Petrochemistry, oxygen isotopes and U-Pb SHRIMP geochronology of mafic-ultramafic bodies from the Sulu UHP terrane, China

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ABSTRACT Two Rongcheng eclogite-bearing peridotite bodies (Chijiadian and Macaokuang) occur as lenses within the country rock gneiss of the northern Sulu terrane. The Chijiadian ultramafic body consists of garnet lherzolite, whereas the Macaokuang body is mainly meta-dunite. Both ultramafics are characterized by high MgO contents, low fertile element concentrations and total REE contents, which suggests that they were derived from depleted, residual mantle. High FeO contents, an LREE-enriched pattern and traceelement contents indicate that the bulk-rock compositions of these ultramafic rocks were modified by metasomatism. Oxygen-isotope compositions of analysed garnet, olivine, clinopyroxene and orthopyroxene from these two ultramafic bodies are between +5.2% and +6.2% (δ^{18} O), in the range of typical mantle values (+5.1 to +6.6%). The eclogite enclosed within the Chijiadian lherzolite shows an LREEenriched pattern and was formed by melts derived from variable degrees (0.005-0.05) of partial melting of peridotite. It has higher δ^{18} O values (+7.6% for garnet and +7.7% for omphacite) than those of lherzolite. Small O-isotope fractionations (Δ Cpx-OI: 0.4‰, Δ Cpx-Grt: 0.1‰, Δ Grt-OI: 0.3–0.4‰) in both eclogite and ultramafic rocks suggest isotopic equilibrium at high temperature. The P-T estimates suggest that these rocks experienced subduction-zone ultrahigh-pressure (UHP) metamorphism at \sim 700–800 °C, 5 GPa, with a low geothermal gradient. Zircon from the Macaokuang eclogite contains inclusions of garnet and diopside. The 225 \pm 2 Ma U/Pb age obtained from these zircon may date either the prograde conditions just before peak metamorphism or the UHP metamorphic event, and therefore constrains the timing of subduction-related UHP metamorphism for the Rongcheng maficultramafic bodies.

Key words: eclogite; garnet lherzolite; oxygen isotope; Sulu UHP terrane; zircon SHRIMP dating.

INTRODUCTION

Garnet peridotites are volumetrically minor, but widespread in high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic terranes within continental collision zones such as the Western Gneiss Region (WGR) of Norway, the Bohemian Massif of central Europe and the Dabie-Sulu UHP terrane of east-central China (Medaris, 1999; Zhang et al., 2000). Most previous investigations in UHP terranes have focused on coesite- and diamond-bearing eclogites and their associated gneisses. Widespread garnet peridotites together with eclogites are an integral petrological component of many UHP terranes. They may reflect the early stages of orogenic development, and carry important geodynamic implications for continental collision. Garnet peridotites are also a source of information on the chemistry and thermal history of the local upper mantle in addition to the well-studied xenocrysts and xenoliths in mantle-derived basalt and kimberlite. They can potentially provide information on the composition and evolution of the mantle wedge above a subducting slab, crust-mantle interactions, and emplacement mechanisms of mantle rocks into continental crust during continental collision. Thus, garnet peridotites are considered to be an additional window in understanding upper mantle processes.

Recent petrochemical studies of peridotites suggest that HP/UHP peridotites vary in initial tectonic setting, evolutionary history and emplacement mechanism in different orogens, and in individual terranes (Brueckner & Medaris, 1998, 2000; Medaris, 1999; Zhang et al., 2000). Medaris (1999) subdivided garnet peridotites from Eurasian HP and UHP terranes into: (i) UHP peridotites related to continental subduction, (ii) high P/T relict peridotites derived from ancient depleted mantle and (iii) low P/T peridotites that may be related to upwelling asthenosphere. Dabie-Sulu peridotites have been classified as mantle-derived (type A) and crust-hosted (type B) peridotites (Zhang & Liou, 1998a; Zhang et al., 2000). Both types were subjected to Triassic UHP metamorphism at about 4-6.7 GPa and 750-950 °C (Zhang et al., 1994, 2000, 2003).

Rongcheng is located in the north-eastern part of the Sulu terrane (Fig. 1a). The Chijiadian and



Fig. 1. (a) Simplified geological map of the Sulu terrane in east-central China, showing the localities of garnet peridotite and eclogite in the UHP unit. (b) Geological sketch map of the Rongcheng area showing localities of the Chijiadian and Macaokuang bodies and investigated samples (modified after Zhang *et al.*, 2000). Abbreviations: HP, high pressure; UHP, ultrahigh pressure; F, fault; JXF, Jiashan-Xianshui fault; YQWF, Yantai-Qingdao-Wulian fault; QDCZ, Qinling-Dabie collision zone.

Macaokuang peridotite bodies contain eclogite lenses and occur in the Rongcheng area. The Chijiadian eclogite-bearing garnet lherzolite body (Fig. 1b) forms a small hill of 0.6×0.2 km² surrounded by gneiss; its margins are extensively serpentinized. Garnet lherzolite and eclogite lenses are well preserved in the centre of the body and their petrogeneses have been described by Cong et al. (1992); Hiramatsu et al. (1995) and Zhang et al. (1994, 2000. Olivine with ilmenite exsolution lamellae was reported from the Chijiadian garnet lherzolite (Hacker et al., 1997); the interpretation of the origin of such ilmenite exsolution was paradoxical (e.g. Dobrzhinetskaya et al., 1996; Hacker et al., 1997; Ulmer & Trommsdorff, 1997). However, further experimental data have shown that the ilmenite lamellae from the Alpe Arami garnet lherzolite in the Central Alps were originally an HP perovskite polymorph of ilmenite, and the precursor phase formed at 10-15 GPa (Green et al., 1997a,b; Dobrzhinetskava et al., 2000). The enclosed eclogite contains quartz pseudomorphs after coesite in garnet and omphacite (Zhang et al., 1994). The Macaokuang peridotite body also occurs in gneiss to the south-east of the Chijiadian body (Fig. 1b), but has not been systematically studied so far. It has been extensively serpentinized, and only minor meta-dunite and associated eclogite are present.

Ultramafic rocks were considered to lack zircon, and therefore age constraints for their formation and subsequent recrystallization have been difficult to obtain. In the last several years, however, zircon has been successfully separated from some orogenic peridotites, and SHRIMP U-Th-Pb analyses of the zircon have been employed to constrain formation time and evolution history of orogenic peridotites (Rumble *et al.*, 2002; Yang *et al.*, 2003; Zhang *et al.*, 2005a; Zhao *et al.*, 2005, 2006). Moreover, eclogite enclosed in peridotite contains sufficient zircon for SHRIMP U-Pb dating, and can also provide time constraints for the host peridotite body. Here, we provide new U-Pb zircon geochronological data from the Macaokuang eclogite, together with petrochemical and stable isotope studies of both the Chijiadian and Macaokuang bodies. These data allow us to place constraints on the initial tectonic setting, P-T estimates and timing of UHP metamorphism for the two bodies.

GEOLOGICAL OUTLINE

The Qinling-Dabie-Sulu collision zone lies between the Sino-Korean and Yangtze cratons. The Sulu terrane is the eastern extension of the Qinling-Dabie belt, bounded by the Yantai-Qingdao-Wulian (WQYF) fault on the north-west and the Jiashan-Xiangshui (JXF) fault on the south (Fig. 1a). It extends for about 320 km from Weihai, north-eastern Shandong Province, to Donghai, northern Jiangsu Province. It consists of two fault-bounded UHP and HP belts, both intruded by post-orogenic Cretaceous granite. The UHP belt consists mainly of orthogneiss, paragneiss, marble and minor coesite-bearing quartzite, eclogite and UHP garnet peridotite. Although most gneisses and marbles show assemblages of granulite-amphibolite facies, coesite inclusions in zircon were commonly found in these rocks (Liu et al., 2004b,c, 2005). Garnet peridotites occur sporadically as blocks (metre to kilometre size) and thin layers in the gneiss (Zhang & Liou, 1998b). Most eclogites (>90%) occur extensively as lenses and layers in gneiss. The rest are enclosed in UHP

garnet peridotite (Zhang et al., 2000) and in marble (Liu et al., in press). Coesite and coesite pseudomorphs are widespread in eclogites from many localities (e.g. Rongcheng, Weihai) (Liou et al., 1995), and interstitial coesite occurs in the matrix of an eclogite at Yangkou (Liou & Zhang, 1996). The HP belt, south-east of the UHP belt, consists mainly of quartz-mica schist, chloritoid-kyanite-mica-quartz schist, marble and rare blueschist (Zhang et al., 1995: Liu et al., 2004a). Many lines of evidence indicate that the Proterozoic supracrustal rocks experienced Triassic UHP metamorphism together with intruded mafic-ultramafic complexes (e.g. Zhang et al., 1995, 2000; Liou et al., 1996). Proterozoic protolith ages of 910-574 Ma were reported from zircon cores or the upper intercept of discordia in U-Pb dating of a variety of gneisses, marbles and eclogites, whereas the zircon rims or the lower intercepts of the discordia consistently yield 240-220 Ma, the age of peak UHP metamorphism (Ames et al., 1996; Hacker et al., 1998; Rumble et al., 2002; Yang et al., 2003; Liu et al., 2004a,b, 2005, 2006; Zheng et al., 2004). These Triassic ages are consistent with previously reported Sm-Nd isochron ages (Li et al., 1993, 1994; Chavagnac & Jahn, 1996; Jahn et al., 2003).

PETROGRAPHY

Chijiadian garnet lherzolite (CJ3A, 3B, 1R, 1V, 2B, 5A, 5B, 1Rb)

Garnet lherzolite samples are massive with near-equigranular texture and composed mainly of olivine, orthopyroxene, clinopyroxene and garnet together with minor secondary amphibole. Garnet ranges from 0.3 to 1.5 mm in size. Most garnet has a thin brownish kelyphitic rim consisting of extremely fine-grained fibre aggregates composed of orthopyroxene and clinopyroxene recording granulite-facies retrograde metamorphism (Zhang et al., 1994); some garnet is even partially or totally replaced by these aggregates. Minor Ca-amphibole also replaces garnet as a secondary phase (Fig. 2a), suggesting amphibolite facies retrogression. Olivine ranges from 0.1 to 0.5 mm in size, and contains ilmenite lamellae as reported by Hacker et al. (1997). Rounded olivine relicts are first surrounded by a thin rim of talc, and then by an outer rim of serpentine. Such replacements are due to H₂O infiltration during the last metamorphic stage (VI_B) , described by Zhang et al. (1994). Orthopyroxene is relatively more abundant than clinopyroxene, and ranges from 0.3 to 1 mm in size. Some lherzolites from the same outcrop have been partially altered to serpentinite, and only a few relict islands of olivine, garnet, orthopyroxene and clinopyroxene remain.

Chijiadian eclogite (CJ2N, 4A)

Eclogites occur as isolated nodules (<1 m) in the Chijiadian garnet lherzolite, and consist of bimineralic

porphyroblastic garnet + omphacite (Fig. 2b). Coarse-grained garnet (2–3 mm) and omphacite (1– 1.2 mm) occur in a fine-grained (0.4–0.7 mm) matrix of Grt + Omp. Rutile occurs as an interstitial phase between garnet and omphacite grains. Minor apatite is present as inclusions in porphyroblastic garnet. A previous study reported that inclusions of quartz pseudomorphs after coesite occur in omphacite and very minor kyanite grains are present in some eclogites (Zhang *et al.*, 1994).

Macaokuang meta-dunite (MC3B, K489, 5A) and eclogite (MC7A, 7B, 7C)

The Macaokuang meta-dunite mainly consists of olivine (>90 vol.%) with minor enstatite, euhedral amphibole and Cr-spinel or chromite. Some of them contain rounded porphyroblastic enstatite of 3-8 mm in size with exsolution lamellae and coarse-grained (up to 1 mm) red-brown Cr-spinel or chromite. Olivine, ranging from 0.2 to 0.4 mm in size, is replaced by serpentine, and shows typical mesh texture (Fig. 2c). Recently recovered Macaokuang meta-dunite cores from Chinese Continental Scientific Drilling (CCSD) contain trace garnet (Y.F. Ren personal communication, 2006). The Macaokuang eclogite occurs as an elongated lens $(1 \times \text{several } m)$ within meta-dunite. Because of significant serpentinization of peridotite and poor exposure, it is not clear if there is a reaction zone between peridotite and eclogite. The eclogite consists of variable amounts of inequigranular (0.05-0.6 mm) garnet and clinopyroxene (Fig. 2d). The clinopyroxene of variable sizes forms packets and some garnet shows relict corona texture, implying that the rock has not reached equilibrium in both composition and texture. Rutile prisms are also present between garnet and omphacite grains. Secondary amphibole occurs between garnet and clinopyroxene grains along margins of the eclogite body. Zircon of the enclosing eclogites may have grown during the initial metamorphism and contains low-jadeite bearing omphacite and higher Mn-bearing garnet as inclusions described below.

MAJOR AND RARE-EARTH ELEMENT GEOCHEMISTRY

Analytical method

Representative samples of Chijiadian garnet lherzolite (CJ1R, 1V, 2B, 5A, 5B, 1Rb), Macaokuang meta-dunite (MC3B) and Chijiadian eclogite (CJ2N, 4A) were analysed for major elements and trace and REE elements at the National Analytical Center, Chinese Academy of Geological Sciences (CAGS). Analyses of most major elements were carried out on a fused glass disc by X-ray fluorescence (XRF, Rigaku 3080E) and FeO, H_2O^+ and CO_2 by ICP-AES (JIA IRIS); analytical uncertainties for all major elements are < 0.5%.



Fig. 2. (a) Backscattered electron (BSE) image of the Chijiadian lherzolite (CJ3A). Garnet is replaced by fine-grained fibrous aggregates and relatively coarser amphibole. (b), (c) and (d) are photomicrographs showing mineral assemblages and characteristic textures in plane polarized light. (b) and (d) Bimineralic Grt + Omp assemblage from the Chijiadian (CJ4A) and Macaokuang eclogite (MC7A), respectively. (c) Olivine in dunite (MC5A) is surrounded and separated by a serpentine network. Abbreviations of minerals follow Kretz (1983).

The samples for trace-element analyses (Zr, Nb, V, Cr, Sr, Ba, Ni, Rb and Y) were made as compressed powder discs and analysed by XRF (Rigaku-2100) with analytical uncertainties of < 3% except Ba (< 5%). Other trace elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS, TJA-ExCell); when element concentrations are > 1 ppm, their uncertainties are 1-5%; if the concentrations are < 1 ppm, the uncertainties are up to 5-10%. Rare earth elements (REE) were separated using cation exchange techniques. Analytical (ICP-MS, TJA-ExCell) uncertainties are 10% for trace elements with abundances of < 10 ppm, and $\sim 5\%$ for those > 10 ppm.

Geochemistry of the Rongchen peridotites and eclogites

The garnet lherzolite and meta-dunite contain higher MgO (41–48 wt%) but lower concentrations of TiO_2

(0.02-0.1 wt%), Al₂O₃ (0.55-2.94 wt%) and CaO (0.23-1.46 wt%) (Table 1) than those of primitive mantle as defined by Ringwood (1975). Most samples also show low FeO contents (7.08–7.84 wt%); however, two relatively less depleted lherzolites have higher FeO contents than that of the primitive mantle. As shown in Fig. 3, TiO₂, Al₂O₃ and CaO display negative correlation with MgO. As with other Sulu peridotites (Zhang et al., 2000), this compositional trend is consistent with the suggestion of a depleted residual mantle origin. In contrast, the eclogites have much higher contents of TiO₂ (~0.9 wt%), Al₂O₃ (16-18 wt%), CaO (~11 wt%) and Na₂O (1.8–2.4 wt%), and much lower MgO (10-12 wt%) than the enclosing peridotite. Eclogites contain \sim 45–46 wt% SiO₂; according to the classification of Irvine & Baragar (1971), protoliths of the eclogites have tholeiite compositions.

Sample: Rock type:	CJ1R ^a Lherzolite	CJ1V ^a Lherzolite	CJ2B ^a Lherzolite	CJ5A ^a Lherzolite	CJ5B ^a Lherzolite	CJ1Rb ^a Lherzolite	MC3B ^a Dunite	CJ2N Eclogite	CJ4A Eclogite
SiO ₂	45.24	44.36	45.37	44.31	44.41	45.49	43.87	45.30	45.67
TiO ₂	0.10	0.02	0.05	0.02	0.05	0.08	0.02	0.92	0.91
Cr ₂ O ₃	0.40	0.37	0.38	0.41	0.38	0.38	0.38	_	_
Al ₂ O ₃	1.21	0.94	1.90	0.94	1.51	2.94	0.55	18.11	16.39
FeO	7.98	7.77	7.40	7.84	7.70	8.34	7.08	11.53	11.38
MnO	0.12	0.12	0.12	0.12	0.12	0.12	0.10	0.23	0.22
MgO	44.55	45.27	43.32	45.59	44.56	41.11	47.59	10.10	12.36
CaO	0.23	1.08	1.24	0.71	1.17	1.46	0.29	11.29	11.23
Na ₂ O	0.10	< 0.01	0.10	< 0.01	0.05	< 0.01	0.05	2.41	1.76
K ₂ O	0.01	0.01	0.06	0.01	0.01	0.01	0.01	0.05	0.02
Trace elements (i	in ppm)								
La	0.99	0.41	0.69	0.40	0.60	1.04	0.24	31.90	15.10
Ce	1.41	0.76	1.42	0.70	1.20	1.42	0.41	50.00	24.50
Pr	0.14	0.09	0.17	0.09	0.14	0.18	0.05	5.55	2.83
Nd	0.51	0.34	0.57	0.35	0.59	0.70	0.17	22.10	11.60
Sm	0.09	0.08	0.06	0.08	0.12	0.18	< 0.05	4.44	2.81
Eu	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.06	< 0.05	1.38	1.01
Gd	0.10	0.09	0.07	0.07	0.12	0.24	< 0.05	4.27	3.05
Tb	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.05	< 0.05	0.70	0.55
Dy	0.11	0.08	0.06	0.07	0.14	0.35	< 0.05	3.91	3.31
Но	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.08	< 0.05	0.79	0.66
Er	0.07	0.05	0.06	< 0.05	0.09	0.23	< 0.05	2.41	1.99
Tm	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.32	0.27
Yb	0.06	0.05	0.08	< 0.05	0.09	0.23	< 0.05	2.21	1.86
Lu	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.34	0.27
Y	0.61	0.45	0.48	0.42	0.83	2.05	0.13	21.80	19.10
Hf	0.25	0.11	0.07	0.12	0.15	0.22	0.07	1.35	1.33
Zr	9.20	4.34	3.15	4.51	6.78	7.20	3.63	49.00	44.70
Be	0.02	0.02	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.23	0.36
Sc	7.88	7.13	9.74	7.21	8.43	13.60	5.54	42.50	37.00
Cu	24.30	7.80	12.00	5.30	13.30	12.80	3.22	33	49.60
Zn	54.70	48.50	52.90	48.70	51.50	58.70	35.00	92.70	68.20
Rb	0.30	0.24	0.33	0.47	0.53	0.28	0.23	0.80	0.82
Мо	0.33	0.47	0.19	0.40	0.25	0.09	0.11	0.17	0.17
Cd	0.06	0.07	0.08	0.05	0.07	< 0.05	0.05	0.19	0.13
In	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.08	0.06
W	0.39	0.27	0.44	0.28	0.33	0.28	0.26	0.44	0.49
TI	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Pb	2.27	2.38	3.46	2.32	2.23	3.41	2.31	3.21	12.80
Bi	0.05	0.05	0.06	< 0.05	0.05	< 0.05	0.05	0.05	0.05
Th	0.13	< 0.05	0.13	0.05	0.06	0.05	< 0.05	0.93	0.68
U	0.06	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.08	0.10
Co	184	171	171	173	172	170	175	72.60	75.20
Nb	2.35	0.26	1.29	0.35	1.25	0.38	0.20	1.81	2.61
Та	0.08	< 0.05	0.07	< 0.05	0.05	< 0.05	< 0.05	0.08	0.13
Ba	25.90	16.20	17.10	16.80	16.20	33.60	14.40	200.00	84.10
Sr	5.70	18.30	16.70	11.50	15.20	18.50	10.30	185.00	163.00
v	12.90	8.52	15.60	7.78	13.80	37.50	1.63	277.00	218.00
Ni	2271	2200	2166	2279	2192	2044	2264	115	233

Table 1.	Bulk-rock majo	r (wt%)) and trace	element (ppn) concentrations	of the H	Rongcheng	lherzolite,	dunite and	eclogite.
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^aBulk compositions of lherzolite, dunite and eclogite have been normalized to 95.95% (assuming rock contains 0.05 wt% P₂O₅ and other volatile components).

The plot of trace elements v. MgO for the Rongcheng lherzolite and meta-dunite is shown in Fig. 4. Compatible Cr, Ni, Sc and V elements tend to remain in the residual mantle after partial melting (Hofmann, 1988; Haggerty, 1995). In those samples, Ni shows a positive trend with MgO, which is typical of mantle peridotites worldwide (McDonough & Sun, 1995). However, random to negative correlations are observed for Cr, Sc and V v. MgO, possibly due to mantle metasomatism. REE patterns of the Rongcheng peridotite and eclogite are shown in Fig. 5a. The two rock types show distinct REE patterns. The analysed garnet lherzolites and meta-dunite have low (≤ 1.42 ppm) REE abundances. Meta-dunite sample MC3B shows the lowest LREE abundances among all analysed samples; middle to heavy REE concentrations are below the detection limit. Most lherzolite samples (CJ1R, 1V, 2B, 5A, 5B) show fractionated chondrite-normalized REE patterns with LREE enrichment and HREE depletion; $(La/Yb)_N$ ratios range from 5 to 12. One garnet-rich sample (CJ1Rb) shows a V-shaped REE pattern with slight HREE enrichment and the lowest $(La/Yb)_N$ ratio of 3. In a primitive mantle-normalized spider diagram (Fig. 5b), both garnet lherzolite and meta-dunite show positive anomalies in Ba, and negative anomalies in K (Table 1).

Eclogites within the garnet lherzolite (CJ2N & 4A) have high REE abundances (REE^{total} = 69.81– 130.32 ppm) (Table 1). Their chondrite-normalized REE patterns are characterized by LREE enrichments with (La/Yb)_N of 6 to 10. Eclogites exhibit high concentrations in Ba and La and negative anomalies in K,



Sr and HFSE (high-field-strength element) such as Zr, Hf and Ti as shown in Fig. 5b. Ba/Nb ratios vary from 32 to 110.

OXYGEN-ISOTOPE COMPOSITIONS

Oxygen-isotope analyses were performed using laser fluorination in the Stable Isotope Biogeochemistry Laboratory at Stanford University. Approximately 0.8–1.0 mg mineral separates were heated with a CO₂infrared laser in the presence of BrF₅ (Sharp, 1990). Oxygen gas was directly analysed using a Finnigan MAT 252 mass spectrometer, and isotopic values corrected relative to standard UWG-2 garnet (Valley *et al.*, 1995) and internal quartz standard L1 (18.15‰). Table 2 lists the analytical results on mineral separates from the two Chijiadian lherzolites (CJ3A, 3B), one Chijiadian eclogite (CJ4A) and two Macaokuang meta-dunites (MCK489, 5A). The precision of analyses is typically better than 0.2‰. The δ^{18} O values are + 5.6‰ for all lherzolitic garnet

The δ^{18} O values are +5.6‰ for all lherzolitic garnet (CJ3A, 3B). Olivine from both samples have slightly lower oxygen-isotope values (+5.2 to +5.3‰). Orthopyroxene from sample CJ3A has an isotopic composition of +6.2‰, the highest among all analysed lherzolitic minerals. Clinopyroxene from sample CJ3B has a δ^{18} O value of +5.7‰. The sequence of

decreasing ¹⁸O/¹⁶O ratio in analysed minerals is consistent with that at thermodynamic equilibrium as follows: Opx > Cpx > Grt > Ol. Zheng *et al.* (2003) estimated the O-isotope fractionations at >800 °C to be about <0.95% between Cpx and olivine, <0.45%between Cpx and garnet and <0.49% between garnet and olivine. Inter-mineral O-isotope fractionations between studied Cpx and olivine, Cpx and garnet, garnet and olivine pairs are 0.4%, 0.1% and 0.3-0.4%, respectively; such small fractionations suggest hightemperature isotopic equilibrium between these minerals. The largest fractionations from lherzolite samples are between Opx and olivine ($\Delta Opx-Ol =$ 1.0%), and between Opx and garnet (ΔOpx -Grt = 0.6%) from sample CJ3A. Two meta-dunites from the Macaokuang body (MCK489, MC5A) show consistent O-isotopic ratios for olivine (+5.3%). All the O-isotopic compositions of the analysed minerals from ultramafic rocks in the Rongcheng area fall within the range of typical mantle-derived ultramafic rocks (δ^{18} O: +5.1 to +6.6%) (Taylor, 1967) (Fig. 6). The Chijiadian eclogite sample (CJ4A) yielded the highest δ^{18} O values of 7.6% and 7.7% for garnet and omphacite, respectively. The inter-mineral fractionation is also very small, which is typical for minerals from hightemperature eclogites and garnet peridotites (Ongley et al., 1987; Deines et al., 1991; Medaris et al., 1995).



MINERAL CHEMISTRY

Mineral compositions of representative lherzolite (CJ3A, 3B) and eclogite (MC7A) samples were analysed at the Stanford University employing a JEOL superprobe 733 equipped with five wavelength-dispersive spectrometers. Operating conditions were 15 kV acceleration potential, 12 nA beam current and peak counting times of 20 s. The results are described as follows (see Table 3).

Compositions of minerals from the Chijidian Iherzolite

Olivine is chemically homogeneous Mg-rich forsterite (Fo_{91}) , and contains very little MnO (<0.14 wt%), CaO (<0.02 wt%) and TiO₂ (<0.04 wt%). Orthopyroxene is characterized by high En (En₉₂) and shows an increase in Al₂O₃ from core (0.09–0.37) to rim (0.16–0.75). Garnet has a homogeneous pyrope-rich composition (Prp₆₇Grs₁₀Alm₂₂Sps₁) (Fig. 7a). The Cr₂O₃ content is up to 2.5 wt%. Clinopyroxene is diopside (Jd₁₀), and contains considerable Cr₂O₃ (0.8–1.2 wt%) and Na₂O (1.1–1.8 wt%), but low Al₂O₃ (1.1–1.7 wt%).

Compositions of minerals from the Macaokuang eclogite

Garnet listed in the Table 3 is almandine-rich and contains considerable amounts of grossular and

pyrope components (Prp₃₅Grs₂₄Alm₄₀Sps₁) (Fig. 7a); Cr_2O_3 content is very low (<0.02 wt%). Clinopyroxene is omphacite (Jd_{26}) and has Cr_2O_3 content below the detection limit. Compositions for both eclogitic and lherzolitic clinopyroxenes are plotted in Fig. 7b; Ac content is low for all analysed clinopyroxene. In addition, unpublished compositional data of both garnet and clinopyroxene from other samples in the same locality show a large variation from grain to grain. Garnet has constant almandine, but varies in pyrope and grossular components (Alm₃₆₋₃₇Prp₂₈₋₃₇Grs₂₄₋₃₅Sps₁). Jadeite component of clinopyroxene ranges from 13 to 22 mol.%. The compositional variation and texture described above indicate that the eclogitic minerals have not yet reached equilibrium.

P-T ESTIMATES

The P-T conditions of the ultramafic rocks and eclogites studied were estimated using various geothermobarometers. The Fe-Mg exchange thermometers between Grt-Opx (Harley, 1984), Grt-Cpx (Powell, 1985; Krogh, 1988; Ravna, 2000), and Grt-Ol (O'Neill & Wood, 1979) were used to estimate temperatures. The Grt-Opx barometers (Nickel & Green, 1985; Brey & Köhler, 1990) were used for pressure calculations. For P-T estimates, Fe³⁺ of omphacite in eclogites was assumed to be equal to



 Table 2. Oxygen-isotopic compositions of minerals from the Rongcheng lherzolite, eclogite and dunite.

Sample	Rock	Mineral	δ^{18} O (SMOW)	ΔA-B	
Chijiadian maf	ic-ultramafic bod	ły			
CJ3A	Lherzolite	Grt	5.6	Grt-Ol	0.4
		Opx	6.2	Opx-Grt	0.6
		Ol	5.2	Opx-Ol	1.0
CJ3B	Lherzolite	Grt	5.6	Grt-Ol	0.3
		Срх	5.7	Cpx-Grt	0.1
		Ol	5.3	Cpx-Ol	0.4
CJ4A	Eclogite	Grt	7.6	Cpx-Grt	0.1
		Cpx	7.7		
Macaokuang n	nafic-ultramafic b	ody			
MCK489	Dunite	Ol	5.3		
MC5A	Dunite	Ol	5.3		

Fig. 5. Chondrite-normalized REE patterns (a) and primitive mantle-normalized spidergram, (b) for the Chijiadian lherzolite samples (CJ1R, 1V, 2B, 5A, 5B, 1Rb), the Macaokuang dunite sample (MC3B) and the Chijiadian eclogite samples (CJ2N, 4A) from the Rongcheng area. Normalized chondrite and primitive mantle (P.M.) values are after Sun & McDonough (1989).

Na-Al (when Na > Al) or negligible (Na < Al). Garnet in both ultramafics and eclogites, and olivine, Cpx and Opx in ultramafics were also considered to contain Fe^{2+} only.

The results of the P-T estimates based on exchange geothermobarometry are listed in Table 4. Because inclusions of coesite pseudomorphs were reported from the Rongcheng eclogite (Zhang *et al.*, 1994), the mafic–ultramafic bodies must have experienced a minimum pressure of 3.0 GPa. Thus, for Chijiadian lherzolites, the peak temperatures range from 620 to 860 °C at an assumed pressure of 3.0 GPa, and the majority is about 700–800 °C. The Powell (1985) Grt-Cpx thermometer yielded the highest temperature



Fig. 6. Oxygen isotopic compositions of garnet, olivine, orthopyroxene and clinopyroxene from type A and B garnet peridotites and associated eclogites. For comparison, δ^{18} O values of mantle rocks (Taylor, 1967) are also shown. L, lherzolite; E, eclogite; D, dunite; U, ultramafic rocks; T, transitional rocks.*This study; ¹Zhang *et al.* (2000); ²Zhang *et al.* (2005c); ³Zhang *et al.* (2005b); ⁴Zhang *et al.* (1998).

estimates, whereas the O'Neill & Wood (1979) Grt-Ol thermometer gave the lowest values. This might be due to the retrograde equilibrium between the

coexisting minerals, as the Grt-Ol thermometer is most easily affected by retrogression. Cpx core-Grt core compositions yield consistently higher temperatures (750-860 °C) than those of rim-rim pairs (690-830 °C). For the Macaokuang eclogite, the Fe-Mg partitioning between garnet and clinopyroxene listed in Table 3 yields a peak temperature range of 730-780 °C at 3 GPa, which is consistent with that of the Chijiadian lherzolites. Peak metamorphic pressures are obtained only from the Chijiadian lherzolites using Grt-Opx barometers. Pressures of 4.5-5.3 GPa were estimated for Grt core-Opx cores and 4.1-4.3 GPa were obtained for the rim-rim pairs, assuming a temperature of 800 °C. Among all reported Eurasian garnet peridotites and Kokchetav diamondbearing rocks, those in the Dabie-Sulu UHP terrane yield the highest P/T ratios: 750–950 °C and ≥ 4 – 7 GPa (Zhang et al., 1995, 2000; Liou & Zhang, 1998). The peak P-T estimates (4.5–5.3 GPa at 800 °C) for the Rongcheng mafic-ultramafic bodies lie within the P-T region for Dabie-Sulu peridotites. Therefore, the Rongcheng mafic-ultramafic bodies recrystallized at mantle depths of \sim 120–200 km under UHP conditions.

Oxygen-isotope geothermometry was not applied to temperature estimates for the studied samples because of the inherent imprecision resulting from the small O-isotope fractionation between coexisting minerals (garnet, olivine, clinopyroxene and orthopyroxene) from the eclogite and ultramafic rocks. Zhang et al. (2005c) reported large discrepancies in estimated temperatures for garnet peridotite based on O-isotope geothermometry, and attributed such discrepancies to both uncertainties in mineral analytical data and uncertainties in calibrations of fractionations v. temperature. However, the small fractionations between analysed minerals from our samples at least suggest an isotopic equilibrium at a temperature above 800 °C (Zheng et al., 2003).

SHRIMP U-PB ZIRCON DATING

Sample descriptions and analytical methods

Three adjacent Macaokuang eclogite samples (MC7A, 7B, 7C) of 1–2 kg each were treated as one sample named MCK7 for zircon separation, following a fivestep procedure as described in Zhao *et al.* (2006). Zircon separates were then mounted in epoxy, polished and coated with gold before analysis. Cathodoluminescence (CL) examination was carried out using a JEOL JSM 5600 scanning electron microscope; U-Pb analyses employed the SHRIMP-RG (sensitive high-resolution ion-microprobe reverse geometry) at the Stanford/U.S. Geological Survey Microanalytical Center at Stanford University (the details see Zhao *et al.*, 2005). Isotope ratios and single ages in Table 5 are reported with 1 σ error, but the weighted mean ages

Table 3. Representative mineral analyses of the Rongcheng lherzolite and e	clogite.
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Sample:	Lherzolite			herzolite C	J3A	A Lherzolite CJ3B								
Mineral:	Ol	Grt (core)	Grt (rim)	Cpx (core)	Cpx (rim)	Opx (core)	Opx (rim)	Ol	Grt (core)	Grt (rim)	Cpx (core)	Cpx (rim)	Opx (core)	Opx (rim)
SiO ₂	41.16	41.91	40.76	55.54	55.38	58.20	58.60	41.33	41.98	41.47	54.77	55.06	58.83	58.52
TiO ₂	0.04	0.00	0.01	0.05	0.03	0.00	0.04	0.00	0.05	0.03	0.05	0.05	0.03	0.00
Cr ₂ O ₃	0.04	1.38	1.85	0.88	0.96	0.02	0.08	0.08	2.21	2.49	1.04	0.90	0.09	0.11
Al_2O_3	0.01	22.65	21.59	1.11	1.48	0.14	0.36	0.02	21.82	20.85	1.27	1.40	0.35	0.42
FeO	9.15	11.20	11.58	2.64	2.25	5.60	5.74	8.83	11.25	11.42	2.58	2.56	5.61	6.12
MnO	0.07	0.44	0.51	0.05	0.04	0.03	0.11	0.06	0.53	0.49	0.05	0.03	0.06	0.12
MgO	49.40	19.11	18.83	16.42	16.21	35.79	35.83	49.80	18.69	17.89	16.21	16.02	35.81	35.68
CaO	0.01	4.32	4.07	21.80	22.26	0.11	0.12	0.00	3.97	4.06	21.35	21.08	0.12	0.12
Na ₂ O	0.00	0.00	0.01	1.67	1.44	0.01	0.00	0.00	0.01	0.00	1.55	1.67	0.01	0.00
Total	99.88	101.02	99.22	100.14	100.05	99.89	100.87	100.12	100.51	98.70	98.88	98.77	100.91	101.09
Si	1.01	2.99	2.97	2.01	2.00	2.00	1.99	1.01	3.01	3.04	2.01	2.01	2.00	1.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.08	0.11	0.03	0.03	0.00	0.00	0.00	0.13	0.14	0.03	0.03	0.00	0.00
Al	0.00	1.90	1.86	0.05	0.06	0.01	0.01	0.00	1.85	1.80	0.05	0.06	0.01	0.02
Fe ²⁺	0.19	0.67	0.71	0.08	0.07	0.16	0.16	0.18	0.68	0.70	0.08	0.08	0.16	0.17
Mn	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.00
Mg	1.80	2.03	2.05	0.89	0.87	1.83	1.82	1.81	2.00	1.95	0.89	0.87	1.81	1.81
Ca	0.00	0.33	0.32	0.85	0.86	0.00	0.00	0.00	0.31	0.32	0.84	0.83	0.00	0.00
Na	0.00	0.00	0.00	0.12	0.10	0.00	0.00	0.00	0.00	0.00	0.11	0.12	0.00	0.00
Total	2.99	8.02	8.04	4.01	4.00	4.00	4.00	2.99	8.00	7.99	4.01	4.00	3.99	4.00
Sample:		Eclogite	MC7A						Zircon from	MCK7				
Mineral:		Grt	Срх		Grt inc 1	Grt inc 2		Grt inc 3	Cpx inc 1		Cpx inc 2	C ir	Cpx nc 3	Cpx inc 4
5:0		40.28	55.24		20.70	20.7	1	28.52	54.00		54.57	E.	2 80	52.00
SIO ₂		40.28	55.24		39.70	39.74	+	38.32	54.00		54.56	5.	5.89	55.99
110 ₂		0.00	0.04		0.00	0.00)	0.01	0.01		0.00		0.05	0.00
Cr ₂ O ₃	22.70 7.0		0.00		22.18 21.99)	0.00	0.00		0.00		0.00	0.00
Al ₂ O ₃	22.70 7.02 19.02 3.38			22.18 21.99		,)	21.10	1.50		0.76		0.80	0.62	
FeO	0.17 0.00		3.38		1/.11 19.80) :	19.01	2.23		2.17		0.00	
Mio		0.17	11.81		1.48		0.86 1.97		16.56		16.77	1	0.00	16.75
MgO CoO		9.67	11.01		9.21	7.95	7.99		0.27 10.30		24.22	2	4.72	24.79
CaO No O		0.90	17.70		9.24	9.06		0.00	10.10 23.44		24.22		+.72	24.70
Tatal	101.03		5.94		0.00	0.00	,	0.00	0.00		0.43	0.22		0.20
rotai S:	3.00		1.00		2.02	99.43		2.02	3.03 1.09		20.24 98.35 2.00 1.00		1.00	2.00
- 51 Ti		0.00	0.00		0.00	3.0.	,)	0.00	1.95		2.00		1.99	2.00
Cr		0.00	0.00		0.00	0.00)	0.00	0.00		0.00		0.00	0.00
A1		1.00	0.00		1.00	1.00) >	1.06	0.00	,	0.00		0.00	0.00
Fe^{2+}		1.77	0.50		1.22	1.90	5	1.20	0.07	,	0.05		0.04	0.03
Mn		0.01	0.10		0.10	0.04	5	0.13	0.07		0.07		0.05	0.00
Ma		1.10	0.00		1.04	0.00	,	0.15	0.00	,	0.00		0.00	0.00
Ca		0.72	0.04		0.75	0.91	1	0.85	0.91		0.92		0.95 N 98	0.92
Na		0.00	0.09		0.00	0.7-		0.00	0.92		0.03		0.20	0.90
Total		8.00	3 00		7 99	7.00	, }	7 90	1.00		4.00		4.00	4.00
iotai		3.00	5.99		1.77	7.90	,	1.77	4.00	,	7.00		1.00	ч.00



Fig. 7. Compositions of garnet (a) and clinopyroxene (b) from matrix of the Chijiadian Iherzolite (CJ3A, 3B), and both matrix and zircon inclusions of the Macaokuang eclogite (MC7A, MCK7). Unpublished composition data of both garnet and clinopyroxene from Macaokuang eclogites are also plotted. CJ, Chijiadian; MC, Macaokuang.

							$T \circ C$	at $P = 30$ kbar			
Locality	Rock type	Sar	nple	Grt-Opx (Harley, 1984)	Grt-Cpx core (Powell, 1985)	Grt-Cpx rim (Powell, 1985)	Grt-Cpx core (Krogh, 1988)	Grt-Cpx rim (Krogh, 1988)	Grt-Cpx core (Ravna, 2000)	Grt-Cpx rim (Ravna, 2000)	Grt-Ol (O'Neill & Wood, 1979)
Chijiadian Chijiadian Macaokuang Macaokuang	Lherzolite Lherzolite Eclogite Eclogite	CJ3A CJ3B MC7A MCK7	Matrix Matrix Matrix Zrc Inc.	726 (core pair) 719 (core pair)	860 839 782 624 ^a	787 826	784 756 768 602ª	703 746	768 747 726 571ª	691 733	669 616
				P kbs	ur at $T=800$ °C						
Locality	Rock type	San	nple	Grt-C	Dpx core (Nickel & Green	, 1985) Grt-C	bpx rim (Nickel & Green,	1985) Grt-Op	x core (Brey & Köhler, 1	990) Grt-Opx	im (Brey & Köhler, 1990)
Chijiadian Chijiadian	Lherzolite Lherzolite	CI3 CI3	3A M BB M	latrix 50 atrix 46			43 43		53 45		43 41
^a Temperature es	timates are obta	ined from r	nineral inclusion	ons in zircon from t	he Macaokuang eclogite.						

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are quoted at 2σ . Zircon inclusions were analysed at Stanford University employing a JEOL superprobe 733.

Results

Zircon from the Macaokuang eclogite is rounded to subhedral, equant, 50–60 μ m grains. They show a dark, homogeneous CL image, without zoning (Fig. 8a). In addition to rare quartz and titanite, four garnet and more than 10 clinopyroxene inclusions were found in these zircon (Fig. 8b), and representative analyses of garnet and clinopyroxene are listed in Table 3. Garnet inclusions show clear variations in content of MgO (9.06–11.03 wt%). CaO (6.29–9.21 wt%) and MnO (0.37-1.97 wt%) and, therefore in pyrope and grossular components ($Prp_{25-35}Grs_{25-31}Alm_{37-43}Sps_{1-4}$). The compositional variation is similar to those of matrix garnet except for higher average MnO content (1.17 wt%); such higher MnO content in inclusion garnet suggests its earlier crystallization than matrix garnet. Clinopyroxene inclusions in zircon are diopside (Jd_{25}) , whereas the clinopyroxenes in the matrix contain much higher Jd component (Jd_{13-26}). Cr₂O₃ (below detection limit) contents are very low in both garnet and clinopyroxene inclusions; Al₂O₃ (0.62–1.56 wt%) are low in clinopyroxene (Table 3, Fig. 7).

The SHRIMP U-Pb zircon ages from the Macaokuang eclogite are summarized in Table 5. Because the grains are only 50–60 μ m in size and show homogeneous CL patterns, only one spot analysis was conducted for each grain. Among analyses on 14 grains, most yielded low U contents of 13-50 ppm and Th contents of 3-95 ppm. Three analysed grains are relatively less luminescent in CL image, and contain higher U (116-214 ppm) and Th (129–184 ppm) concentrations. Th/U ratios are also variable, ranging from 0.28 to 3.47. Nine analyses yielded high Th/U ratios from 1.14 to 3.47, not consistent with the typical low Th/U ratio of the metamorphic zircon (Rubatto & Gebauer, 2000; Hokada et al., 2004). The 14 analyses cluster on the concordia on a Tera-Wasserburg (TW) diagram; most data lie on or close to the concordia curve (Fig. 9). The ²⁰⁷Pb-corrected ²⁰⁶Pb/²³⁸U age for each analysis ranges from 233 to 220 Ma; the weighted mean 206 Pb/ 238 U age is 225 ± 2 Ma (n = 14; MSWD = 1.09).

DISCUSSION

Dabie-Sulu garnet peridotites have been classified into two distinct types based on the mode of occurrence and petrochemical characteristics (Zhang *et al.*, 2000). Type A peridotites are considered to have been derived from the mantle wedge and were emplaced into the subducting slab. Based on bulk-rock major, trace and REE concentrations (e.g. Zhang *et al.*, in review), most type A protoliths appear to be depleted mantle rocks that were subjected to some degree of partial melting and metasomatism in the upper mantle. Type B crustal

Table 4. *P-T* conditions for peak metamorphism for the Rongcheng lherzolite and eclogite.

Spot name	U (ppm)	Th (ppm)	Th/U	Common 206Pb (%)	Uncorrected ²³⁸ U/ ²⁰⁶ Pb	Uncorrected ²⁰⁷ Pb/ ²⁰⁶ Pb	$^{206} Pb^{a} / ^{238} U$	²⁰⁶ Pb ^a / ²³⁸ U Age (Ma)
MC-1	30	48	1.66	0	28.3282 ± 2.4640	0.0493 ± 8.1876	0.0354 ± 0.0009	224 ± 6
MC-2	13	3	0.28	0	27.2831 ± 3.0520	0.0469 ± 12.1711	0.0368 ± 0.0012	233 ± 7
MC-5	214	156	0.75	0.27	28.0410 ± 0.7738	0.0528 ± 3.0131	0.0356 ± 0.0003	225 ± 2
MC-6	46	73	1.62	0	28.0292 ± 1.6114	0.0503 ± 6.4292	0.0357 ± 0.0006	226 ± 4
MC-8	116	129	1.14	0.02	27.6578 ± 1.0406	0.0509 ± 4.0784	0.0361 ± 0.0004	229 ± 2
MC-9	50	95	1.97	0	28.2295 ± 1.5844	0.0502 ± 6.2055	0.0354 ± 0.0006	225 ± 4
MC-11	35	68	1.99	0.74	28.4384 ± 1.9067	0.0565 ± 7.1774	$0.0349~\pm~0.0007$	221 ± 4
MC-12	45	32	0.73	0.33	28.7285 ± 1.7104	0.0531 ± 6.7470	0.0347 ± 0.0006	220 ± 4
MC-13	18	16	0.88	1.16	28.1032 ± 2.6703	0.0599 ± 9.8164	0.0352 ± 0.0010	223 ± 6
MC-16	32	44	1.41	0.25	27.4059 ± 1.9168	0.0528 ± 7.7303	0.0364 ± 0.0007	231 ± 5
MC-18	118	184	1.61	0.17	28.7143 ± 1.0760	0.0519 ± 4.2268	0.0348 ± 0.0004	220 ± 2
MC-23	42	49	1.20	0	27.6172 ± 1.7297	0.0507 ± 11.3236	0.0362 ± 0.0007	229 ± 4
MC-25	17	58	3.47	0.12	28.0930 ± 2.7824	0.0516 ± 11.5486	0.0356 ± 0.0010	225 ± 6
MC-26	44	72	1.70	0.07	28.7075 ± 1.7553	$0.0511\ \pm\ 6.9302$	$0.0348~\pm~0.0006$	$221~\pm~4$

Table 5. U-Th-Pb SHRIMP zircon data from the Macaokuang eclogite (MCK7) from the Rongcheng area.

^aPb corrected for common Pb using ²⁰⁷Pb (Williams, 1998). All errors are 1σ of standard deviation.



Fig. 8. (a) Cathodoluminescence (CL) images of zircon from the Macaokuang eclogite sample (MCK7). (b) BSE images of zircon from the same sample showing inclusions of garnet and clinopyroxene. Scale bars are 30 μ m.

peridotites are mafic–ultramafic complexes intruded into the continental crust prior to subduction, and thus have been contaminated by crustal rocks. Based on our petrochemistry, stable isotope ratios and geochronology, several questions regarding the origin, P-T constraints and timing of the UHP metamorphism of the Rongcheng mafic–ultramafic bodies are discussed below.

Origin of the Rongcheng garnet lherzolite and meta-dunite

Rongcheng garnet lherzolite and meta-dunite display overall depleted bulk-rock compositions characterized by relatively higher MgO contents when compared with primitive mantle (Ringwood, 1975) coupled with low concentrations in 'fertile elements' (Al, Ca & Ti). Positive correlations between trace element Ni and



Fig. 9. Tera-Wasserburg (TW) diagram showing SHRIMP U-Pb analyses of zircon from the Macaokuang eclogite sample (MCK7). Uncorrected ratios are plotted. Error ellipses are show as 1σ , whereas the uncertainty of the weighted mean age is 2σ . MSWD, mean square of weighted deviates.

MgO contents, and low total REE concentrations relative to primary mantle also suggest that they originated from a depleted mantle source. The meta-dunite is more depleted than garnet lherzolite. This depletion may have resulted from partial melting during evolution of the mantle before Triassic collision. The oxygen isotopic compositions of garnet, olivine, orthopyroxene and clinopyroxene from the Chijiadian lherzolite and Macaokuang meta-dunite (CJ3A, CJ3B, MCK489, MC5A) range from + 5.2 to + 6.2‰, which is consistent with the mantle values (δ^{18} O: + 5.1 to + 6.6‰) reported by Taylor (1967).

These rocks may have experienced metasomatism that modified their major- and trace-element compositions. For example, two slightly depleted lherzolites show higher FeO contents than primitive mantle, indicating that they may have been refertilized by interaction with FeO-rich basaltic melt. Moreover, the Rongcheng lherzolite and meta-dunite exhibit a slight LREE enrichment and slightly to moderately fractionated REE patterns (Fig. 5a). Typical depleted peridotites would show LREE depletion instead, because LREE behave as highly incompatible elements during partial melting, and would be less concentrated in the residual mantle. The negative correlations for Sc and V v. MgO content (Fig. 4) also suggest that Rongcheng lherzolite and meta-dunite may represent mantle modified by metasomatic processes. These metasomatic effects may be due to the infiltration of melts derived from the asthenosphere (Griffin *et al.*, 1999) or partial melting of the subducted slab (Sen & Dunn, 1994). On the other hand, the Rongcheng lherzolite and meta-dunite lack hydrous phases (phlogopite) and HFSE-bearing minerals (Ti-clinohumite), as reported from other metasomatic peridotites (Zhang *et al.*, 2005a). Therefore, they are considered to have experienced cryptic metasomatism (Dawson, 1984) which only results in the variations of major- or trace-element compositions.

The Rongcheng lherzolite and meta-dunite should be classified as type A mantle-derived peridotites based on geochemical and stable isotopic characteristics. The REE patterns of the Rongcheng lherzolite are similar to other Sulu type A peridotites with slight HREE depletion and LREE enrichment. Most Sulu peridotites are interpreted to have originated from depleted mantle, and were subjected to metasomatism at mantle wedge or in subducted continental slab (Zhang et al., 2000, 2007). Furthermore, O-isotopic ratios are an important indicator to distinguish type A mantle-derived peridotite from type B crustal peridotite (Zhang et al., 2000). Type A peridotites from Rizhao, Donghai, the CCSD-PP1 drill hole and Yangkou in the Sulu terrane preserve typical mantle isotopic compositions of 4.4 - 5.6%(Zhang et al., 2000, 2005b,c). The δ^{18} O values from our Rongcheng ultramafic samples overlap with those from type A peridotites from those areas (Fig. 6). On the other hand, type B peridotites from Dabie have low δ^{18} O values (e.g. 2.9-4.5%; most <4%) compared with unaltered mantle rocks (Zhang et al., 1998, 2000). Such type B peridotites have been subjected to rock-meteoric water interactions at crustal levels prior to the Triassic UHP metamorphism (Zhang et al., 2000).

Origin of the Rongcheng eclogite

Eclogite occurs as small lenses within mantle-derived lherzolite and meta-dunite. The protoliths of two Chijiadian eclogite samples (CJ2N, 4A) having Ba/Nb ratios of 32–110 are unlike oceanic basalts (most ≤ 20) and island arc volcanic rocks (average ~ 200), although some chemical data (such as negative Zr and Ti anomalies) seem to be a signature of magma emplaced in island arc or continental crust (Jahn, 1998). Moreover, previous Nd-Sr isotopic data [ϵ Nd(t) \approx -5 for a Chijiadian eclogite and associated lherzolite] indicated that the rocks were probably derived from long-term enriched mantle segments or was subjected to crustal contamination (Jahn, 1998). If the eclogite has not been subjected to extensive metasomatism which caused significant change of REE concentration, La, Sm and Lu contents can be employed to differentiate eclogites formed by melts derived from partial melting of peridotite, from those formed by cumulates (\pm trapped melt) that precipitate from such melts (Ottonello et al., 1984). The chondrite-normalized (Sun & McDonough, 1989) La:Sm:Lu ratios of Rongcheng eclogite samples CJ2N and CJ4A are 76:16:8 and 69:20:11, respectively, corresponding to calculated melts that were formed by various degrees (0.005-0.05) of partial melting of peridotite (Beard et al., 1992). Sample CJ4A lies close to the liquid composition from the partial melting of spinel peridotite, therefore the Chijiadian eclogite could have formed by partial melting of spinel peridotite instead of garnet peridotite. A similar result has been reported for an eclogite collected from the same outcrops (Zhang et al., 1994).

The Chijiadian eclogite sample CJ4A shows the highest δ^{18} O values for garnet (7.6%) and omphacite (7.7%). These values are slightly higher, but still consistent with the isotopic compositions (+5.5 to)+7.5%) of pristine mantle-derived basalts that have been the protoliths of these eclogites (Ito et al., 1987; Harmon & Hoefs, 1995). However, the Chijidian eclogite is enclosed within the host garnet lherzolite, so they should share the same origin and should not show such a difference in O-isotope ratios. Several high δ^{18} O values were also reported from other eclogites associated with peridotites. An eclogite from Maowu shows high δ^{18} O values of +8.1% for garnet and +9.4% for omphacite (Zheng *et al.*, 1999). Fu *et al.* (2003) reported even higher δ^{18} O values of +11.0% for garnet and +11.4% for omphacite from an eclogite hosted by ultramafic rocks in Houshuichegou from Rizhao. Why such eclogites show higher δ^{18} O values than the host peridotites is unknown, and may require more O-isotope analyses on the eclogites associated with ultramafic rocks.

The Chijiadian eclogite shows a different O-isotopic signature than eclogites enclosed within the country rock gneiss. Most garnet and omphacite from Dabie-Sulu eclogites in quartzofeldspathic gneiss range in δ^{18} O values from +0.1% to +5.8% (Fu *et al.*, 2003). Extremely low δ^{18} O values (-9.2 to -10.4%) were also reported from eclogite interlayered with quartzite from Qinglongshan (Yui *et al.*, 1995; Zheng *et al.*, 1996). These low δ^{18} O values may reflect hydrothermal

alteration of these basaltic rocks by meteoric waters during the Snowball Earth episode prior to the Triassic subduction. The Chijiadian eclogite, on the other hand, preserved the mantle O-isotope signature, and thus was derived from the mantle before Triassic emplacement into the subducting slab.

Timing of UHP metamorphism

Because of their low Zr and Si contents, most ultramafic rocks lack zircon. We suggest that the eclogitic zircon in these rocks grew mainly during recrystallization related to UHP metamorphism. During continental collision, zircon may have formed from a metasomatic fluid derived either from the subducting slab or from the mantle. The LREE-enriched whole-rock peridotite REE patterns suggest that the metasomatic fluid was also enriched in LREE in addition to Zr. The formation of zircon in hydrous-phase bearing peridotites from the CCSD-PP1 drill hole was also attributed to metasomatism (Zhang *et al.*, 2005a).

All zircon grains from the Macaokuang eclogite (MCK7) are isometric and rounded with a homogeneous CL pattern. Their morphology and lack of inherited igneous cores suggest a metamorphic origin (Vavra *et al.*, 1999). Their Th/U ratios are higher than those of the typical metamorphic zircon (Hokada *et al.*, 2004). Most zircon from Macaokuang eclogite has high Th/U ratios of 0.73–3.47 (Fig. 10), which may be related to their host rock having high Th/U ratio. In addition, the rapid kinetics and chemically less selective continuous growth mechanism, make the Th/U ratios in the crystal more similar to that of the environment where the Th/U ratio is commonly greater than 1 (Faure, 1986).

The growth of zircon may take a long period; inclusion assemblages in zircon provide important information of the crystallization history of zircon and the ages of various evolution stages (e.g. Rubatto & Hermann, 2003; Liu et al., 2004c). Garnet and clinopyroxene are the most common inclusions in zircon and show compositional variation. Garnet inclusions with higher MnO content and clinopyroxene inclusions with lower jadeite content than those in the matrix suggest low pressures. The zircon may have formed at lower P-T than the peak metamorphism of the Macaokuang eclogites. No low-pressure retrograde minerals are present as inclusions in zircon. Therefore, these zircon may have formed during the prograde period just before the peak UHP conditions, probably during the initial incorporation of the ultramafic body into the subducting slab. The eclogite later experienced prograde subduction-zone metamorphism as seen from the transformation of diopsidic clinopyroxene inclusions in zircon to the omphacitic clinopyroxene in the matrix from the Macaokuang eclogite. The age of 225 \pm 2 Ma is thus considered to constrain the prograde metamorphic age of this eclogite.



Fig. 10. U and Th concentrations (a) and Th/U ratio v. ²⁰⁶Pb/²³⁸U age of zircon (b) from the Macaokuang eclogite sample (MCK7).

However, this age of 225 ± 2 Ma for prograde metamorphism is in the middle of the well-established range (240-220 Ma) for UHP ages from the Sulu terrane (Li et al., 1993, 1994; Ames et al., 1996; Yang et al., 2003: Liu et al., 2004b.c. 2005: Zheng et al., 2004), and is lesser than some reported UHP ages from this terrane. An alterative interpretation of zircon crystallization and its age is given below. Garnet as a metamorphic mineral enclosed in zircon exhibits distinct variation (Prp₂₅₋₃₅Grs₂₅₋₃₁Alm₃₇₋₄₃Sps₁₋₄). Most garnet were formed from metamorphic reaction between plagioclase and pyroxene of gabbroic rocks; garnet adjacent to plagioclase and pyroxene are rich in grossular and pyrope (+almandine) components, respectively, before they equilibrated. The variation in composition is similar to that of some matrix garnet apart from the high MnO content, but Cpx inclusions are quite different from matrix Cpx in jadeite component, suggesting that Cpx and garnet do not represent a prograde, equilibrium assemblage. Most samples from this area contain garnet and Cpx, as both may have not yet reached equilibrium at eclogite facies P-T conditions because of the lack of fluid and fast subduction and exhumation; only a few samples are composed of Grt + Omp with a low jadeite component. A similar example is the Yangkou eclogite enclosed within gneiss, which displays a transition sequence in a block of ~ 30 m from metagabbro in the centre through a transitional rock to coesite eclogite at the margin (Zhang & Liou, 1997). The Macaokuang zircon began to grow during prograde metamorphism, and continued to recrystallize until the P-T conditions of UHP metamorphism were attained. The U-Pb age of the Macaokuang eclogite may represent the UHP metamorphic event of the Sulu terrane, although we cannot differentiate whether this age is slightly prior to the UHP, or the age of UHP metamorphism. The Macaokuang eclogites within the mantle-derived dunite preserve transitional textures and compositions from gabbroic to eclogitic rocks, and they have subsequently experienced subduction-zone recrystallization. During a prolonged eclogite-facies metamorphism and continuous subduction, zircon may have grown at different times during its protracted residence at eclogite facies conditions. This suggestion is consistent with the growing number of reports for long eclogite facies residence times reported in other UHP terranes (Lapen *et al.*, 2003; Kylander-Clark *et al.*, 2005; McClelland *et al.*, 2006). However, further investigations will be necessary to validate such a suggestion.

CONCLUSIONS

The Rongcheng lherzolite and meta-dunite show depleted mantle signatures characterized by high MgO contents, low fertile element concentrations and total REE contents, and mantle O-isotope compositions (δ^{18} O: +5.2 to +6.2‰). However, high FeO contents, slightly LREE-enriched patterns and trace-element contents indicate that they may have been modified by weak metasomatism because of infiltration of melts (± fluid).

The Chijiadian lherzolites were subjected to subduction zone UHP metamorphism at 4.5–5.3 GPa, at a temperature of 800 °C. Eclogite within the Chijiadian lherzolite also exhibits mantle O-isotope ratios, and was formed by melts derived from varying degrees (0.005– 0.05) of partial melting of peridotite.

The Macaokuang eclogite preserves locally relict transitional texture and mineral composition from gabbroic rock to eclogite, which may be attributed to rapid subduction and exhumation of continental slab and/or lack of fluid during the processes. The U-Pb age of 225 ± 2 Ma from the Macaokuang eclogite may represent either the prograde metamorphism just before peak UHP metamorphism or the UHP metamorphic event of the Sulu terrane.

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