5–2.8 GPa, where Ttn and Ep are titanite and epidote, respectively.

(2) Mid exhumation: Jd + Qtz = Ab, Agt = Cal, Grt + Jd + Qtz + H_2O = Hbl +Ab, at 680–780 °C and 1.2–1.8 GPa.

(3) Late exhumation: Amphibolite-facies mineral assemblages and textural relationships dominate the UHP rocks. Preserved mineral assemblages are Ep + Bt + Pl + Kfs + Qtz, Ms + Bt + Pl + Kfs + Qtz, Grt + Bt ± Ms + Pl + Kfs + Qtz, Grt + Hbl + Bt + Pl + Qtz, and Ep + Hbl + Bt + Ms + Pl + Kfs + Qtz. Pressure and temperature estimates from various geothermometers and geobarometers, such as Grt–Hbl, Grt–Hbl–Pl–Qtz, Grt–Bt, and Hbl–Pl, suggest metamorphism occurred at 550–650 °C and 0.5–0.7 GPa.

Northern Sulu UHP Zone IV

Zone IV is ~40 km wide and lies between the Wulian-Yantai fault and ductile shear zone DF9. It consists of granitic gneiss and subordinate supracrustal rock intercalated with eclogites and ultramafic blocks (Fig. 1). The supracrustal rocks, eclogites, and Weihai garnet peridotite contain coesite; the granitic gneiss does

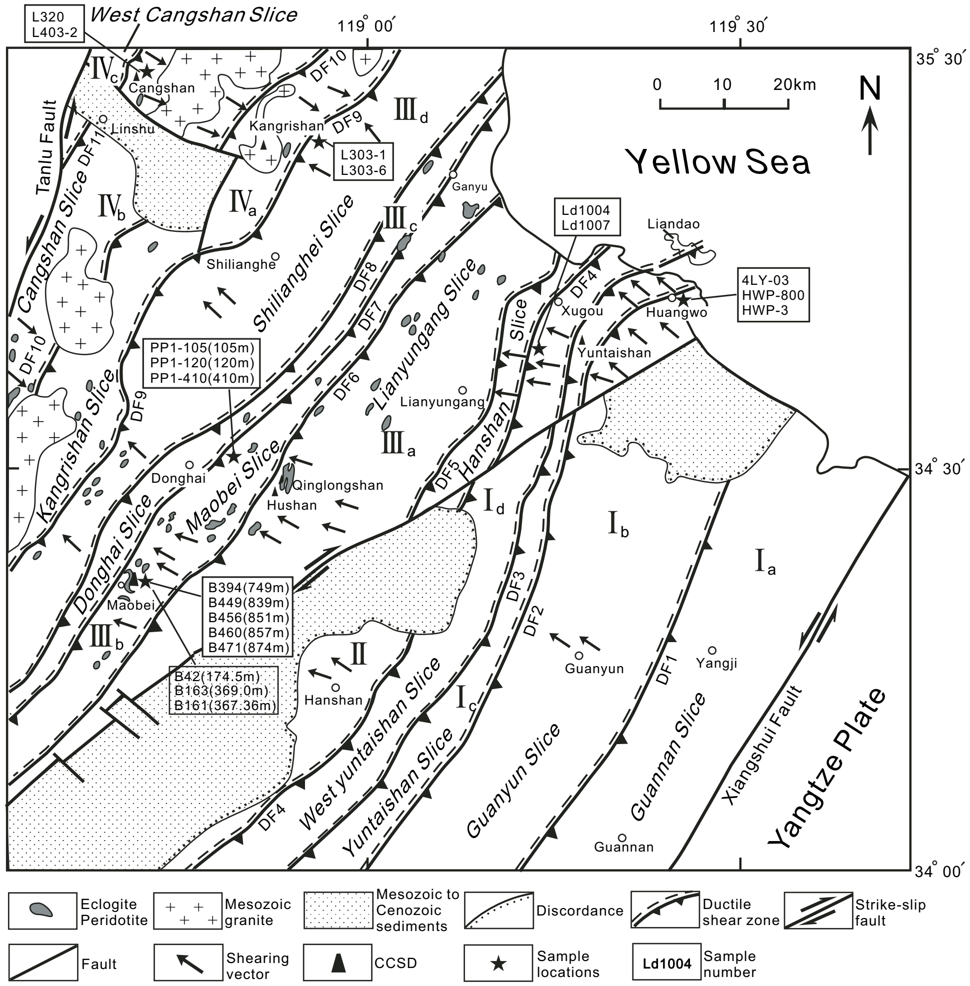

Figure 3. Tectonic map of the Lianyungang area showing the distribution of various high-pressure and ultrahigh-pressure (UHP) slices, major ductile shear zones DF_1 to DF_{11}, and samples for quartz lattice preferred orientation studies. CCSD—Chinese Continental Scientific Drilling Project.

not (Liu et al., 2002; Yang et al., 2003), but zircons separated from granitic gneisses contain coesite and UHP mineral assemblages typical of the area near the Wulian-Yantai fault. Foliations dip gently NW to WNW, but southeastward away from the fault, foliations dip gently SE to ESE. This regional change in dip direction suggests a broad antiform (Fig. 1), which is also shown by seismic reflection data (Fig. 2) (Yang et al., 2004). Such an antiform structure was also suggested by Faure et al. (2003). North of Lingshu, we identified three structural subslices. From top to bottom they are: Kangrishan (IVa), Cangshan (IVb), and West Cangshan (IVc); they are separated by ductile shear zones DF9, DF10, and DF11 (Fig. 3). Each shear zone consists of hundreds of meters of E-dipping mylonitic rocks.

The antiform was significantly modified by the emplacement of Triassic–Jurassic granites, which have U-Pb zircon and whole-rock Rb-Sr ages that range from 210 to 109 Ma, representing magmatic additions during and after exhumation (Wang et al., 2005).

POLYPHASE DEFORMATION IN THE SULU HIGH-PRESSURE–UHP BELT

The observed tectonic framework (tectonic slices bounded by ductile shear zones) was produced during exhumation as mid- to deep-level ductile deformation was superseded by shallower-level ductile deformation and, ultimately, brittle deformation. In particular, the deformation associated with the movement of the Tan-Lu fault, and large-scale post-Mesozoic extension in central and north China have greatly affected the early structures formed in subduction and early exhumation of the Sulu UHP terrane. Knowledge of the structure, kinematics, *P-T* conditions, and deformation mechanisms of the ductile shear zones is essential to an understanding of the structural evolution of the Sulu high-pressure–UHP belt, but in this strongly retrogressed and reworked UHP terrane, it is difficult to identify early structural details. Here, we try to reveal them through detailed examination of microstructures and strain analyses, in combination with well-documented mineral assemblages for each episode of metamorphic evolution of the Sulu terrane. Detailed structural analyses were performed to delineate the structural relationships between the different tectonic units as discussed in the preceding section. Textural and structural relationships among various generations of mineral assemblages were also carefully examined to relate deformation episodes with metamorphic reactions from subduction to exhumation of the Sulu continental crust. Structural data, in conjunction with U-Pb zircon sensitive high-resolution ion microprobe (SHRIMP), biotite, and hornblende $^{40}Ar/^{39}Ar$ ages, allow us to differentiate subduction-related structures from those formed during exhumation.

We measured quartz lattice preferred orientation in the *x-z* plane of oriented thin sections on a U-stage to determine quartz plastic deformation mechanism and sense of shearing, and to obtain the corresponding *P-T* conditions for such plastic deformation. Previous studies (Mainprice et al., 1986; Ji, 1988) have identified four types of quartz lattice preferred orientations resulting from preferential activation of one of the slip systems in quartz to accommodate shear strain at various temperature conditions: (1) high-*T* (>650 °C) prismatic $(10\bar{1}0)$ <c> slip system; (2) intermediate-*T* (650–550 °C) prismatic $(10\bar{1}0)$ <a> slip system; (3) intermediate- to low-*T* (550–450 °C) prismatic $(10\bar{1}1)$ <c> slip system; and (4) low-*T* (<400 °C) basal $(10\bar{1}1)$ <c> slip system. Quartz lattice preferred orientation has been widely used to infer the shear sense as well as corresponding temperature conditions for the formation of a quartz-bearing ductile shear zone. Olivine lattice preferred orientation is also used in a similar fashion but for olivine-rich rocks. We used quartz lattice preferred orientation to infer temperature conditions for the ductile deformations observed in the Sulu high-pressure–UHP metamorphic belt. We also compared *P-T* conditions obtained from these analyses with those from olivine lattice preferred orientation studies on olivine-bearing ultramafic rocks and from thermobarometric studies both for the surface and CCSD borehole samples to evaluate the consistency between these independent data sets, and in turn to constrain the kinematics of deformation associated with subduction and exhumation.

Ductile Deformation During Subduction (D1)

Near Donghai, Maobei UHP slice IIIb is sandwiched between SE-dipping ductile shear zones DF6 and DF7 (Fig. 3). In the western part of the Maobei slice, the sigmoidal Maobei eclogite has an overall trend of NNE-SSW and dips 50° to 55°E (Fig. 4A). Refolding of "A" folds represented by small-scale folds of red garnet and green omphacite bands is common in the Maobei eclogites (Fig. 4). The CCSD drill hole at Maobei (Fig. 3) reveals 600 m of rutile eclogite, phengite eclogite, and quartz eclogite in its uppermost part, all of which experienced various degrees of retrogression (Zhang et al., 2004). During the drilling of the CCSD project, the core was restored to its original position with the image logging technique, and thus the structures observed in these core samples can be compared with those from surface geology. Early structures are recognized in fresh eclogites; they differ from the regional NE-SW–trending structures formed during exhumation. These early foliations trend nearly N-S and dip steeply 50–55°E (Fig. 4A), consistent with surface observations. Subhorizontal stretching lineations defined by elongated omphacite, rutile, and apatite grains are parallel to the strike of the Maobei eclogite. Strain measurements on oriented thin sections of fresh eclogite from samples B42R41P1d and B161R140P1 (Fig. 5; Table 1) yield a maximum aspect ratio of 26:1 for omphacite and 24:1 for rutile, respectively. Taking an undeformed rutile grain to be an equiaxis sphere and applying the Flinn index $K = (x/y - 1)/(y/z - 1)$, sheared rutiles have K = 1.26. Projected onto a Woods diagram (Fig. 5), the rutile data suggest 92%–160% elongation and 51%–60% shortening, assuming no strain along the intermediate axis (Fig. 5). Quartz eclogite from the borehole at 174.5 and 369.0 m exhibits a quartz lattice preferred orientation that suggests activity of the high-*T* (>650 °C) $\{10\bar{1}0\}$ <c> slip system (Ji, 1988) and top-S shear sense (Fig. 5D). Rutile eclogite and phengite eclogite experienced a less intense retrograde overprint and record peak metamorphic conditions of 700–850 °C and >2.8 GPa. Quartz eclogite formed during early retrogression at 700–800 °C and >2.5 GPa (Zhang et al., 2005). Such temperature conditions are consistent with those inferred from quartz lattice preferred orientation studies.

In eastern Donghai, the Qinglongshan eclogite that is cut by shear zones DF6 and DF7 dips steeply to the east. But early structures preserved in the Qinglongshan eclogite include stretching lineations plunging 45°NNE and tight A folds, similar to those in the Maobei slice.

Using the electron-backscatter diffraction (EBSD) technique, Xu et al. (2005) measured lattice preferred orientation for olivines from the CCSD-PP1 peridotite samples. They found that Zhimafang peridotites have C-type olivine fabric of Jung and Karato's classification (Jung and Karato, 2001), in which the olivine [001] axis is subparallel to the stretching lineation and the (100) plane is subparallel to the foliation, despite different deformation intensity and strain regimes (simple shear or uniaxial compression). It was suggested that such olivine lattice preferred orientation was formed at UHP metamorphic conditions and was preserved during exhumation of the Zhimafang garnet peridotite, though olivine lattice preferred orientation was formed at a substantially higher temperature than high-*T* quartz lattice preferred orientation. Observations from quartz and olivine lattice preferred orientation measurements, as well as mineral assemblages, suggest that the nearly N-S–trending structure may represent the early structures formed during subduction of the Sulu continental crust.

Early Deformation (D1) in the High-Pressure Zone

In Zhangbaling area of the southern Sulu high-pressure zone, a mylonite belt with a subhorizontal foliation was found within the glaucophane-bearing metavolcanics (Fig. 6). Within

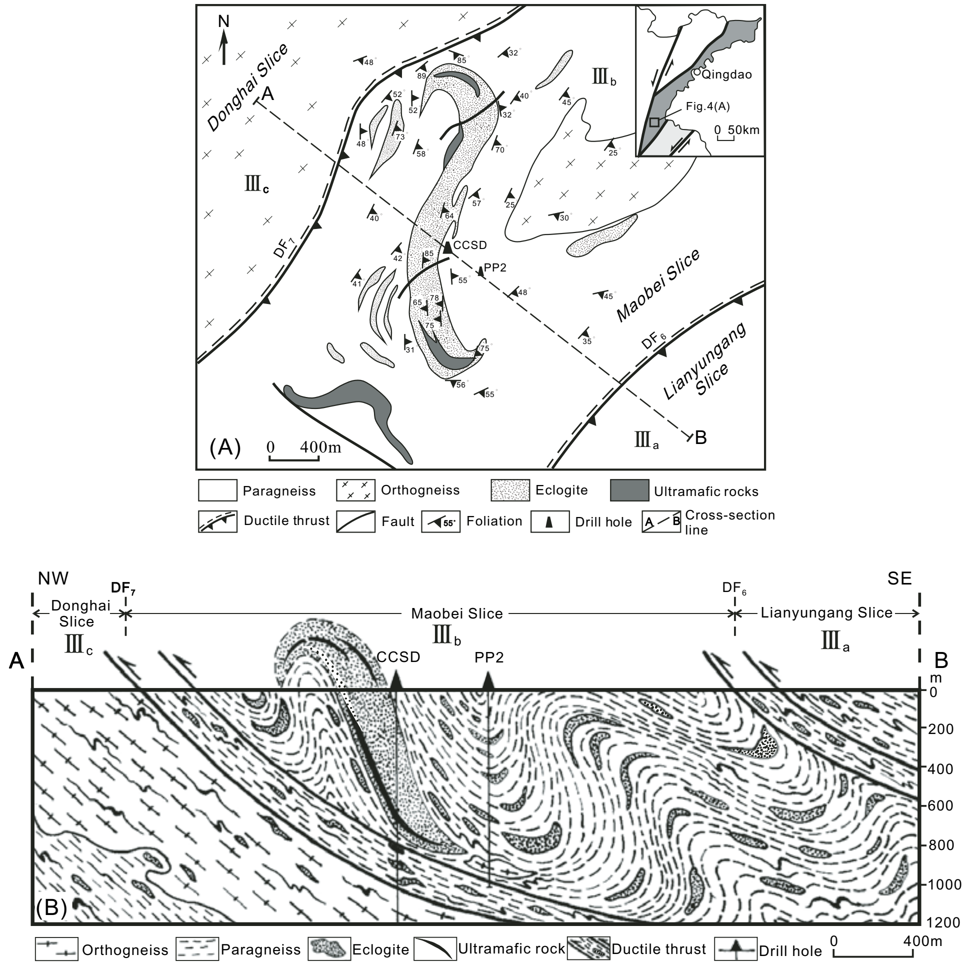

Figure 4. Geologic map (A) and cross section (B) of the Maobei area around the Chinese Continental Scientific Drilling Project (CCSD) drill site showing distribution of eclogite, ultramafic rocks, and major structures. DF—ductile shear zone.

this shear zone, penetrative cleavages, N-S–trending stretching lineations defined by preferentially oriented glaucophanes, quartzes, and feldspars, type-A folds and sheath folds are well preserved. Structures such as σ- and δ-type feldspar porphyroblasts, S-C fabric, and domino structure all indicate top-to-the-S shear sense. Quartz lattice preferred orientation measurements yield a low-*T* (<400 °C) basal (10$\bar{1}$1) <c> fabric and top-to-the-S shear sense (Xu et al., 1997). In the southeast of Zhangbaling, Neoproterozoic to Ordovician metasediments of lower-greenschist facies overlie the mylonite belt and have experienced progressive decreasing shear strain upward. Such a strain gradient resulted in the gradual transition from gently SSE-dipping penetrative foliations and nearly N-S-trending stretching lineations to steeply dipping spaced foliations and nearly vertical stretching lineations. Using a Dunnet diagram, strain analysis on the boulders (sample ZBL-Z1 and ZBL-Z2) in the Neoproterozoic conglomerate yields a Flint index of ~1.0 (Fig. 6B). These observations suggest that this mylonite zone is a gently southward-dipping ductile shear zone that was cut by the NW-SW–trending shear zones. We interpret this to mean that this shear zone may have resulted from deformation at high-pressure conditions during northward subduction of the Yangtze plate.

In summary, we conclude that simple shear was the principal mechanism for deformation in the subduction stage, probably including early exhumation (D1) both in UHP (700–850 °C and 2.5–2.8 GPa) and high-pressure conditions.

Shear Strain during Main Exhumation (D2)

Examination of subtle but systematic changes in the trend of stretching lineations helps to better define the deformation associated with the exhumation. The stretching lineations of this stage of deformation trend WNW-ESE overall, but change from E-W in the NE to NW-SE in the SW part of the metamorphic slice. During 1:250,000 regional mapping of the Lianyungang area, we identified 11 ductile shear zones as boundaries to the structural slices. Type-A folds and other structures indicative of high ductile shear strain are widespread within the shear

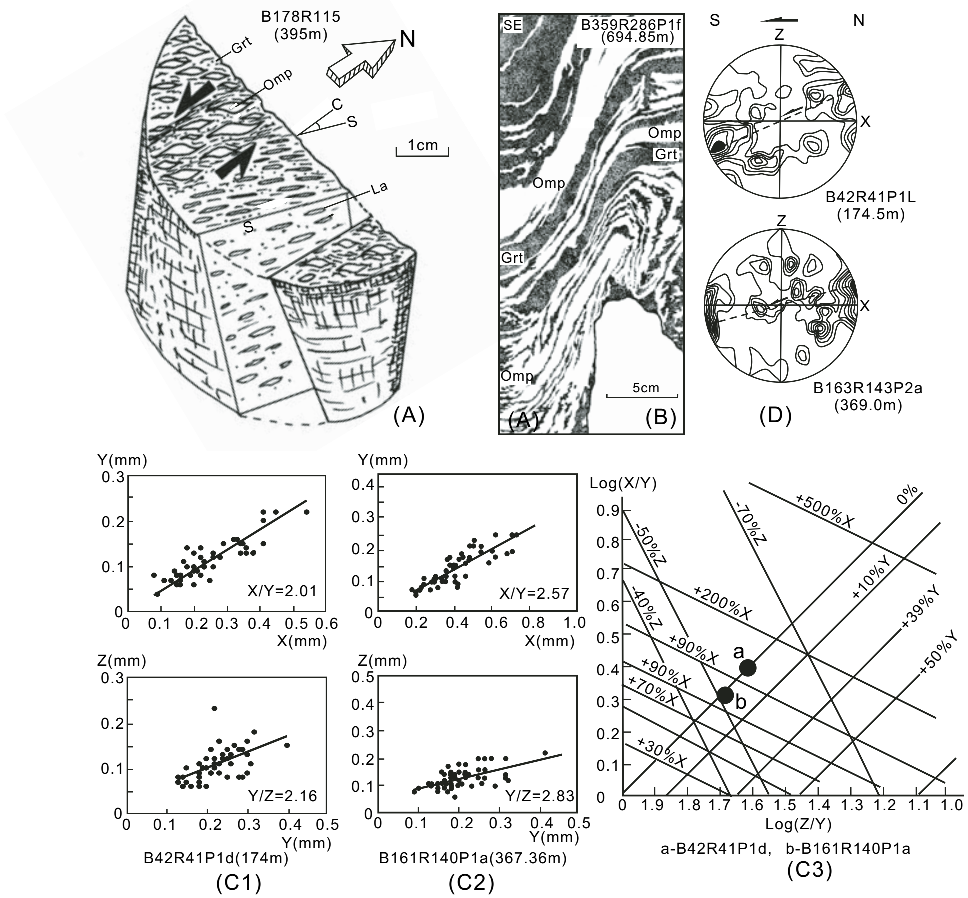

Figure 5. Features of early deformation (D1) in the eclogites of the Chinese Continental Scientific Drilling Project (CCSD) core. (A) Hand drawing of an eclogite core sample (396 m deep) from the CCSD main hole showing nearly N-S–trending stretching lineation and characteristics of shear deformation. Grt—garnet, Omp—omphacite, La—stretching lineation. (B) Hand drawing of an eclogite core sample (694.85 m deep) showing refolded A-type fold. (C) Strain analyses of rutile from eclogite core samples of the CCSD main hole showing shearing mechanism during early subduction deformation. C1 and C2 are for samples B42R41P1d (174.5 m) and B161R140P1a (369.0 m), respectively; C3 is a Wood diagram showing that rutile has undergone shearing; a—rutiles from sample B161R140P1a; b—rutiles from sample B42R41P1d. (D) Lattice preferred orientations of quartz in eclogite cores from the CCSD main borehole: (top) sample B42R41P1 (174.50 m), $N = 120$, contours at densities 0.8%, 1.7%, 2.5%, 3.3%, 4.2%, 5.0%, 5.8%, and 6.7%; (bottom) sample B163R143P2a (369 m), $N = 120$, contours at densities 0.8%, 1.7%, 2.5%, 3.3%, 4.2%, 5.0%, 5.8%, and 6.7%.

TABLE 1. SUMMARY OF STRAIN ANALYSES ON RUTILES AND OMPHACITES IN ECLOGITES FROM THE CHINESE CONTINENTAL SCIENTIFIC DRILLING PROJECT BOREHOLE

Sample	Depth (m)	Rutile			*N*	Omphacite			*N*
		x:y	x:z	y:z		x:y	x:z	y:z	
B42R41P1d	174.50	2.01		2.16	50				
B130R112P1-1	316.73	2.12	2.55	1.89	50	2.65	2.14	3.06	50
B161 R140P1	369.00	2.57		2.83	50				
B161R140P1c	369.10	2.54		2.71	50				
B208R185P1f	448.02	4.61	3.35	2.33	25	4.08		2.09	50
B270R226P2-2	545.00				50	3.80		1.70	50

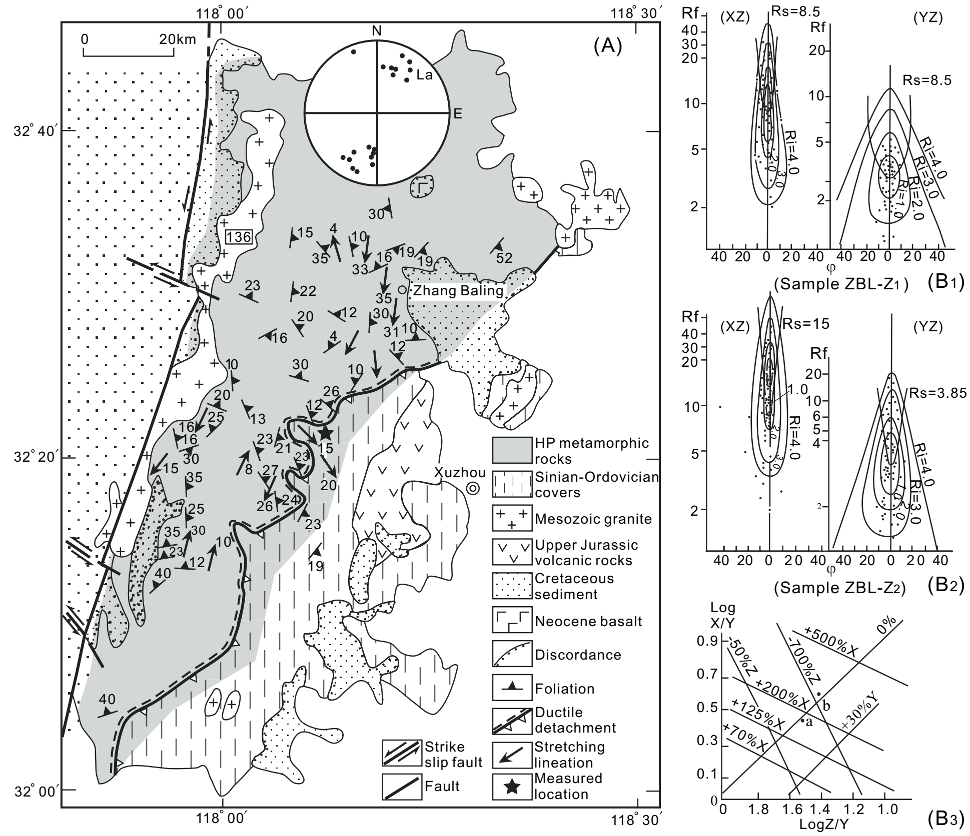

Figure 6. Simplified geologic map of the Zhangbaling area (A) and strain analyses (B) showing the early deformation (D1) in the high-pressure (HP) metamorphic unit. Strain analysis on the boulders from the Neoproterozoic conglomerates using the Dunnet diagram (B1 for ZBL-Z1 and B2 for ZBL-Z2) yielded a Flin index of ~1.0. These results were also resolved in a Wood diagram (B3), in which a and b represent strain values of rutile along *x*, *y*, and *z* axes for samples ZBL-Z1 and ZBL-Z2, respectively.

zones. Stretching lineations defined by elongations in metavolcaniclastic rocks, elongated quartzes, and strain shadows around garnet porphyroblasts, are common. These were used to infer the kinematics of the ductile shear zones (Fig. 7).

A series of imbricate, gently SE-dipping slices are separated by mylonites that dip gently SE. Structures in mylonitic paragneisses that enclose eclogitic lenses from 750 to 1105 m in the CCSD main borehole and from 950 to 1008 m in the CCSD-PP1 borehole, together with surface observations show that shear zone DF7 dips to the SE at 35° (Fig. 7).

Shear Strain of the South Sulu High-Pressure Imbricated Structural Slice

In zones I and II, the boundaries between the slices are mylonites that dip gently to the SE. On the *x-z* plane, variable scales of asymmetric folds, S-C structures, σ and δ porphyroclasts, and domino structures all suggest top-NW sense of shear (Fig. 7). In the ductile shear zones, syndeformational assemblages are dominated by transitional blueschist–greenschist facies retrogression at 400 °C and 1.2–2.0 GPa. Mineral assemblages are Wnc + Ab + Act + Grt + Phe + Arg, Bar + Ab + Phe + Grt + Act, Bar + Ab + Phe + Act, and Wnc + Ab + Act + Ep + Phe. These minerals are typically confined to strongly penetrative S_1 shear foliations. In contrast, greenschist-facies minerals, such as chlorite, epidote, actinolite, albite, biotite, and calcite, formed at 350–410 °C and 0.2–0.4 GPa (Qiu et al., 2002) and are distributed along S_2 spaced cleavages resulting from refolding of S_1 shear foliations.

Quartz lattice preferred orientations were determined from samples of metavolcanic mylonites (GLY-03, HWP-800-1, HWP-3 and HWP-4) from DF2 at Huanwo and from mylonitic kyanite-bearing schists (Ld1004 and Ld1007) at Hanshan, between the Yuntaishan slice Id and zone II. These measurements show that quartz exhibits an intermediate- to low-*T* (<400–450 °C) {10$\bar{1}$0} <a> fabric and low-*T* (<400 °C) {0001} <a> fabric suggestive of top-NW shear (Fig. 8A). The inferred temperature conditions for quartz plastic deformation are well matched to those that defined the syndeformational metamorphic mineral assemblages. Therefore, we conclude that ductile deformation in this part of high-pressure zone was mainly associated with exhumation, which is different from the Zhangbaling area, where early structures associated with subduction are preserved.

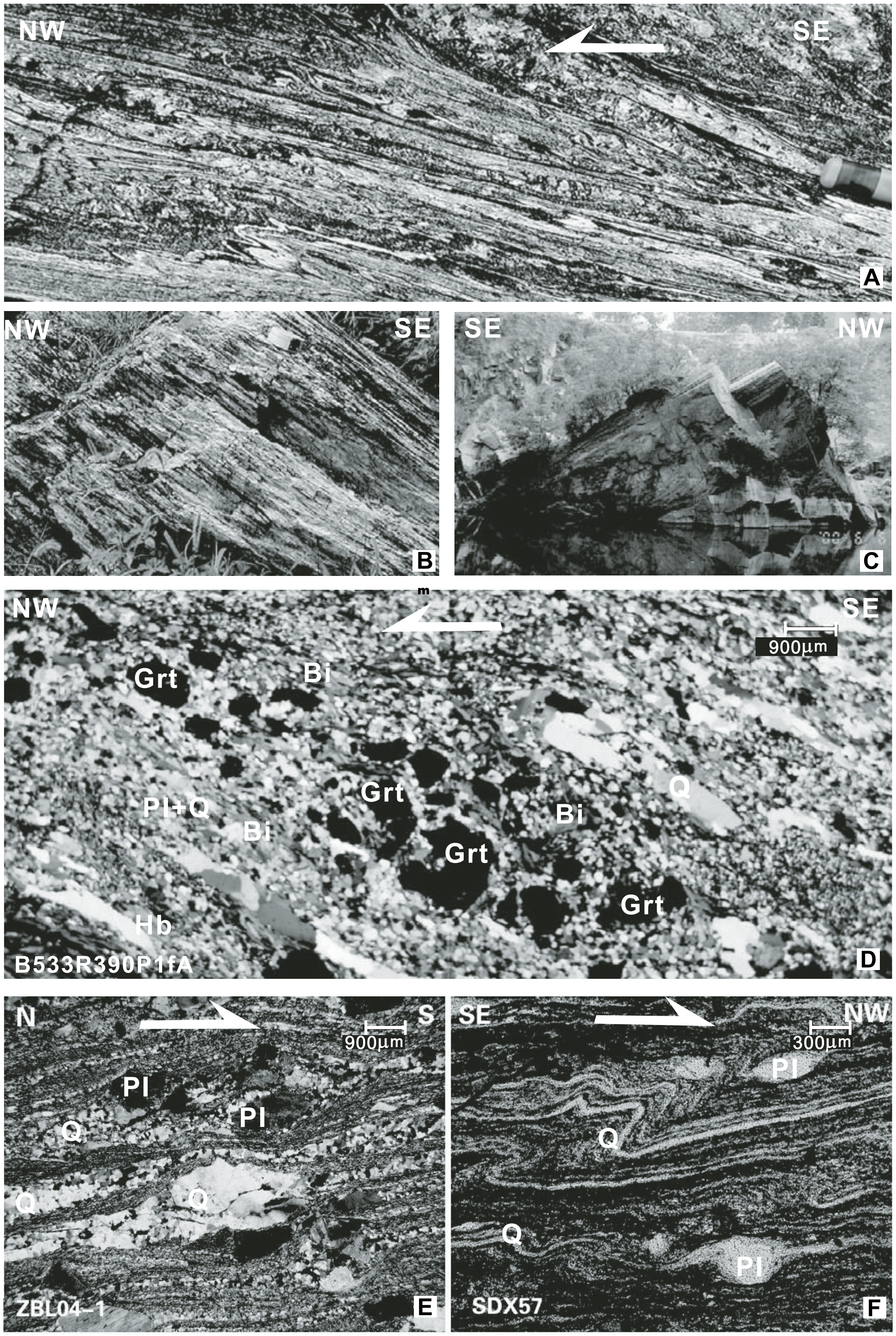

Figure 7. Field and microphotographs showing the nature of ductile deformation in the Sulu high-pressure–ultrahigh-pressure (UHP) terrane. (A) Structures in the metavolcanic mylonite of ductile shear zone 2 (DF2) between the Guanyun (Ib) and Yuntaishan slice (Ic), indicating the top-NW shear sense. (B.) SE-dipping stretching lineation near Xugou of DF4. (C) Structures in the amphibolite of DF6 between Lianyungang slice (IIIa) and Maobei slice (IIIb) showing the shear deformation of the A-type fold. (D) Mylonitic paragneiss in DF8 from Chinese Continental Scientific Drilling Project (CCSD) core composed of garnet, hornblende, quartz, and biotite porphyroclasts (sample B533R390P1fA, 970.80 m). (E) Metavolcanic mylonite from Zhangbaling ductile detachment that has S-C fabric and plagioclase porphyroblasts suggesting top-S shear sense. (F) Ultramylonite from the Wulian-Weihai ductile detachment, in which σ- and δ-type porphyroclasts, as well as shear folds, indicate top-NW shear sense. Q—quartz; Pl—plagioclase; Q + Pl—felsic; Bi—biotite; Grt—garnet; Hb—hornblende.

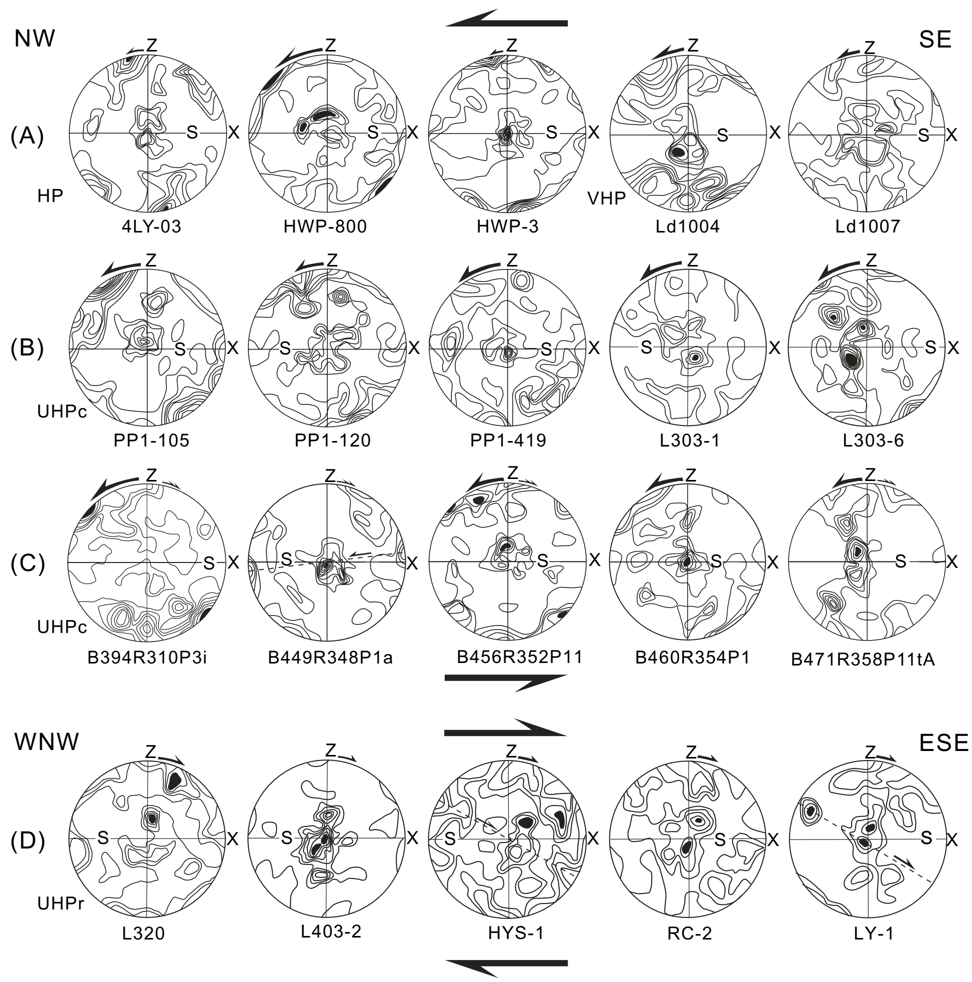

Figure 8. Lattice preferred orientations of quartz in the ductile shear zones from different structural units of the Sulu high-pressure–ultrahigh-pressure (UHP) terrane. (A) Samples 4LY-03, HWP-800, and HWP-3 from the high-pressure unit; Ld1004 and Ld1007 from the very high-pressure (VHP) unit; $N = 120$, contours at densities 0.8%, 1.7%, 2.5%, 3.3%, 4.2%, 5.0%, 5.8%, and 6.7%. (B) Samples PP1-105 (105 m), PP1-120(120 m), and PP1-419 (419 m) from Chinese Continental Scientific Drilling Project (CCSD) cores CCSD-PP1; L303-1, and L303-6 from surface in the UHP III unit; $N = 120$, contours at densities 0.8%, 1.7%, 2.5%, 3.3%, 4.2%, 5.0%, 5.8%, and 6.7%. (C) Samples B394R310P3i (748.9 m), B449R348P1a (838.65 m), B456R352P11 (851.50 m), B460R354P1 (856.95 m), and B471R358P11tA (873.67 m) from CCSD main hole in the UHP III unit; $N = 120$, contours at densities 0.8%, 1.7%, 2.5%, 3.3%, 4.2%, 5.0%, 5.8%, and 6.7%. (D) Samples L320, L403-2, HYS-1, RC-2, and LY-1 from the UHP IV unit; $N = 120$, contours at densities 0.8%, 1.7%, 2.5%, 3.3%, 4.2%, 5.0%, 5.8%, and 6.7%.

Shear Strain in the Northern Sulu UHP Slice

Seven structural slices and six ductile shear zones were identified in the northern Sulu UHP zones III and IV. They have penetrative foliations gently dipping SE to ESE. Rocks within these ductile shear zones include variably mylonitic granitic gneiss, metavolcanic gneiss, eclogite and marble with type-A folds, sheath folds, and two generations of folds. Microstructures, including asymmetric folds, S-C structures, and asymmetric strain shadows, mostly indicate top-NW shear, but in some areas top-SE shear sense is also observed. Mineral assemblages that formed concurrently with this stage of deformation—Kfs + Pl + Qtz + Mus + Bt + Ep, Kfs + Pl + Qtz + Grt + Bt + Ep, Kfs + Pl + Aeg + Bt, Pl + Qtz + Hbl + Bt ± Grt, and Kfs + Pl + Qtz + Ms + Bt—suggest deformation under amphibolite- to greenschist-facies conditions of 550–650 °C and 0.5–0.7 GPa. Additionally, some rocks within the shear zones exhibit various degrees of greenschist-facies overprinting at 300–400 °C and 0.30–0.35 GPa.

Three sample sets from the northern Sulu UHP slice were used to determine quartz lattice preferred orientation and deformation kinematics. The first set is from the CCSD-PP1 borehole and includes PP1-105, PP1-120 and PP1-419. The second

(L303 and L303-6) is from mylonitic paragneiss in shear zone DF6. The third (B394R310P3i, B449R348Pia, B456R352P11, B460R358P11tA, and B471R358P11tA) is from mylonitic paragneiss in DF7 of the main CCSD borehole. Quartz lattice preferred orientation studies show that, in addition to an intermediate- to low-*T* and low-*T* fabric of $\{10\bar{1}0\}\langle a\rangle$, $\{10\bar{1}\bar{1}\}\langle a\rangle$, and $\{0001\}\langle a\rangle$, a high-*T* fabric (>650 °C) of $\{10\bar{1}0\}\langle c\rangle$ is present in samples PP1-419 and B449R348P1a. The lattice preferred orientation variation indicates that the ductile shear zones experienced shear during progressive cooling. The obliquities of the lattice preferred orientation concentrations indicate top-NW sense of shear, whereas the weak concentration of [0001] poles in the intermediate-temperature fabric is indicative of top from NW to SE shear, which may represent late brittle-ductile normal faulting (Fig. 8B–C).

To characterize the deformation kinematics in these UHP slices, quartz lattice preferred orientations were studied in samples L320 and L403-2 from DF10 and DF11 mylonitic granitic gneisses, and samples HyS-1, RC-2, and Ly-1 from zone IV in Rongcheng. These results (Fig. 8D) show that quartz fabrics in zone IV also record deformation at conditions varying from high-*T* $\{10\bar{1}0\}\langle c\rangle$, intermediate-*T* $\{10\bar{1}0\}\langle a\rangle$, intermediate–low-*T* $\{10\bar{1}\bar{1}\}\langle a\rangle$, to low-*T* $\{0001\}\langle a\rangle$ fabric. These data also indicate top from WNW to ESE normal slip.

Our data show that ductile shear in the high-pressure–UHP slab during exhumation can be explained by extrusion with shear toward the NW or WNW at the top and toward the SE or ESE at the bottom.

Postexhumation Extension (D3)

Rocks from the Sulu high-pressure and UHP metamorphic slice experienced postexhumation extension accompanied by Mesozoic magmatism and the formation of continental sedimentary basins, signaling the transition to brittle deformation.

Wulian-Yantai Extensional Detachment

The NE-SW–striking Wulian-Yantai ductile shear zone is the northern boundary of the Sulu high-pressure–UHP terrane, separating the Sulu UHP zone from the Laiyan basin (Fig. 9). Granite mylonite and eclogite mylonite are abundant in this zone. Near Taolin in the NE, W-plunging stretching lineations occur on mylonite foliations that dip 20–25°W. Near Jiaozhou in the SW, stretching lineations trend at 60°NW with respect to the strike of mylonite foliations that dip 15–20°NW (Fig. 9B). S-C structures, σ and δ feldspar porphyroclasts, domino structures, and asymmetric drag folds of quartz bands indicate oblique-normal slip of the hanging wall. Quartz from five samples of granitic ultramylonites from Taoyuan and Taocun have lattice preferred orientations that suggest activity of the low-*T* (<350 °C) $\{0001\}\langle a\rangle$ slip system, and top-NW or -W shear sense (Fig. 9C). This slip system is compatible with the greenschist-facies retrogression common for the highly strained rocks within the Wulian-Yantai ductile shear zone. Movement on this fault contributed to the formation of the Cretaceous Laiyang basin and a NE-SW–trending antiform and facilitated emplacement of Mesozoic granites into the antiform. (Wang et al., 2005).

NW-SW–Trending Upright Concentric Folds

Upright flexural box folds with NW-SE–trending axial planes occur in the SE limb of the antiform in the UHP zone III. Axial cleavage is not well developed in these folds, which presumably formed at relatively shallow depths. Near Yushan and Sanqingge of Shilianghe slice IIId, these upright folds are superimposed on top-SE ductile shear zones. The upright concentric folds were formed during NE-SW contraction and NW-SE extension. These folds and the Wulian-Yantai ductile décollement shear zone appear to have formed in the same stress field.

In summary, our data presented herein indicate four types of quartz lattice preferred orientation in samples from the surface as well as from the CCSD boreholes. Some of the samples clearly have low-*T* fabric superimposed on the earlier high-*T* fabric. The data imply that these quartz-bearing rocks have undergone early high-*T* deformation, versus intermediate-*T* and intermediate- to low-*T*, and latest low-*T* deformation. Such a pattern is consistent with *P-T* paths inferred from metamorphic mineral assemblages (Fig. 10). The Sulu high-pressure–UHP metamorphic belt has experienced three episodes of deformation: (1) subduction-stage ductile deformation (D1), in which the high-pressure zone and UHP zone have undergone ductile deformation in corresponding peak metamorphic conditions; (2) exhumation-stage ductile deformation (D2); and (3) postexhumation deformation (D3). The latter two episodes of deformation have reworked and overprinted the earliest D1 deformation.

TIMING OF EXHUMATION OF THE SULU HIGH-PRESSURE–UHP METAMORPHIC BELT

To better constrain the timing and sequence of exhumation of the Sulu high-pressure–UHP slice, we dated biotite and muscovite from various rock types by $^{40}Ar/^{39}Ar$. These new data, in conjunction with published ages, help constrain the tectonic evolution of the Sulu high-pressure–UHP metamorphic slice.

Formation and Exhumation of Sulu UHP Metamorphic Terrane

The $^{40}Ar/^{39}Ar$ ages of biotites from the ductile shear zones in the CCSD main borehole were measured at the Guangzhou Institute of Geochemistry. The plateau ages of biotites from samples B475R359P3v (891 m), B527R388P1f (960 m), B608R432P1f (1097 m), and B627R441P3n (1130 m) of CCSD-MH cores range from 200.9 ± 1.1 to 214.1 ± 4.3 Ma, with corresponding isochron ages from 198.2 ± 3.9 to 218.7 ± 4.4 Ma (Table 2; Fig. 11A–B). These data are similar to those of Li et al. (2003) and Liu et al. (2004a), suggesting retrograde metamorphism at 220, 213, and 204 Ma (see also Webb et al., this volume). These results and our new biotite $^{40}Ar/^{39}Ar$ age

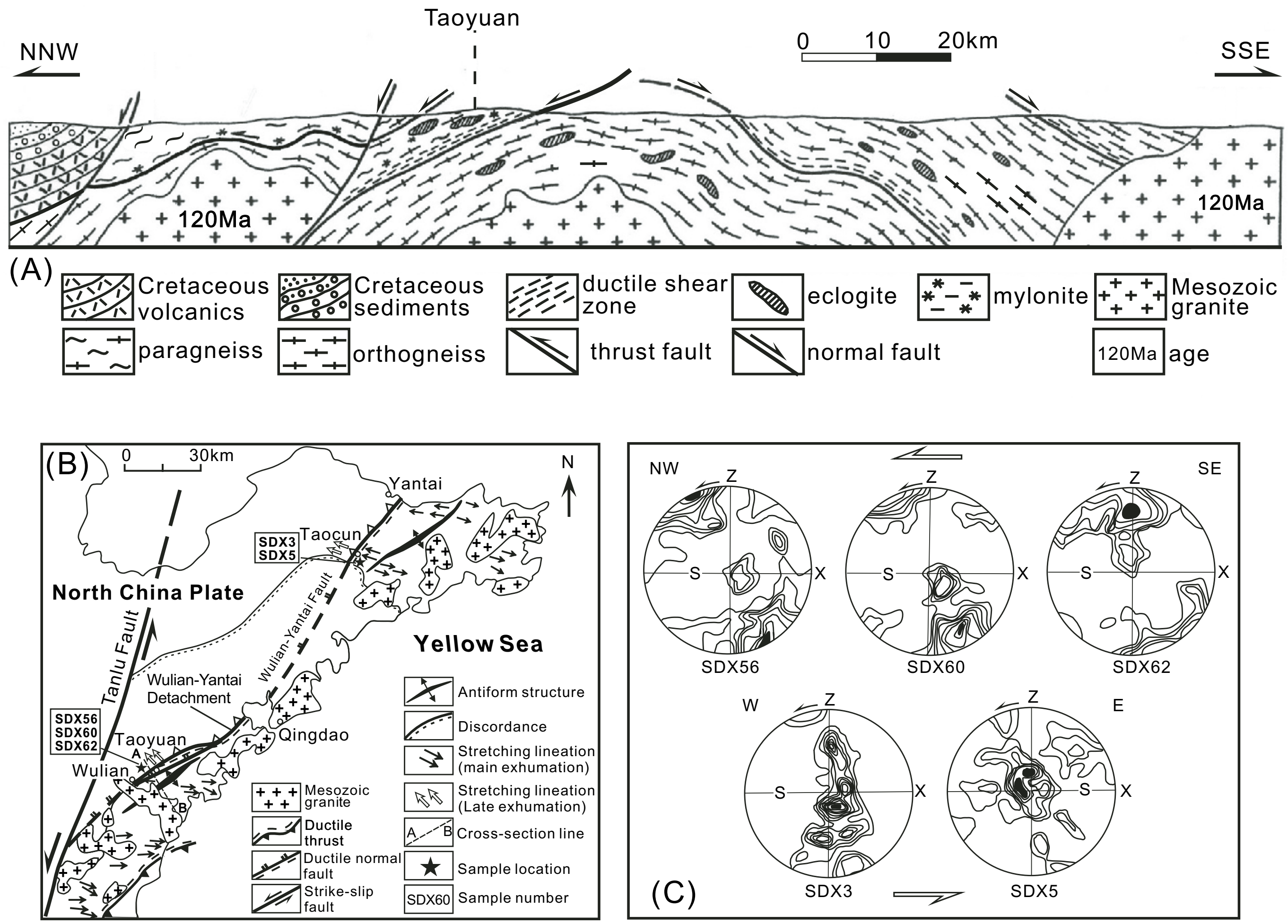

Figure 9. Cross section (A) and simplified geologic map (B) showing the major structures in the Sulu ultrahigh-pressure (UHP) IV zone. Quartz lattice preferred orientations for the Wulian-Yantai ductile detachment are shown in C. Samples SDX56, SDX60, and SDX62 are from Taoyuan, SW of the Wulian-Yantai detachment fault; samples SDX3 and SDX5 are from Taocun, NE of the Wulian-Yantai detachment fault.

data indicate that the earliest exhumation of the UHP rocks occurred at 220–200 Ma. The short interval between UHP metamorphism and early exhumation implies very rapid exhumation.

Age Constraints on the Exhumation of the Sulu High-Pressure Metamorphic Zone

Biotite and muscovite from the ductile shear zones of the high-pressure slice were dated at Stanford University. Biotite from sample L806 in Yuntaishan slice Ic does not yield a formal plateau age. A good estimate of the $^{40}Ar/^{39}Ar$ closure age of this biotite is its weighted mean age of 232.5 ± 2.4 Ma, with a corresponding isochron age of 232.9 ± 2.5 Ma (mean square of weighted deviates [MSWD] = 6.3, $^{40}Ar/^{36}Ar$ = 178 ± 70 Ma). Biotites from samples LYG1025-08 and LYG-20 in the Yuntaishan slice yield formal plateau ages of 253.8 ± 2.6 and 243.9 ± 2.6 Ma, and isochron ages of 254.0 ± 2.7 Ma (MSWD = 1.2, $^{40}Ar/^{36}Ar$ = 279 ± 23) and 244.2 ± 2.6 Ma (MSWD = 0.7, $^{40}Ar/^{36}Ar$ = 262 ± 28), respectively (Fig. 12). We analyzed muscovite from samples HWP-33 and SDX80 separated from gneiss and schist of the Yuntaishan slice by $^{40}Ar/^{39}Ar$, yielding weighted mean ages of 214.2 ± 2.3 and 218.7 ± 2.3 Ma and isochron ages of 213.8 ± 2.7 (MSWD = 5.52, $^{40}Ar/^{36}Ar$ = 307 ± 27) and 218.8 ± 2.4 Ma (MSWD = 1.41, $^{40}Ar/^{36}Ar$ = 293 ± 18) for muscovites from HWP-33 and SDX80, respectively (Table 3). These ages indicate that exhumation of the Sulu high-pressure slice started from 254 to 232 Ma to 214 Ma, earlier than the Sulu UHP slice (220–200 Ma; Fig. 12C–D), similar to the results of Li et al. (2000b).

Muscovite from the Wulian-Yantai ductile detachment yielded a $^{40}Ar/^{39}Ar$ isochron age of 148.7 ± 2.6 Ma and a plateau age of 146.7 ± 0.9 Ma (Yang et al., 2002), similar to the Cretaceous depositional age of the Laiyang sedimentary basin. This relationship suggests that normal slip along the Wulian-Yantai shear zone contributed to the formation and evolution of

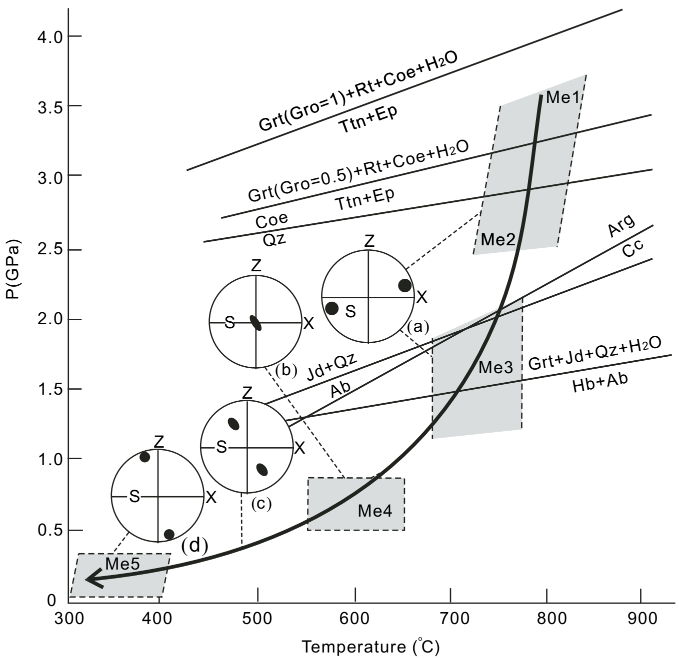

Figure 10. Relation between retrograde pressure-temperature (P-T) path and quartz lattice preferred orientations of Donghai ultrahigh-pressure (UHP) gneiss. Me2—first exhumation stage, T = 750–850 °C, P = 2.5–2.8 GPa; Me3—second exhumation stage, T = 680–780 °C, P = 1.2–1.8 GPa; Me4—third exhumation stage, T = 550–650 °C, P = 0.5–0.7 GPa; Me5—latest exhumation stage, T = 300–400 °C, P = 0.3–0.35 GPa. (a) High-T fabric of quartz with slip system of $\{10\bar{1}0\}\langle c\rangle$ (T > 650 °C). (b) Intermediate-T fabric of quartz with slip system of $(10\bar{1}0)\ \langle a\rangle$ (T = 550–650 °C). (c) Low–intermediate-T fabric of quartz with slip system of $(10\bar{1}\bar{1})\ \langle a\rangle$ (T = 450–550 °C). (d) Low-T fabric of quartz with slip system of $\{0001\}\ \langle a\rangle$ (T < 400 °C). Mineral abbreviations are from Kretz (1983).

the Laiyang basin. Formation of an antiform in the slice III–IV, emplacement of a number of Mesozoic granitic plutons (210–101 Ma), and the occurrence of NW-SE–trending upright concentric folds testify to extensional deformation during the late exhumation of the Sulu UHP terrane.

DISCUSSION AND CONCLUSION

Surface samples and CCSD drill cores of the Sulu UHP rocks vary in composition and metamorphic grade (Zhang et al., 2000, 2004, 2005; Liu et al., 2004c). The eclogite and country rocks experienced in situ UHP metamorphism when large tracts of continental crust were subducted to >100 km and later exhumed (Liu et al., 2004c). The mechanism by which deeply subducted continental crust is exhumed and returned to Earth's surface is a challenging research problem (Ernst and Liou, 1999). Various hypotheses have been proposed to explain the rapid exhumation of UHP metamorphic rocks, including eroding and floating (Platt, 1993), extension (Harrison, 1992), vertical extrusion (Chemenda et al., 1995, 1996; Maruyama et al., 1994), and upper-crust extension and lower-crust shortening (Anderson et al., 1990; Ballevere et al., 1990). Chemenda et al. (1995, 1996) suggested that rocks that experience UHP metamorphism become relatively soft and are squeezed from the subduction channel by plate convergence. In the Dabie-Sulu area, models of extrusion and extension (Faure et al., 2001; Maruyama et al., 1994) have been invoked for the exhumation of this UHP metamorphic slice. Hacker et al. (2004) suggested that in Late Permian–Early Triassic times, the northern edge of the South China plate was subducted to >150 km, creating UHP metamorphic rocks of the Dabie and Sulu slice; exhumation by extension occurred between 245 and 195 Ma during clockwise rotation of the craton. All these models assume subduction and exhumation of an intact continental slab.

Recent petrologic, geochemical, structural, and seismic studies have generated new data that enable us to examine the tectonics of the Sulu high-pressure–UHP metamorphic slices in greater detail:

TABLE 2. ^{40}Ar/^{39}Ar AGES FOR BIOTITES AND MUSCOVITES FROM THE SULU HIGH PRESSURE AND ULTRAHIGH-PRESSURE BELTS

Sample	Depth (m)	Location	Tectonic unit	Host Rock	Mineral	Plateau age	Isochron age
B475R359P3v	891	Maobei CCSD	UHP (III)	Mylonitic paragneiss	Biotite	210.9±1.1 Ma	218.7±4.4 Ma
B527R388P1f	960	Maobei CCSD	UHP (III)	Mylonitic paragneiss	Biotite	214.1 ± 4.2 Ma	214.1±4.3 Ma
B608R432P1f	1097	Maobei CCSD	UHP (III)	Mylonitic paragneiss	Biotite	200.9±1.1 Ma	198.2±4.0 Ma
B627R441P3n	1130	Maobei CCSD	UHP (III)	Mylonitic paragneiss	Biotite	202.4±1.0 Ma	201.1±3.0 Ma
LYG-20	0	Pingshan, Lianyungang	HP (I)	Mylonitic Ep-Pl-gneiss	Biotite	243.7±2.5 Ma	244.2±2.6 Ma
LYG-1025-08	0	Xueqigou, Lianyungang	HP (I)	Mylonitic Ep-Pl-gneiss	Biotite	254.11±2.6 Ma	254.0±2.7 Ma
HWP-33	0	Dongxiliandao, Lianyungang	HP (I)	Mylonitic Ep-Pl-gneiss	Muscovite	215.1±2.3 Ma	213.8±2.7 Ma
SDX-80	0	Ganyu	HP (I)	Pl-gneiss	Muscovite	218.4±2.3 Ma	218.8±2.7 Ma

Note: ^{40}Ar/^{39}Ar biotite and muscovite dating performed at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, and Stanford University. CCSD—Chinese Continental Scientific Drilling Project; HP—high pressure; UHP—ultrahigh-pressure; Ep—epidote; Pl—plagioclase.

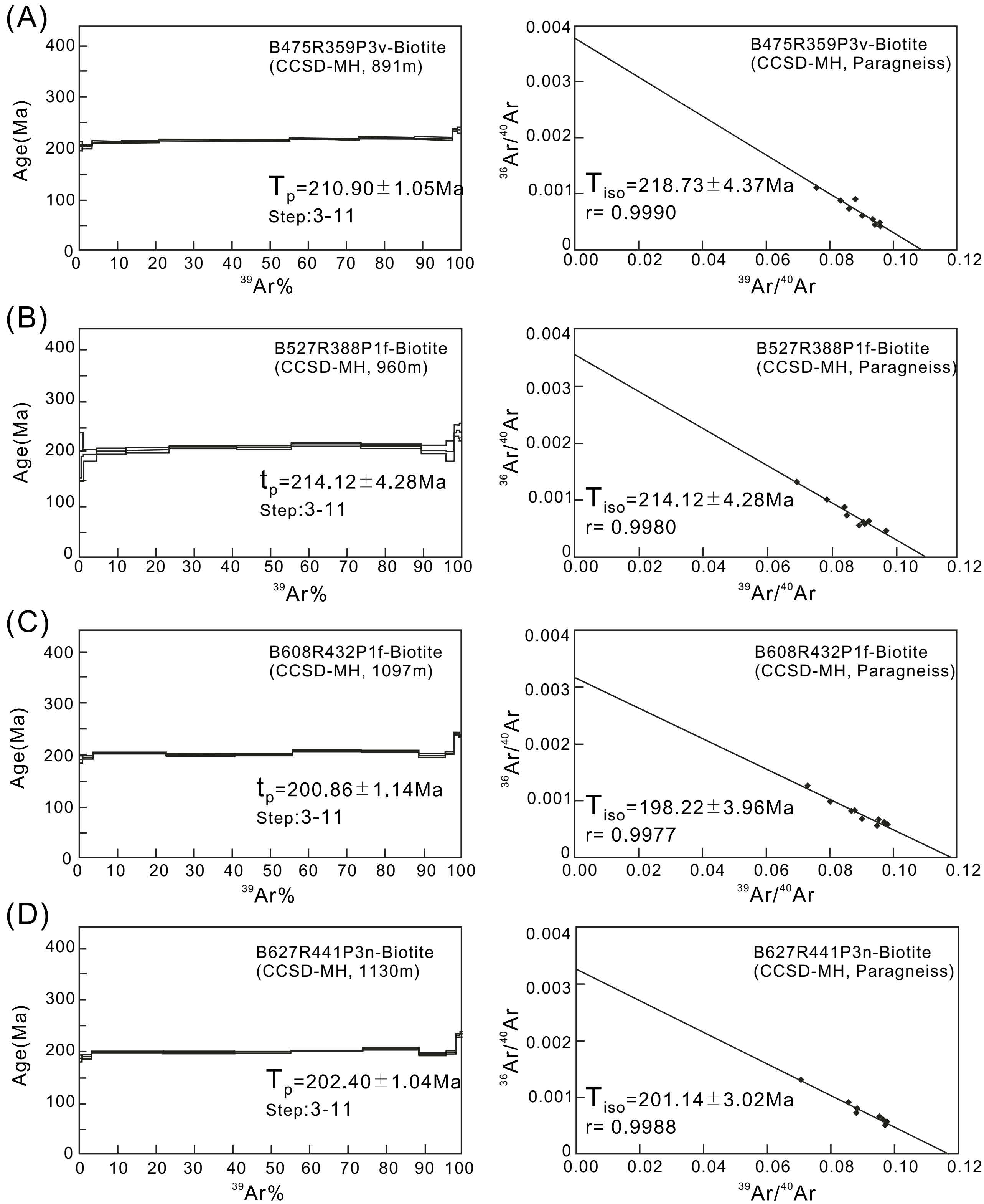

Figure 11. $^{40}Ar/^{39}Ar$ isochron and plateau ages of biotite from the Chinese Continental Scientific Drilling Project (CCSD) main hole in the ultra-high-pressure (UHP) III zone: (A) sample B475R359P3v (891 m); (B) sample B527R388P1f (960 m); (C) sample B608R432P1f (1097 m); and (D) sample B627R441P3n (1130 m).

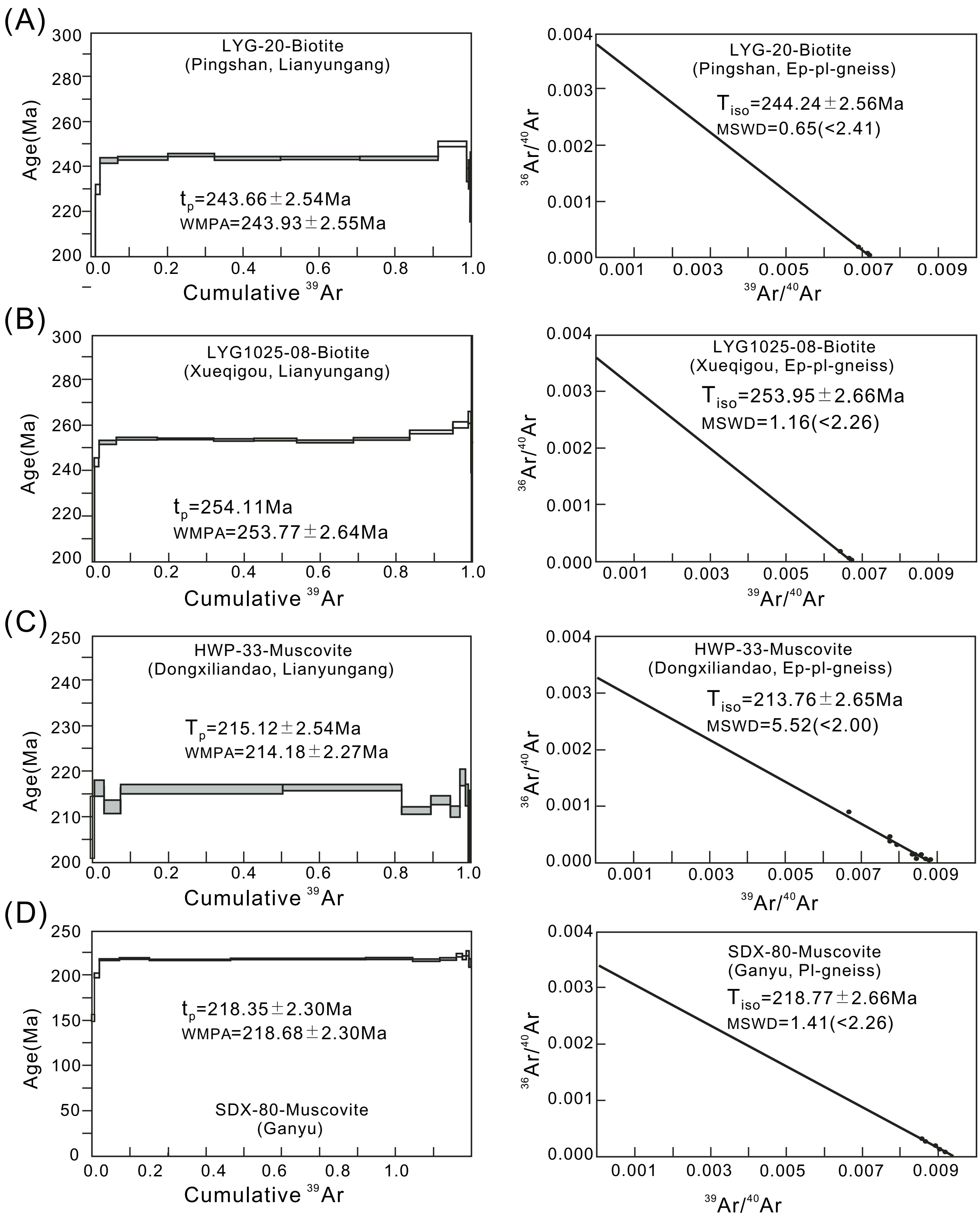

Figure 12. ^{40}Ar/^{39}Ar isochron and plateau ages of biotite and muscovite from ductile shear zones in the high-pressure zone: (A) sample LYG-20; (B) sample LYG-102-08; (C) sample HWP-33; and (D) sample SDX-80. MSWD—mean square of weighted deviates, WMPA—weighted mean plateau age.

TABLE 3. SUMMARY OF RADIOMETRIC DATA ON THE SULU HIGH PRESSURE (I) AND ULTRAHIGH-PRESSUREP (III AND IV) METAMORPHIC BELTS FROM PREVIOUS STUDIES

Location	Host Rock	Method	Age (Ma)	Reference
Sulu UHP belt IV				
Weihai	Garnet peridotite	SHRIMP U/Pb Zircon	225 ± 5 Ma	Yang et al., 2003
Rongcheng	Garnet peridotite	SHRIMP U/Pb zircon	229±39 Ma	Yang et al., 2003
Majiagou, Rizhao	Eclogite	Sm-Nd whole rock	209 ~211 Ma	Li et al., 1993
Zhubian	Eclogite	Sm-Nd whole rock	228±6 Ma	Li et al., 1993
Yangkou, Rizhao	Eclogite	U-Pb zircon	202±13Ma	Li et al., 1993
Linshu	Eclogite	U-Pb zircon	217.1±8.7 Ma	Ames et al., 1996
Yangkou, Rizhao	Eclogite	U-Pb zircon	224±14 Ma	Zheng et al., 2004
Lanshantou, Rizhao	Eclogite	U-Pb zircon	224 ± 27 Ma	Zheng et al., 2004
Sulu UHP belt III				
Qinglongshan, Donghai	Eclogite	Sm-Nd whole rock	226 ± 3 Ma	Li et al., 1993
Qinglongshan, Donghai	Eclogite	U-Pb zircon	218 ± 16 Ma	Zheng et al., 2004
Qinglongshan, Donghai	Orthogneiss	U-Pb zircon	221 Ma	Rumble et al., 2002
Zhimafang, Fangshan	Garnet peridotite	U-Pb zircon	216–233 Ma	Rumble et al., 2002
CCSD-PP2, Donghai	Orthogneiss	SHRIMP U/Pb zircon-mantle & core	232 ± 4.0Ma	Liu et al., 2004b
CCSD-PP2, Donghai	Paragneiss	SHRIMP U/Pb zircon-mantle & core	228 ± 5.0 Ma	Liu et al., 2004b
CCSD-PP2, Donghai	Orthogneiss	SHRIMP U/Pb zircon-rim	213 ± 5.0 Ma	Liu et al., 2004b
CCSD-PP2, Donghai	Paragneiss	SHRIMP U/Pb zircon-rim	208 ± 4.0 Ma	Liu et al., 2004b
CCSD-MH, Donghai	Orthogneiss	SHRIMP U/Pb zircon	227 ± 2.0 Ma	Liu et al., 2004c
CCSD-MH, Donghai	Orthogneiss	SHRIMP U/Pb zircon-rim	209 ± 3.0 Ma	Liu et al., 2004c
Niushan, Donghai	Eclogite	$^{40}Ar/^{39}Ar$ amphibole	213.4 ± 4.1 Ma	Li et al., 2003
Fangshan, Donghai	Eclogite	$^{40}Ar/^{39}Ar$ biotite	200.6 ± 3.1Ma	Li et al., 2003
Fangshan, Donghai	Eclogite	$^{40}Ar/^{39}Ar$ biotite	204 ± 2.0 Ma	Li et al., 2003
Sulu HP belt I				
Zhangbaling	Eclogite	$^{40}Ar/^{39}Ar$ Biotite	245.1 ± 0.5 Ma	Li et al., 1993

Note: CCSD—Chinese Continental Scientific Drilling Project; SHRIMP—sensitive high-resolution ion microprobe; HP—high pressure; UHP—ultrahigh-pressure.

(1) The paragneiss, granitic gneiss, marble, and quartzite that host the eclogite and ultramafic blocks and lenses account for ~95% of the Sulu slices. In these country rocks, coesite inclusions and other UHP diagnostic minerals are common in zircon (Liu et al., 2002, 2004b), demonstrating that large amounts of Yangtze craton continental crust was subducted below 100 km under the Sino-Korean craton at 240–220 Ma.

(2) The Sulu high-pressure and UHP slices preserve structures formed at crustal to mantle depths, corresponding to transitions from high-pressure–low-temperature, through very high-pressure–middle-temperature, to UHP metamorphism. As discussed above, the Sulu UHP belt can be subdivided into the supracrustal rock–dominant UHP III zone and granitic rock–dominant UHP IV zone, which is not only well expressed at the surface but also in the 5180 m CCSD borehole (Fig. 1). Such a stratigraphic relationship might suggest an original vertical crustal section of shallower supracrustal rocks underlain by granitic rocks. Both rock types were intruded by basaltic or gabbroic magma, the protolith of eclogites (Jahn, 1998). SHRIMP U-Pb zircon dating of Sulu high-pressure rocks suggests that the protoliths of eclogite and granitic gneiss formed at 700–800 Ma (see summaries in Leech et al., this volume, and Hacker et al., this volume; Liu et al., 2004b; Zheng et al., 2004). Together with the field relationships among eclogite, paragneiss, and granitic gneiss, these ages suggest that the eclogite protoliths were mafic magmas intruded into the country rocks as dikes or sills.

(3) A seismic refraction profile across the Sulu high-pressure–UHP terrane (Fig. 2) reveals an eroded dome or slab 10 km deep at its center and 15 km wide (Yang et al., 2004). UHP rocks dominate the core of this slab. High-pressure slices I, II, and III successively overlie the UHP slice and dip to the SE. To its NW, a high-pressure slice dipping to the NW overlies the UHP slice. Atop the UHP IV slab, shear sense is top from SE to NW (Fig. 10). Shear sense is top-SE at its bottom, suggesting that the whole slab experienced southeastward extrusion along the subduction channel. A strong N-dipping seismic reflector at depths of 18–20 km near Donghai may represent an intermediate-level detachment separating the Sulu high-pressure–UHP rocks from Yangtze continental rocks.

(4) Radiometric data from numerous U-Pb, Sm/Nd, and Rb/Sr studies (Table 3; Fig. 13) suggest that peak UHP metamorphism in the Sulu area occurred between 200 and 240 Ma (Liu et al.. 2004a; see summaries in Leech et al., this volume, and Hacker et al., this volume). The high-pressure metamorphic slice formed before 250 Ma and was exhumed from 250 to 210 Ma; subduction and exhumation of the high-pressure slices occurred earlier (240–220 Ma and 220–200 Ma, respectively) than in the UHP metamorphic slice.

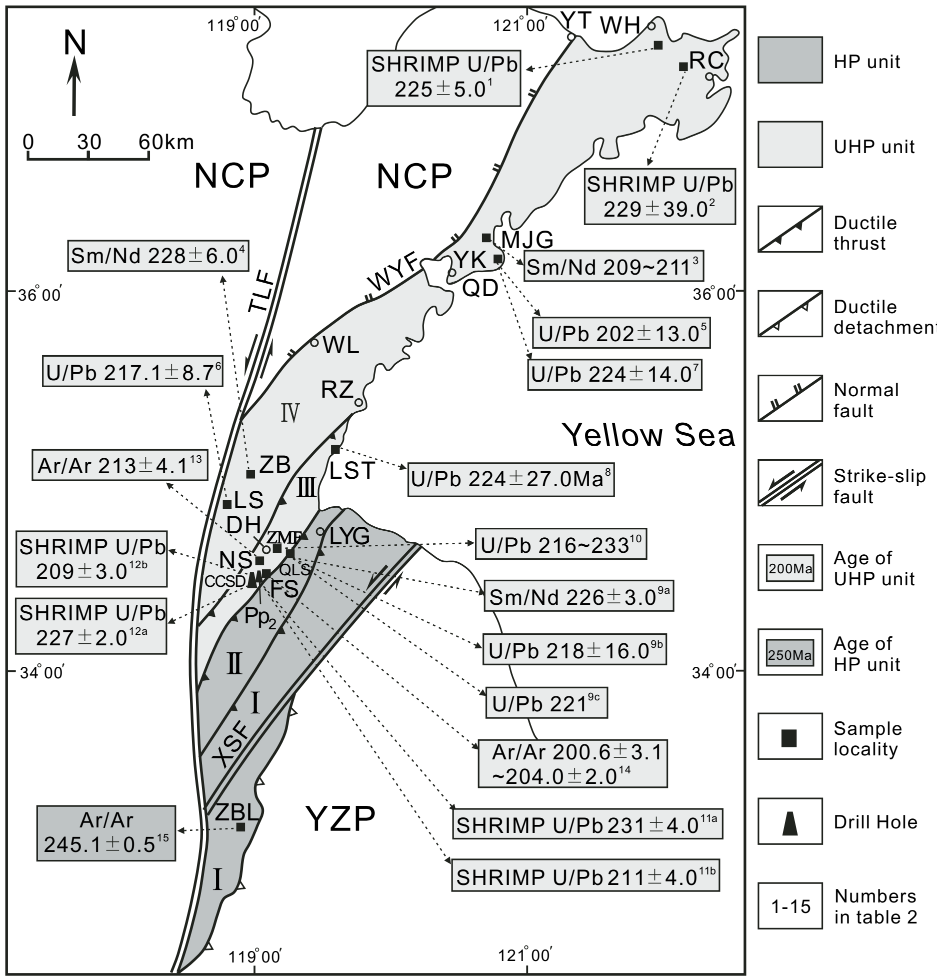

Figure 13. Summary of previous dating results using different methods in the Sulu high-pressure–ultrahigh-pressure (UHP) metamorphic terrane. For each location, dating method and corresponding result are shown in the box. CCSD—Chinese Continental Scientific Drilling Project site, TLF—Tan-Lu fault, XSF—Xiangshui fault, WYF—Wulian-Yantai fault, YT—Yantai, WH—Weihai, RC—Rongcheng, WL—Wulian, MJG—Majiagou, YK—Yangkou, QD—Qingdao, RZ—Rizhao, LST—Lanshantou, ZB—Zhubian, LS—Linshu, DH—Donghai, LYG—Lianyungang, ZMF—Zhimafang, NS—Niushan, QLS—Qinglongshan, FS—Fangshan, and ZBL—Zhangbaling.

These data suggest a working model that incorporates observations from surface geology and the CCSD boreholes. Prior to 250 Ma, passive-margin rocks from the leading edge of the Yangtze craton were subducted beneath the Sino-Korean craton. Sedimentary and granitic rocks, together with the enclosing mafic and ultramafic materials, were subducted and experienced variable high-pressure to UHP metamorphism.

Several lines of evidence imply a difference in timing of metamorphism between the Sulu high-pressure and UHP rocks. The four slices are separated by major ductile shear zones (Fig. 1). While the overall structural relations among these zones have been reworked by exhumation (particularly Mesozoic extension and intrusion of granitic plutons), their original relationship is probably similar to that observed today. Rocks in the high-pressure zone experienced metamorphism at 300–360 °C and 0.7–0.85 GPa, equivalent to subduction to a depth of 30 km. In contrast, rocks in the UHP zone experienced peak metamorphism at pressures equivalent to depths >100 km. Radiometric data indicate that high-pressure rocks underwent high-pressure metamorphism and were exhumed beginning at ca. 250 Ma and 254–232 Ma, respectively, substantially before the 220–240 Ma and 200–220 Ma ages observed for UHP rocks.

Based on the observations presented herein, we propose an alternate model (Fig. 14) for the formation and exhumation of the Sulu high-pressure–UHP metamorphic slice. High-pressure rocks represent the uppermost crustal rocks of the Yangtze craton. Because of their low density, they were only subducted to ~30 km, underwent peak high-pressure metamorphism at ca.

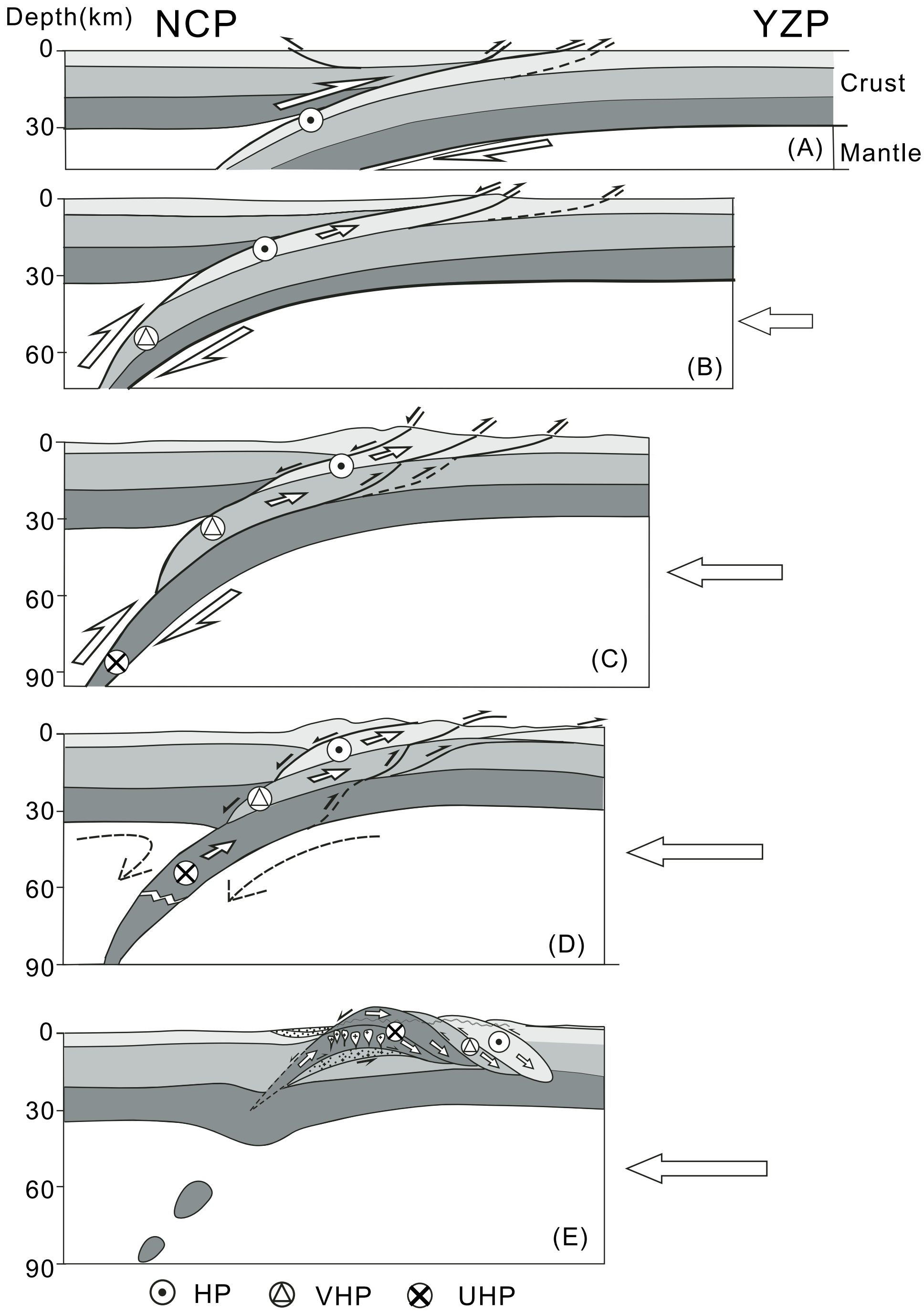

Figure 14. Model for the differential subduction and exhumation of a continental lithosphere proposed in this study: (A) older than 253 Ma, high-pressure (HP) rocks were formed at 30 km depth; (B) 250–240 Ma, very high-pressure (VHP) rocks were formed ~60 km deep, and the onset of exhumation of the high-pressure slabs occurred; (C) 240–220 Ma, ultrahigh-pressure (UHP) rocks were formed at ~100 km depth, and in contrast, very high-pressure and high-pressure slabs were exhumed; (D) 220–200 Ma, high-pressure, very high-pressure, and UHP slabs were exhumed; (E) postcollisional deformation resulted in a series of top-S thrusts and the antiform structure of the Sulu high-pressure–ultrahigh-pressure (UHP) metamorphic belt. NCP—North China plate (Sino-Korean craton), YZP—Yangtze craton (plate).

250 Ma, and began to be exhumed along the subduction channel as early as 232 Ma. In contrast, UHP rocks representing deeper levels in the Yangtze craton were denser and more easily subducted. They experienced peak UHP metamorphism below 80 km at 240–220 Ma and started exhumation at 220–200 Ma.

ACKNOWLEDGMENTS

This work was supported by Chinese National Science Foundation grant 40399141, Ministry of Science and Technology through a 973 National Basic Research Project 2003CB716500 and Chinese Geological Survey grant 121201056606. This is a China–United States cooperative project supported by National Science Foundation (NSF) grant EAR-003355. We thank Bradley Hacker, Mary Leech, Martin Wong, and an anonymous reviewer for critical and thoughtful reviews. Thanks are due to Fangyuan Chen, Fenghua Liang, and Xiaowei Zhang for their help in preparation of the figures.

REFERENCES CITED

Ames, L., Tilton, G.R., and Zhou, G., 1993, Timing of collision of the Sino-Korean and Yangtze cratons: U-Pb zircon dating of coesite-bearing eclogites: Geology, v. 21, p. 339–342, doi: 10.1130/0091-7613(1993)021<0339:TOCOTS>2.3.CO;2.

Ames, L., Zhou, G., and Xiong, B., 1996, Geochronology and isotopic character of ultrahigh-pressure metamorphism with implications for collision of the Sino-Korean and Yangtze cratons, central China: Tectonics, v. 15, p. 472–489, doi: 10.1029/95TC02552.

Anderson, T.B., and Jamerit, B., 1990, Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of western Norway: Tectonics, v. 9, p. 1097–1111.

Ballevere, M., Lagabrille, Y., and Merlr, O., 1990, Tertiary ductile normal faulting as a consequence of lithospheric stacking in the Western Alps: Mémoires de la Société Géologique de France, v. 156, p. 227–236.

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

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

Chopin, C., 2003, Ultrahigh-pressure metamorphism: Tracing continental crust into the mantle: Earth and Planetary Science Letters, v. 212, p. 1–14, doi: 10.1016/S0012-821X(03)00261-9.

Cong, B.L., and Wang, Q.C., 1999, The Dabie-Sulu UHP rocks slice: Review and prospect: Chinese Science Bulletin, v. 44, p. 1074–1085.

Ernst, W.G., 2001, Subduction, ultrahigh-pressure metamorphism, and regurgitation of buoyant crustal slices—Implications for arcs and continental growth: Physics of the Earth and Planetary Interiors, v. 127, p. 253–275, doi: 10.1016/S0031-9201(01)00231-X.

Ernst, W.G., and Liou, J.G., 1999, Overview of UHP metamorphism and tectonics in well-studied collisional orogens: International Geology Review, v. 41, p. 477–493.

Ernst, W.G., Maruyama, S., and Wallis, S., 1997, Buoyancy-driven, rapid exhumation of ultrahigh-pressure metamorphosed continental crust: Proceedings of the National Academy of Sciences of the United States of America, v. 94, p. 9532–9537, doi: 10.1073/pnas.94.18.9532.

Faure, M., Lin, W., and Le Breton, N., 2001, Where is the North China–South China block boundary in eastern China?: Geology, v. 29, p. 119–122, doi: 10.1130/0091-7613(2001)029<0119:WITNCS>2.0.CO;2.

Faure, M., Lin, W., Monie, P., Le Breton, N., Poussineau, S., Panis, D., and Deloule, E., 2003, Exhumation tectonics of the ultrahigh-pressure metamorphic rocks in the Qinling orogen in east China: New petrological-structural-radiometric insights from the Shandong Peninsula: Tectonics, v. 22, p. 1018, doi: 10.1029/2002TC001450.

Hacker, B.R., Ratschbacher, L., Webb, L., Ireland, T., Walker, D., and Dong, S., 1998, U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinling-Dabie orogen, China: Earth and Planetary Science Letters, v. 161, p. 215–230, doi: 10.1016/S0012-821X(98)00152-6.

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

Harrison, C.G.A., 1992, Rates of continental erosion and mountain building: Abstracts of the 29th International Geologic Congress, Kyoto, Japan, v. 1, p. 95.

Jahn, B.M., 1998, Geochemical and isotopic characteristics of UHP eclogites and ultramafic rocks of the Dabie orogen, *in* Hacker, B.R., and Liou, J.G., eds., When continents collide: Geochemistry of ultrahigh-pressure rocks: Dordrecht, Kluwer Academic Publishers, p. 203–239.

Ji, S.C., 1988, Tectonic significance of partial melting (1) Experiment study on transition of deformation mechanism: Acta Geoscientia Sinica, v. 4, p. 347–356.

Jung, H., and Karato, S., 2001, Water-induced fabric transitions in olivine: Science, v. 293, p. 1460–1463, doi: 10.1126/science.1062235.

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

Li, J.Y., Yang, T.N., Chen, W., and Zhang, S.H., 2003, $^{40}Ar/^{39}Ar$ dating of deformation events and reconstruction of exhumation of ultrahigh-pressure metamorphic rocks in Donghai: East China: Acta Geologica Sinica, v. 77, p. 155–168.

Li, S.G., Hart, S.R., Zhang, S.G., Liu, D.L., Zhang, G.W., and Guo, A.L., 1989, Timing of collision between north and south China blocks—The Sm-Nd isotopic age evidence: Science in China, v. 32, p. 1393–1400.

Li, S.G., Xiao, Y.L., Liu, D.L., Chen, Y.Z., Ge, N.J., Zhang, Z.Q., Sun, S.S., Cong, B.L., Zhang, R.Y., Hart, S.R., and Wang, S.S., 1993, Collision of North China and Yangtze blocks and formation of coesite-bearing eclogites: Timing and processes: Chemical Geology, v. 109, p. 89–111, doi: 10.1016/0009-2541(93)90063-O.

Li, S.G., Jagoutz, E., Xiao, Y.L., Ge, N.J., and Chen, Y.Z., 1996, Chronology of ultrahigh-pressure metamorphism in the Dabie Mountains and Sulu terrane: Science in China, ser. D, Earth Science, v. 39, p. 597–609.

Li, S.G., Jagoutz, E., Chen, Y.Z., and Li, Q.L., 2000a, Sm-Nd and Rb-Sr isotopic chronology and cooling history of ultrahigh pressure metamorphic rocks and their country rocks at Shuanghe in the Dabie Mountains, central China: Geochimica et Cosmochimica Acta, v. 64, p. 1077–1093, doi: 10.1016/S0016-7037(99)00319-1.

Li, S.G., Jagoutz, E., Lo, C.H., Chen, Y.Z., Li, Q.L., and Xiao, Y.L., 2000b, Sm/Nd, Rb/Sr, and $^{40}Ar/^{39}Ar$ isotopic systematics of ultrahigh-pressure metamorphic rocks in the Dabie-Sulu slice, central China: A retrospective view, *in* Ernst, W.G., and Liou, J.G., eds., Ultra-high pressure metamorphism and geodynamics in collision-type orogenic slices: Pennsylvania, Sheridan Press, p. 234–244.

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

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

Liu, F.L., Xu, Z.Q., Liou, J.G., Katayama, I., Masago, H., Maruyama, S., and Yang, J.S., 2002, Ultrahigh-pressure mineral inclusions in zircons from gneissic core samples of the Chinese Continental Scientific Drilling site in eastern China: European Journal of Mineralogy, v. 14, p. 499–512, doi: 10.1127/0935-1221/2002/0014-0015.

Liu, F.L., Zhang, Z.M., and Xu, Z.Q., 2003, Three-dimensional distribution of ultrahigh-pressure minerals in Sulu terrane: Acta Geologica Sinica, v. 77, p. 69–84.

Liu, F.L., Xu, Z.Q., and Liou, J.G., 2004a, Tracing the boundary between UHP and HP metamorphic slices in the southwestern Sulu terrane, eastern China: Evidence from mineral inclusions in zircons from metamorphic rocks: International Geology Review, v. 46, p. 409–425.

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

Liu, F.L., Xu, Z.Q., and Xue, H.M., 2004c, Tracing the protolith, UHP metamorphism, and exhumation ages of orthogneiss from the SW Sulu terrane (eastern China): SHRIMP U-Pb dating of mineral inclusion-bearing zircons: Lithos, v. 78, p. 411–429, doi: 10.1016/j.lithos.2004.08.001.

Mainprice, D., Boucher, T.-L., Blumenfeld, P., and Tubia, J.M., 1986, Dominant <c> slip in naturally deformed quartz: Implications for dramatic plastic softening at high temperature: Geology, v. 14, p. 819–822, doi: 10.1130/0091-7613(1986)14<819:DCSIND>2.0.CO;2.

Maruyama, S., Liou, J.G., and Zhang, R., 1994, Tectonic evolution of the ultrahigh-pressure (UHP) and high-pressure (HP) metamorphic slices from central China: The Island Arc, v. 3, p. 112–121.

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

Qiu, H.J., Xu, Z.Q., Zhang, Z.M., Yang, J.S., Yang, T.N., Zhang, J.X., and Li, H.B., 2002, New mineral evidence of high-pressure metamorphism of the Subei high-pressure slice—Aragonite inclusions in garnet from greenschist: Geological Bulletin of China, v. 21, p. 617–624.

Rumble, D., Giorgis, D., Ireland, T., Zhang, Z.M., Xu, H.M., Yui, T.F., Yang, J.S., Xu, Z.Q., and Liou, J.G., 2002, Low $\delta^{18}O$ zircons, U-Pb dating, and the age of the Qinglongshan oxygen and hydrogen isotope anomaly near Donghai in Jiangsu Province, China: Geochimica et Cosmochimica Acta, v. 66, p. 2299–2306, doi: 10.1016/S0016-7037(02)00844-X.

Wang, L.M., Song, M.C., Wang, P.C., Wang, S.J., Song, Z.Y., Liu, J.W., Li, Y.Y., and Zhang, X.D., 2005, The structure and evolution of the Sulu ultrahigh-pressure metamorphic slice: Beijing, Geological Publishing House, 126 p. (in Chinese with English abstract).

Xu, Z.Q., Zhang, J.X., Xu, H.F., Wang, Z.X., Li, H.B., Yang, T.N., Qiu, X.P., Zeng, L.S., Shen, K., and Chen, W., 1997, Ductile shear zones in the main continental mountain chains of China and their dynamics: Beijing, Geological Publishing House, 294 p. (in Chinese and with an extended English abstract).

Xu, Z.Q., Zhang, Z.M., Liu, F.L., Yang, J.S., Tang, Z.M., Cheng, S.Z., Cai, Y.C., Li, T.F., and Cheng, F.Y., 2004, The structure profile of 0–1200 m in the main borehole, Chinese Continental Scientific Drilling and its preliminary deformation analysis: Acta Petrologica Sinica, v. 20, p. 53–72.

Xu, Z.Q., Chen, J., Wang, Q., Zeng, L.S., Yang, J.S., Chen, F.Y., Li, T.F., and Liang, F.H., 2005, Type-C olivine fabric in the Zhimafang garnet peridotite of the southern Sulu ultrahigh-pressure metamorphic terrane: Formation conditions and tectonic implications: Acta Petrologica Sinica, v. 21, p. 389–397.

Yang, J.S., Wooden, J.L., Wu, C.L., Liu, F.L., Xu, Z.Q., Shi, R.D., Katayama, L., Liou, J.G., and Maruyama, S., 2003, SHRIMP U-Pb dating of coesite-bearing zircon from the ultrahigh-pressure metamorphic rocks, Sulu terrane, east China: Journal of Metamorphic Geology, v. 21, p. 551–560, doi: 10.1046/j.1525-1314.2003.00463.x.

Yang, T.N., Chen, W., Li, J.Y., Xu, Z.Q., Yin, X.L., and Xu, W.H., 2002, Exhumation history of the Sulu UHPM terrane—Evidence from dating and deformation on its northern boundary: Geological Review, v. 48, p. 176–182.

Yang, W.C., Yang, W.Y., and Chen, Z., 2004, Interpretation of 3D seismic reflection data in the Chinese Continental Scientific Drilling site: Acta Petrologica Sinica, v. 20, p. 127–137.

Zhang, R.Y., Liou, J.G., and Shu, J.F., 2002, Hydroxyl-rich topaz in high-pressure and ultrahigh-pressure kyanite quartzite, with retrograde woodhouseite, from the Sulu terrane, eastern China: The American Mineralogist, v. 87, p. 445–453.

Zhang, S.Y., Hu, K., Qiao, L.Y., and Liu, X.C., 1991, Composition and petrogenesis of the collisions of old blocks inside the continent—Take example for the high-pressure metamorphic slice in the central of China: Proceeding of the Qinling orogen conference: Xian, The NW University Publishing House, p. 48–56 (in Chinese with English abstract).

Zhang, Z.M., Xu, Z.Q., and Xu, H., 2000, Petrology of ultrahigh pressure eclogites from the ZK703 drill hole in the Donghai, eastern China: Lithos, v. 52, p. 35–50, doi: 10.1016/S0024-4937(99)00083-3.

Zhang, Z.M., Xu, Z.Q., Liu, F.L., You, Z.D., Shen, K., Yang, J.S., Li, T.N., and Chen, S., 2004, Geochemistry of eclogites from the main hole (100–2050 m) of the Chinese Continental Scientific Drilling Project: Acta Petrologica Sinica, v. 20, p. 27–42.

Zhang, Z.M., Xiao, Y.L., Liu, F.L., Liou, J.G., and Hoefs, J., 2005, Petrogenesis of UHP metamorphic rocks from Qinglongshan, southern Sulu, east-central China: Lithos, v. 81, p. 189–207, doi: 10.1016/j.lithos.2004.10.002.

Zheng, Y.F., Wu, Y., Chen, F., Gong, B., Li, L., and Zhao, Z., 2004, Zircon U-Pb and oxygen isotope evidence for a large-scale ^{18}O depletion event in igneous rocks during the Neoproterozoic: Geochimica et Cosmochimica Acta, v. 68, p. 4145–4165, doi: 10.1016/j.gca.2004.01.007.

Manuscript Accepted by the Society 21 September 2005

Geological Society of America Special Papers

Polyphase subduction and exhumation of the Sulu high-pressure–ultrahigh-pressure metamorphic terrane

Zhiqin Xu, Lingsen Zeng, Fulai Liu, et al.

Geological Society of America Special Papers 2006;403; 93-113
doi:10.1130/2006.2403(05)

Notes