

Geochemistry of eclogites from the Dabie–Sulu terrane, eastern China: New insights into protoliths and trace element behaviour during UHP metamorphism

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Abstract

The major and trace element compositions of nine eclogites from the Dabie–Sulu ultrahigh pressure (UHP) metamorphic terrane in eastern China were determined for both whole rock and the main constituent minerals, garnet and clinopyroxene. The results indicate that the eclogite protoliths originated from a basaltic magma, which formed in a continental setting as shown by isotopic and immobile element data. Based on the garnet REE characteristics, the eclogites can be roughly divided into two groups. Group 1 has LREE enrichment with no Eu anomaly for whole rock, and smooth LREE depletion but HREE enrichment pattern for garnet, whereas group 2 shows a depletion of LREE with a pronounced positive Eu anomaly and flat HREE pattern for both whole rock and garnet. From these features, we suggest that the protoliths for group 2 are Fe–Ti–gabbros with relatively high cumulus plagioclase and Fe–Ti oxide, whereas the group 1 eclogites are probably from basalts. Therefore, the unusual garnet REE pattern observed in group 2 can be considered as an important signature for identifying gabbro protoliths for eclogites. The identification of gabbro protoliths from the eclogites in the Dabie–Sulu terrane provides evidence for Neoproterozoic rift magmatism in the northern margin of the Yangtze craton. During ultrahigh pressure metamorphism in the Dabie–Sulu terrane, LILEs (including Ba, Rb, Th, U, K) had high mobility, but REEs and HFSEs were immobile, and trace element distribution equilibrium was approached between garnet and clinopyroxene. An estimate of mass balance indicates that garnet and clinopyroxene host the majority of HREEs and Y, and clinopyroxene is a significant host for Sr, but minor and accessory minerals predominantly account for LREEs, Th, U, and Zr.

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1. Introduction

Eclogites are biminerale rocks with a mineral assemblage of garnet and clinopyroxene. They are generally formed under high or ultrahigh pressure

(UHP) conditions created by a specific geological process. A large number of experimental and field-based investigations have shown that subduction and subsequent collision between blocks is the most important among these processes (Wyllie, 1982; Liou et al., 1996; Becker et al., 2000; Hermann, 2002; Spandler et al., 2004). Thus, eclogites have particular geodynamic significance for exploring circulation and interaction of materials between tectonic blocks. In order to show the

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origin and process of UHP metamorphism, we need to firstly determine the nature of the eclogite protolith. Numerous studies have demonstrated that trace element, in particular rare earth element (REE), investigation is a crucial approach for this issue. At an earlier stage, trace element data were mainly obtained by dissolution for whole rocks and mineral separates. With the development of analytical techniques, in situ trace element procedures are now proving to be a more effective method to explore the protolith nature of eclogites, especially for those with alteration produced by retrograde metamorphism, metasomatism, partial melting. Recent studies on some xenolithic eclogites (e.g. Barth et al., 2001, 2002; Jacob et al., 2003) have provided useful results. Another issue closely related to eclogites is trace element behaviour during high or ultrahigh pressure metamorphism such as mobility, distribution and redistribution among phases (Shatsky et al., 1990 and references therein; O'Reilly and Griffin, 1995; Tribuzio et al., 1996; Harte and Kirkley, 1997; Becker et al., 2000; Sassi et al., 2000).

The Dabie–Sulu terrane in eastern China is known to contain the largest distribution of UHP metamorphic rocks in the world (Chavagnac et al., 2001). It has

become an important region for studying UHP metamorphism since the discovery of coesite and microdiamond inclusions in eclogites occurring there (Okay et al., 1989; Wang et al., 1989; Xu et al., 1992). Over the last fifteen years, a number of studies have been carried out on the geology, petrology, mineralogy, and geochemistry of the eclogites and their associated rocks. The results have allowed great progress to be made in understanding the geodynamic and geochemical processes of subduction and the resultant collision between Sino-Korean and Yangtze cratons. Several genetic models have been developed (e.g. Liou et al., 1996; Zheng et al., 2003). However, the trace element compositions of the eclogites and their constituent minerals are not well documented, and thus their protoliths remain controversial. It is now widely accepted that the eclogites occurring in the Dabie–Sulu terrane can be divided into three types based on their occurrence and host rocks, i.e., Type I eclogites occurring as enclaves or layers in granitic orthogneisses, Type II as enclaves in or interlayered with marbles, and Type III as enclaves and interlayers with ultramafic rocks. With only whole rock trace element data, Zhai

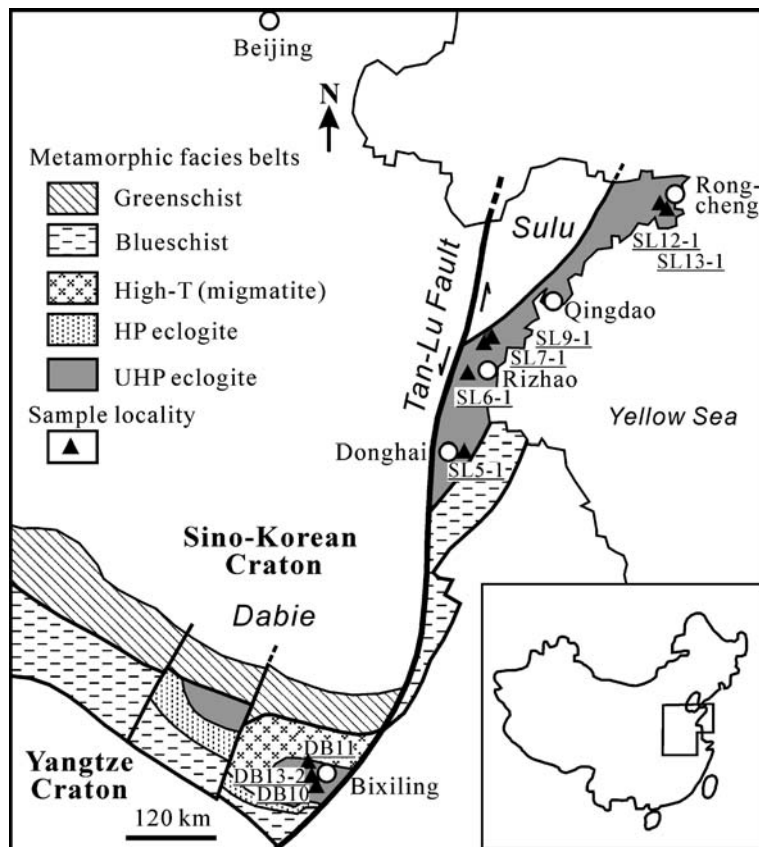


Fig. 1. Geological sketch map of the Dabie–Sulu UHP metamorphic terrane (simplified after Liou et al., 1996) with sample localities.

and Cong (1996) inferred that the eclogite protoliths have multiple origins. For example, continental or island arc tholeiites for Type I, N-MORB for some Type II, and pyroxenitic or gabbroic cumulates for Type III eclogites. Nevertheless, according to whole rock geochemical compositions and Sr–Nd isotope characteristics, Jahn (1998) concluded that all the eclogites in the Dabie–

Sulu terrane have continental affinity, and pointed out that the protoliths of Type I and II eclogites are basalts or gabbros, and the protoliths of Type III eclogites are possibly layered intrusions or cumulate rocks derived from subcontinental lithospheric mantle. Previous studies that focused only on whole rocks have different conclusions, and in particular could not distinguish

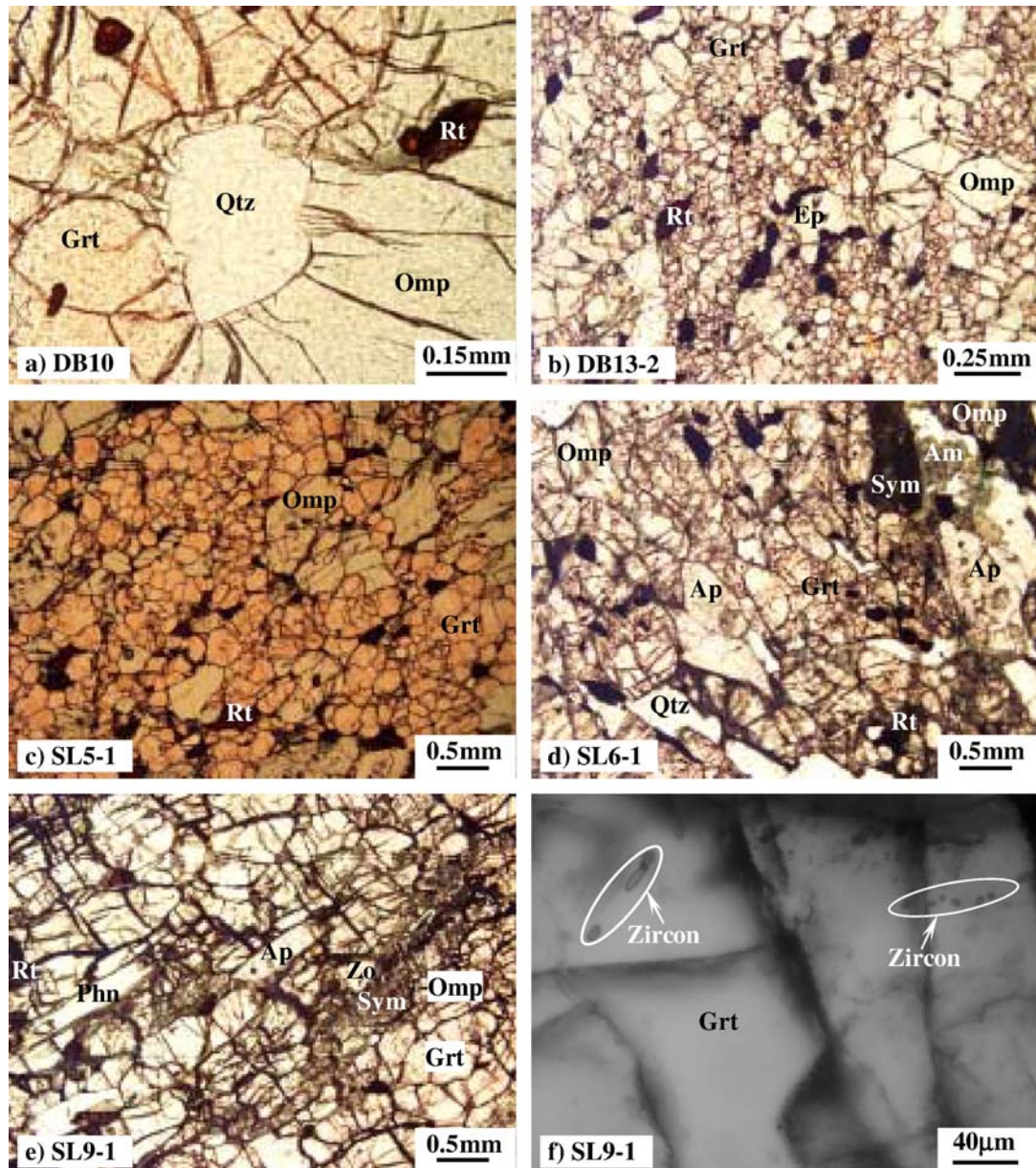


Fig. 2. a–f Photomicrographs under plane light for some studied eclogites showing their mineral and texture features: (a) Polycrystalline quartz after coesite inclusion in omphacite with radial fractures; (b) Fine-grained eclogite with Grt+Omp+Rt+Ep primary assemblage; (c) Fine-grained eclogite with a primary assemblage of Grt+Omp+Rt; (d) Apatite and amphibole development as primary and secondary phase, respectively, in eclogite, and very fine-grained symplectites of diopside+plagioclase+amphibole after omphacite; (e) Eclogite with plagioclase+amphibole symplectites around omphacite grains; (f) Tiny zircon crystals as an accessory phase in garnet; mineral abbreviations as in Table 1.

Table 1

Peak metamorphic condition, mineral assemblage, host rock and eclogite type, and protolith age for analysed samples

Sample	Locality	Peak metamorphic condition	Mineral assemblage (modal abundance)	Host rock (type [§])	Protolith age [£]
DB10	Wumiao	744–778 °C, 29–41 kbar (Wang et al., 1992)	Grt(40), Omp(45), Rt(5), Qtz(4), (Zo, Ap)	Gneiss (I)	685±64 Ma
DB11	Bixiling	610–700 °C, >27 kbar (Zhang et al., 1995c)	Grt(48), Omp(45), Rt(2), Qtz(2), Phn(2)	Ultramafic rock (III)	657–757 Ma
DB13-2	Bixiling	610–700 °C, >27 kbar (Zhang et al., 1995c)	Grt(52), Omp(40), Rt(2), (Qtz, Ep, Ky)	Ultramafic rock (III)	657–757 Ma
SL5-1	Donghai	720–880 °C (Zhang et al., 1995b); 754–893 °C (Rumble and Yui, 1998)	Grt(55), Omp(35), Rt(4), Qtz(2), (Phn, Ky)	Gneiss (I)	762±28 Ma
SL6-1	Rizhao	630–810 °C, 30 kbar (Zhang et al., 1995b)	Grt(40), Omp(35), Sym(10), Rt(2), Qtz(5), Ap(3), Zo(2), (Amp*)	Gneiss (I)	
SL7-1	Zhucheng	690–820 °C, 30 kbar (Ye, 1993)	Grt(60), Omp(28), Qtz(5), Amp*(2), (Rt, Ap, Ky, Ep*)	Gneiss (I)	788±10 Ma
SL9-1	Zhucheng	690–820 °C, 30 kbar (Ye, 1993)	Grt(40), Omp(30), Sym(20), Phn(3), Ap(2), (Rt, Zo, Ky)	Gneiss (I)	788±10 Ma
SL12-1	Datuan, Rongcheng	800 °C, 34 kbar (Nakamura and Banno, 1997)	Grt(60), Omp(25), Sym(10), Qtz(2), Amp*(2), (Rt)	Ultramafic rock (III)	
SL13-1	Tengjia, Rongcheng	791 °C (Ye and Xu, 1992); ~800 °C (Chu et al., 2003)	Grt(60), Omp(25), Sym(5), Qtz(2), Mag(2), Ky(2), Ap(2), (Rt, Zo)	Gneiss (I)	747±13 Ma

Weight percent estimated by combination of point counting under microscope, results from X-ray powder diffraction, and major element compositions of whole rock and minerals garnet and clinopyroxene. Minerals in parentheses occur in small amount, about 1% or less. Grt=garnet, Omp=omphacite, Rt=rutile, Qtz=quartz, Zo=zoisite, Ap=apatite, Phn=phengite, Ep=epidote, Ky=kyanite, Sym=symplectite (amphibole+plagioclase ± diopside after omphacite), Amp=Amphibole, Mag=magnetite. Mineral abbreviations with asterisk indicate the secondary phases.

[§]Following the same classified method as Zhai and Cong (1996) and Jahn (1998), which has been widely accepted.

[£]Protolith age for the eclogite at each locality is from Zheng et al. (2003) and references therein.

Table 2

LA-ICP-MS operating conditions

ICP-MS instrument:

VG Elemental Plasma Quad 3

Laser ablation:

Laser	UV 266 nm (Nd-YAG-Laser)
Mode	Q-switched pulse
Power	0.2 mJ/shot
Crater size	70 µm
Repetition rate	10 Hz
Pre-ablation	5 s
Focus condition	Focus on sample surface

ICP-MS:

Forward power	1350 W	
Lens	VG Chicane Lens	
Gas flow rate	Cool	13.5–14.0 l/min
	Auxiliary	0.8–0.9 l/min
	Nebulizer	1.0–1.1 l/min
Expansion pump	S-option	
Scanning mode	Peak jump	
Integration time	30 s	
Tuning	¹³⁹ La	
Monitor isotopes	⁸⁵ Rb, ⁸⁸ Sr, ⁸⁹ Y, ⁹⁰ Zr, ⁹³ Nb, ¹³⁷ Ba, ¹³⁹ La, ¹⁴⁰ Ce, ¹⁴¹ Pr, ¹⁴⁶ Nd, ¹⁴⁷ Sm, ¹⁵¹ Eu, ¹⁵⁷ Gd, ¹⁵⁹ Tb, ¹⁶² Dy, ¹⁶⁵ Ho, ¹⁶⁶ Er, ¹⁶⁹ Tm, ¹⁷⁴ Yb, ¹⁷⁵ Lu, ¹⁷⁸ Hf, ¹⁸¹ Ta, ¹⁸² W, ²⁰⁸ Pb, ²³² Th, ²³⁸ U	
Standard	NIST SRM 610	

between basalts and gabbros. Sassi et al. (2000) reported trace element data for constituent minerals in a few eclogite samples collected from the Dabie area, and they emphasized the trace element distributions in the context of basaltic mineral assemblages during the UHP metamorphism.

In this paper, new major and trace element data are presented on both main minerals (garnet and clinopyroxene) and whole rocks of UHP eclogites from a wide area of the Dabie–Sulu terrane. These data provide new insights into the protolith nature for these eclogites. Interestingly, our results show that some samples have

Table 3
Major and trace element compositions of analysed eclogites from the Dabie–Sulu terrane

	DB10	DB11	DB13-2	SL5-1	SL6-1	SL7-1	SL9-1	SL12-1	SL13-1
<i>Major element (in wt.%)</i>									
SiO ₂	43.78	44.57	42.69	43.43	44.82	45.20	46.48	44.60	43.69
TiO ₂	5.03	2.28	2.59	4.07	2.46	1.83	1.96	1.95	1.80
Al ₂ O ₃	13.23	15.36	13.67	14.07	14.36	16.12	16.63	15.84	16.00
Fe ₂ O ₃ *	17.56	16.63	19.13	20.34	16.94	17.71	15.44	17.76	18.78
MnO	0.24	0.23	0.22	0.31	0.31	0.21	0.27	0.25	0.26
MgO	6.96	7.72	7.82	5.59	6.46	6.32	5.33	6.43	7.24
CaO	11.15	10.82	9.91	9.80	10.55	11.49	9.19	11.96	10.85
Na ₂ O	1.65	2.96	2.29	2.96	2.34	1.38	3.74	2.31	2.22
K ₂ O	0.06	0.10	0.07	0.03	0.05	0.03	0.50	0.05	0.04
P ₂ O ₅	0.16	0.02	0.07	0.02	0.70	0.21	0.51	0.03	0.41
LOI	0.66	0.03	0.58	0.21	0.07	−0.80	0.78	−0.74	0.10
Total	100.48	100.72	99.04	100.83	99.06	99.70	100.83	100.44	101.39
<i>Trace element (in ppm)</i>									
Sc	45.8	35.3	49.6	55.9	46.3	37.0	35.9	50.6	47.1
V	562	450	698	455	379	444	367	441	463
Cr	178	298	134	53.3	158	94.2	102	122	87.4
Co	50.8	56.5	100	46.3	39.1	54.7	36.2	54.5	48.6
Ni	87.7	134	105	28.1	72.0	40.7	43.2	63.5	39.4
Rb	4.77	2.15	2.00	1.21	0.72	1.16	9.67	0.96	0.30
Sr	103	102	60.8	46.3	127	136	133	74.8	124
Y	10.4	13.4	10.1	14.8	37.8	14.1	33.3	11.6	27.0
Zr	24.5	38.3	12.6	12.1	32.3	32.7	225	18.6	34.5
Nb	5.63	4.05	0.68	4.13	2.96	2.61	7.41	14.2	6.73
Cs	1.32	0.60	0.87	9.77	1.70	0.82	1.44	2.04	3.78
Ba	3.93	43.4	74.3	9.27	34.6	40.0	244	24.7	9.29
Hf	0.82	1.04	0.42	0.42	1.04	1.01	4.60	0.61	1.41
Ta	0.52	0.32	0.05	0.16	0.18	0.14	0.30	1.41	0.35
Pb	67.5	18.6	13.9	6.94	8.58	11.8	12.8	8.59	6.62
Th	0.19	0.22	0.11	0.29	0.38	0.31	1.43	0.20	0.31
U	0.17	0.11	0.09	0.27	0.10	0.10	0.41	0.21	0.10
La	1.01	1.12	0.71	0.69	18.7	6.65	30.9	1.32	8.05
Ce	3.39	3.06	2.32	2.43	51.0	17.2	80.0	3.01	25.4
Pr	0.58	0.55	0.42	0.49	7.19	2.40	10.3	0.47	3.82
Nd	3.31	2.82	2.59	3.01	33.4	11.2	46.1	2.36	18.6
Sm	1.06	1.46	1.20	1.49	7.11	2.82	9.56	1.23	4.90
Eu	0.74	0.96	0.63	0.96	2.67	1.22	3.01	0.73	1.55
Gd	1.61	2.46	1.99	2.76	8.37	3.87	9.89	2.16	5.70
Tb	0.29	0.43	0.32	0.47	1.40	0.56	1.37	0.37	0.90
Dy	2.07	2.50	1.95	2.76	7.72	3.12	6.93	2.12	4.99
Ho	0.48	0.55	0.40	0.58	1.64	0.59	1.43	0.47	1.07
Er	1.28	1.54	1.02	1.55	4.25	1.50	3.48	1.28	3.03
Tm	0.18	0.24	0.15	0.22	0.61	0.21	0.53	0.18	0.45
Yb	1.20	1.34	1.01	1.32	3.52	1.21	2.86	0.98	2.63
Lu	0.17	0.23	0.15	0.23	0.55	0.18	0.46	0.15	0.40
Eu/Eu*	1.73	1.55	1.25	1.45	1.06	1.13	0.95	1.37	0.90

Fe₂O₃ represents that the total iron is given as Fe₂O₃. Eu/Eu = Eu_N / (Sm_N × Gd_N)^{0.5}, where subscript N for each element means normalized by chondrite from Sun and McDonough (1989).

unusual garnet REE characteristics, with a strong positive Eu anomaly and flat chondrite normalized HREE pattern. From these features and the data on corresponding whole rocks, the protoliths for these samples can be well constrained. Trace element behaviour during UHP metamorphism in the Dabie–Sulu terrane is also discussed.

2. Geological background and samples

The Dabie–Sulu terrane in eastern China is generally considered to be a collisional suture zone between Sino-Korean and Yangtze cratons. This terrane is divided into two parts by the NNE trending Tan-Lu fault. The western part is known as Dabie, and the eastern as Sulu (Fig. 1). Three main petro-tectonic zones separated by faults were identified in the Dabie area: North Dabie with high-T migmatites, Central Dabie in which the typical UHP metamorphic rocks including the diamond and coesite eclogites occur, and South Dabie with blueschist facies metamorphic rocks and low-T eclogites in its northern region. The zone between North Dabie and the Sino-Korean craton, Beihuaiyang, contains low-grade greenschist facies metamorphic rocks. In the Sulu area, there are two main tectonic zones separated by faults. They correspond to Central Dabie in the north and to South Dabie in the south. A number of studies have been devoted to the petrology, mineralogy and geochronology of the eclogites in the Dabie–Sulu terrane. The results have been summarized and reviewed in the book edited by Cong (1996) and in Zheng et al. (2003).

The UHP metamorphic rocks occurring in Central Dabie and the northern part of Sulu are characterized by coesite- or diamond-bearing eclogites. Their peak metamorphic temperatures and pressures generally range from 700 to 850 °C and >2.7 GPa, and the UHP metamorphism occurred at 240–245 Ma (Zheng et al., 2003). As mentioned above, the UHP eclogites can be divided into three types based on their occurrence and the lithology of the country rocks. Although the origin of eclogite protoliths differs depending on their modes of occurrence and geochemistry (Zheng et al., 2003), low $\varepsilon_{\text{Nd}}(t)$ values of –20 to –6 reported for Type I UHP eclogites within granitic orthogneisses (Jahn, 1998; Zheng et al., 2003 and references therein) suggest that the protoliths are continental basalts or gabbros. The protoliths for Type III UHP eclogites associated with ultramafic rocks were also mantle-derived (Chavagnac and Jahn, 1996; Jahn, 1998).

In this study, we focus on Type I and III eclogites as: (1) Both Type I and Type III UHP eclogites are abundant and wide spread through the terrane, whereas Type II eclogites are comparatively scarce and may have been

metamorphosed interlayered marl and limestone (Zheng et al., 2003); (2) Type II eclogite has a complex geochemistry, which is difficult to interpret (Zhai and Cong, 1996); and (3) Type II eclogite commonly has a high degree of alteration, and, therefore, it is difficult to find appropriate samples. Nine samples of eclogite with the best preservation of peak UHP metamorphic mineral assemblages and the least alteration were carefully selected after petrographic observation. They were collected from the whole area of distribution of the coesite eclogites. Detailed sample localities and petrographic features are shown in Figs. 1 and 2, respectively. The samples are generally fresh and fine-grained with a grain size of ca. $0.5\text{--}0.7 \times 0.5\text{--}1.4$ mm for garnets, and $0.5\text{--}1.3 \times 0.9\text{--}2.0$ mm for clinopyroxenes. Chemical analysis across individual grains and linear scanning for major elements using an electron microprobe showed all the garnets and clinopyroxenes in these samples to be chemically homogeneous. Previous work has also shown homogeneity in the major elements of the coesite-bearing

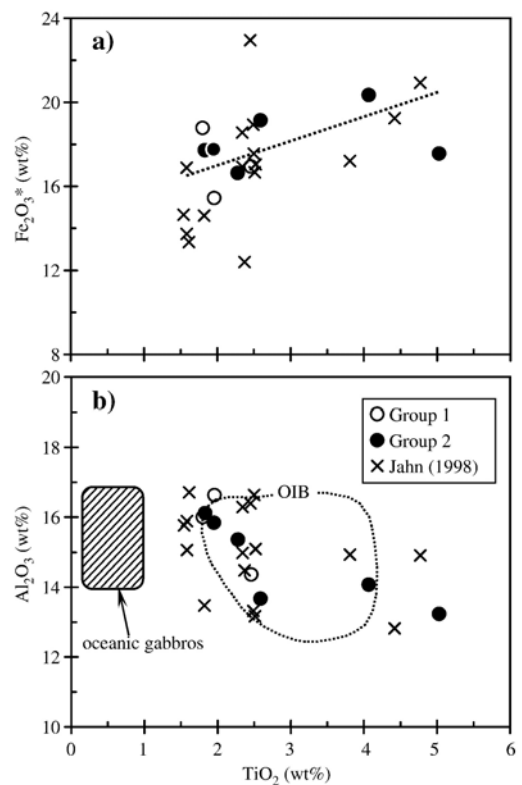


Fig. 3. Plots of Fe_2O_3^* (a) and Al_2O_3 (b) versus TiO_2 for the eclogites in this study, and those with high TiO_2 (>1.5%) from Jahn (1998). OIB field is from Spandler et al. (2004). Note that the eclogites have Al_2O_3 contents comparable to the fresh oceanic gabbros (Bach et al., 2001) with modal abundances of 40–57% and 32–46% respectively for plagioclase and clinopyroxene.

eclogites with relatively high peak temperature from Dabie (Wang et al., 1992) and Sulu (Zhang et al., 1994; Zhang et al., 1996). Information about the mineral composition and estimated modal abundance, peak metamorphic temperatures and pressures from previous research, and country rocks and eclogite types are summarized in Table 1. The dominant minerals are garnet and clinopyroxene (omphacite) in the eclogites with minor rutile, apatite, phengite, zoisite, kyanite, and epidote. Coesite and/or quartz pseudomorphs after coesite are observed in some thin sections (Table 1 and Fig. 2). Zircon is occa-

sionally present as an accessory phase. In sample SL9-1, several tiny, rounded zircon crystals (about 5–20 μm in size) were observed in one garnet grain (Fig. 2f). They likely have an inherited origin.

3. Analytical methods

Major elements were analyzed for garnet and clinopyroxene using a JXA-733 electron microprobe at Institute of Geochemistry, Chinese Academy of Sciences (IGCAS). The accelerating potential and

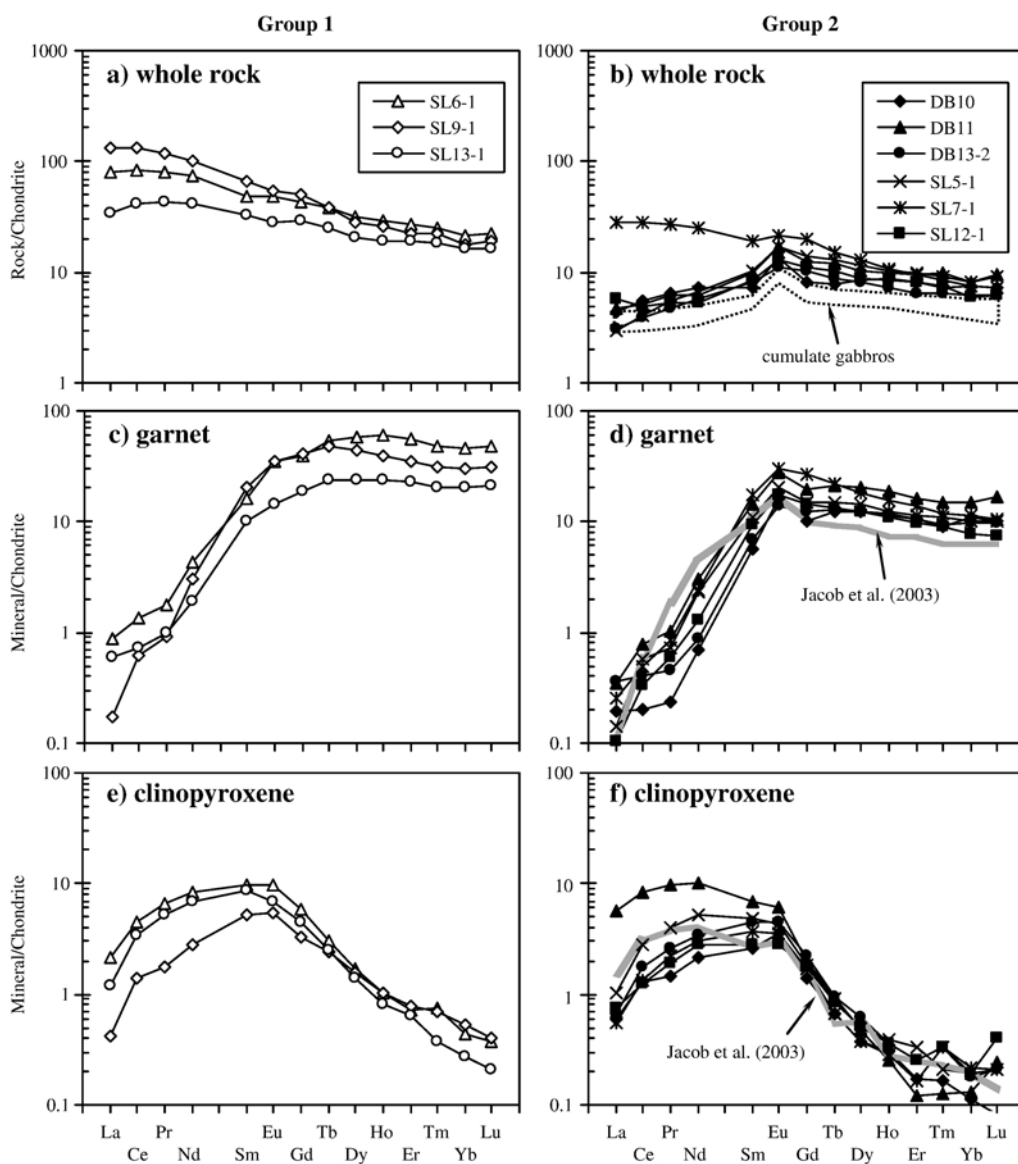


Fig. 4. Chondrite normalized REE patterns for whole rock (a and b), garnet (c and d) and clinopyroxene (e and f) of the eclogites. For comparison, the fresh continental gabbros with cumulate texture from Zhang et al. (1995a), and the garnet and clinopyroxene in the xenolithic eclogites with gabbroic protolith from Jacob et al. (2003) are also respectively shown in (b), (d), and (f). Normalizing values are from Sun and McDonough (1989).

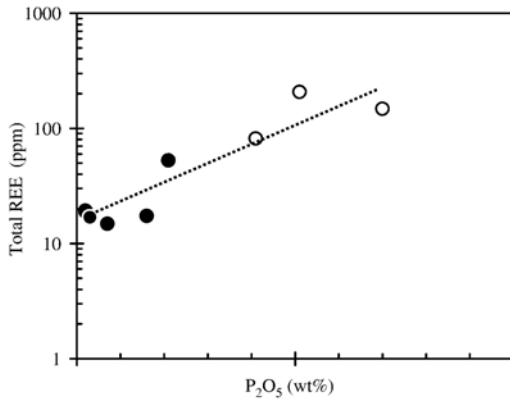


Fig. 5. Plots of total REE contents against P_2O_5 in the eclogites (symbols as in Fig. 3).

beam current used were 20 kV and 22 nA, respectively. The major element compositions for whole rock were obtained on glasses using an Axios (PW4400) X-ray fluorescence (XRF) spectrometer at IGCAS. The trace element compositions for whole rock were determined on a Finnigan MAT ELEMENT high resolution ICP-MS at IGCAS. About 50 mg of sample powder, smaller than 200-mesh, were dissolved using a HF-HNO₃ mixture in closed Teflon bombs at 190 °C for 12 h. A solution containing rhodium (1 µg/ml) was added as an internal standard. After drying, the residue was re-dissolved by adding 40% HNO₃ and reheating. The final solution was made up to 50 ml by the addition of distilled deionized water. For quality control, blanks and standards were run every five samples. Replicate analyses of the standard indicate that the precision was always within

10%, and the accuracy was generally better than $\pm 5\%$ for LREEs and $\pm 10\%$ for other trace elements. The detailed procedure can be seen in Qi and Grégoire (2000) and Qi et al. (2000). Their results for many geochemistry reference materials, including granites with refractory accessory minerals like zircons, have shown that this method is very effective for complete dissolution of samples.

In situ trace element compositions for garnet and clinopyroxene were determined by LA-ICP-MS at the Earthquake Research Institute, University of Tokyo. The instrument used was VG Elemental PQ 3, coupled with a frequency-quadrupled 266 nm wavelength Nd-YAG UV laser system. The instrument and parameters used in this study are shown in Table 2. The detailed procedures were described in Orihashi et al. (2003). Calcium concentrations in the mineral grains analyzed by electron microprobe prior to the LA-ICP-MS analysis were used as internal standards for the measurements. NIST SRM 610 glass was used as the external standard. Average trace element abundances given by Pearce et al. (1997) were chosen as the calibration values for the data reduction following the procedure of Orihashi and Hirata (2003). NIST SRM 612 glass was analyzed to monitor the accuracy. For each sample, at least three garnet and clinopyroxene grains were measured. Each mineral grain was generally analyzed at ten different spots traversing the grain and the results averaged to give the mean composition. There was no difference within or among grains within analytical uncertainty, and the minerals analyzed are homogeneous in trace element composition.

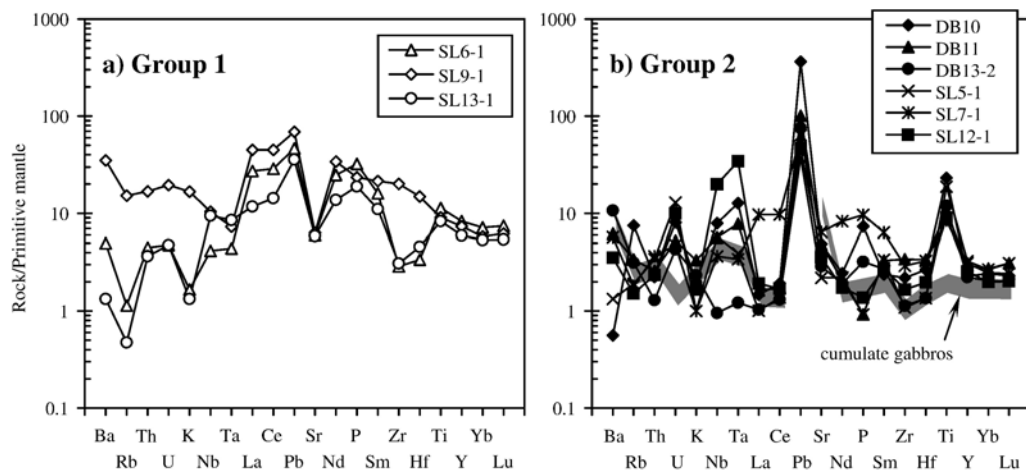


Fig. 6. Primitive-mantle normalized incompatible trace-element spider diagrams for the eclogites of group 1 (a), and group 2 (b). The fresh continental cumulate gabbros from Zhang et al. (1995a) are also shown in (b) for comparison. Normalizing values are from Sun and McDonough (1989). Elements are arranged in order of increasing compatibility (left to right) in oceanic basalts (Sun and McDonough, 1989).

4. Results

4.1. Whole rocks

The studied samples can be approximately divided into two groups, 1 and 2, in terms of their chondrite normalized REE patterns for garnet, which are described below. The major and trace element compositions for whole rocks are listed in Table 3. Generally, SiO₂ contents of all rocks are around 45% although a few samples have less than 44% due to their relatively high contents in Fe₂O₃* (total iron oxides) and TiO₂. The CIPW norm calculation shows that the eclogites were metamorphosed from basic (basaltic or gabbroic) protoliths with plagioclase and pyroxene as the main minerals. All samples have high TiO₂ contents, ranging from 1.80% to 5.03% (Table 3). Their high Fe₂O₃* contents (Table 3) and a slight linear correlation between TiO₂ and Fe₂O₃* (Fig. 3a)

imply that the eclogites, particularly group 2, have high modal Fe–Ti oxides (e.g. ilmenite) in their primary igneous assemblages. The eclogites have moderate Al₂O₃ abundances from 13.23–16.63% (Table 3) comparable to the middle range of values for the oceanic gabbros (Bach et al., 2001) (Fig. 3b). In the plot of Al₂O₃ versus TiO₂ (Fig. 3b), the eclogites are in or near to the field of oceanic island basalts (OIB) from Spandler et al. (2004) due to their high TiO₂ content, which probably resulted from Fe–Ti oxide accumulation. They are plotted in the same region as the high TiO₂ (>1.5%) samples from Jahn (1998) (Fig. 3). Group 1 has a higher content of P₂O₅ than group 2 corresponding to their variable amounts of apatite (Table 1).

The eclogites of group 1 display strong LREE enrichment with high (La/Yb)_N ratio and no Eu anomaly (Fig. 4a). In contrast, the group 2 eclogites have strong LREE-depleted and relatively flat HREE patterns and

Table 4
Major and trace element compositions of garnets

	DB10	DB11	DB13-2	SL5-1	SL6-1	SL7-1	SL9-1	SL12-1	SL13-1
<i>Major element (in wt.%)</i>									
SiO ₂	38.48	38.38	38.66	39.21	39.12	39.95	38.75	38.74	39.96
TiO ₂	0.04	0.04	0.03	0.03	0.04	0.03	0.03	0.12	0.03
Al ₂ O ₃	19.70	20.25	20.39	19.51	19.94	19.69	20.08	19.77	19.61
Cr ₂ O ₃	0.12	0.13	0.02	0.02	0.04	0.03	0.02	0.02	0.07
FeO	23.36	20.66	24.83	28.33	23.62	21.55	25.18	22.79	23.80
MnO	0.33	0.32	0.33	0.48	0.51	0.26	0.53	0.33	0.34
MgO	7.02	7.51	8.01	5.36	7.79	6.84	6.77	6.04	7.80
CaO	10.81	11.73	7.77	7.09	9.36	11.60	8.99	12.42	8.33
Na ₂ O	0.10	0.05	0.15	0.13	0.03	0.00	0.06	0.09	0.13
Total	99.96	99.07	100.19	100.16	100.45	99.95	100.41	100.32	100.07
<i>Trace element (in ppm)</i>									
Sr	1.70	3.63	3.42	5.98	3.21	6.31	5.30	3.98	3.75
Y	15.6	23.6	15.1	17.5	78.6	20.7	50.1	14.8	30.8
Zr	1.29	3.70	1.28	1.58	3.57	1.24	1.70	1.53	2.86
Pb	0.66	1.55	0.68	1.51	1.88	1.70	1.00	0.59	1.30
La	0.046	0.080	0.085	0.033	0.21	0.060	0.041	0.024	0.14
Ce	0.12	0.47	0.24	0.34	0.82	0.30	0.37	0.20	0.43
Pr	0.021	0.090	0.040	0.065	0.16	0.074	0.080	0.053	0.089
Nd	0.31	1.35	0.39	1.04	1.96	1.09	1.36	0.58	0.87
Sm	0.82	2.11	1.01	1.58	2.38	2.59	2.98	1.38	1.47
Eu	0.89	1.54	0.78	1.14	1.96	1.70	2.00	0.96	0.82
Gd	2.00	3.85	2.42	2.95	7.63	5.22	7.97	2.83	3.68
Tb	0.44	0.77	0.47	0.54	1.95	0.81	1.71	0.49	0.86
Dy	2.95	4.85	2.96	3.47	14.3	4.43	10.9	3.00	5.78
Ho	0.65	1.05	0.63	0.69	3.38	0.88	2.19	0.62	1.31
Er	1.70	2.60	1.66	1.80	8.86	2.18	5.64	1.54	3.61
Tm	0.22	0.36	0.23	0.26	1.18	0.29	0.75	0.22	0.49
Yb	1.76	2.47	1.61	1.66	7.54	1.86	4.93	1.26	3.36
Lu	0.25	0.40	0.24	0.25	1.16	0.26	0.77	0.18	0.52
Eu/Eu*	2.12	1.65	1.53	1.61	1.41	1.41	1.25	1.49	1.08

Eu/Eu* is the same as in Table 3.

distinct positive Eu anomalies, similar to young gabbros with cumulate texture in the Dabie area (Zhang et al., 1995a) (Fig. 4b). The young cumulate gabbros are from a basic intrusive body originating from rift magmatism in a continental setting. There are large differences in LREE between the two groups, but their HREE patterns have similar trends but variable normalized abundance. Sample SL7-1 is slightly different from others of group 2 as its LREE content and pattern is closer to the samples of group 1. However, its HREE content and patterns for both whole rock and garnet, that are the important signatures considered in our classification, are consistent with all other samples of group 2 (Fig. 4b and d). It is therefore appropriate to place it in group 2. Plots of total REE concentration against P_2O_5 content clearly show the distinction between group 1 and group 2 (Fig. 5), suggesting that apatite is one of the major hosts for

REE in these samples. This is consistent with our petrographic observation and the results described by Messiga et al. (1995) for the Fe–Ti–gabbros from Ligurian Alps, Italy.

In primitive-mantle normalized spider diagrams (Fig. 6), large-ion lithophile (LILE; here including Ba, Rb, Th, U, K) content in all the samples is relatively low and highly variable. Unlike LILE, other incompatible elements including high field strength elements (HFSEs; Nb, Ta, Zr, Hf, Ti) and REEs are generally consistent within each group. Due to the presence of round zircons (Fig. 2f), sample SL9-1 has much higher Zr and Hf contents than other members of group 1. This result confirms that complete dissolution was obtained by our method of digestion. The REE and P variation between group 1 and group 2 is clearly shown in Fig. 6. In addition, as displayed in Fig. 6b, group 2 has much

Table 5
Major and trace element compositions of clinopyroxenes

	DB10	DB11	DB13-2	SL5-1	SL6-1	SL7-1	SL9-1	SL12-1	SL13-1
<i>Major element (in wt.%)</i>									
SiO ₂	52.65	53.81	53.63	57.54	55.61	56.19	57.74	52.73	56.65
TiO ₂	0.03	0.12	0.01	0.00	0.08	0.06	0.09	0.10	0.05
Al ₂ O ₃	6.01	7.62	6.01	7.28	7.88	7.52	10.57	7.75	6.85
Cr ₂ O ₃	0.18	0.03	0.03	0.01	0.06	0.04	0.01	0.00	0.13
FeO	6.41	5.82	6.33	8.95	5.35	5.06	6.65	6.00	6.31
MnO	0.03	0.02	0.03	0.01	0.03	0.02	0.06	0.03	0.06
MgO	12.37	11.19	12.46	8.87	10.84	11.26	8.36	10.66	11.61
CaO	15.87	13.83	15.17	10.01	14.77	15.40	8.48	15.59	11.82
Na ₂ O	6.21	7.63	5.56	8.07	5.00	4.79	8.71	6.85	6.69
K ₂ O	0.02	0.00	0.02	0.24	0.01	0.00	0.02	0.02	0.01
Total	99.78	100.07	99.25	100.98	99.63	100.34	100.69	99.73	100.18
<i>Trace element (in ppm)</i>									
Sr	163	240	96.3	70.2	120	166	87.2	104	90.1
Y	0.22	0.29	0.44	0.33	1.33	0.32	1.26	0.43	1.14
Zr	1.89	4.41	1.16	1.84	3.10	1.98	2.73	4.46	3.46
Pb	1.41	5.03	1.96	1.78	1.61	2.95	6.29	2.14	0.68
Th	0.026	0.086	0.033	0.039	0.030	0.035	0.036	0.019	0.016
U	0.015	0.022	0.002	0.031	0.006	0.007	0.008	0.056	0.077
La	0.14	1.32	0.16	0.24	0.50	0.13	0.10	0.18	0.28
Ce	0.77	4.94	1.05	1.70	2.70	0.81	0.84	0.76	2.09
Pr	0.13	0.86	0.23	0.36	0.59	0.20	0.16	0.17	0.47
Nd	0.96	4.67	1.56	2.35	3.82	1.38	1.27	1.25	3.11
Sm	0.38	1.00	0.66	0.71	1.43	0.54	0.77	0.42	1.28
Eu	0.20	0.34	0.25	0.24	0.55	0.20	0.31	0.16	0.39
Gd	0.28	0.39	0.44	0.36	1.15	0.33	0.65	0.35	0.87
Tb	0.024	0.034	0.035	0.033	0.11	0.024	0.089	0.031	0.091
Dy	0.090	0.116	0.15	0.12	0.42	0.090	0.378	0.124	0.34
Ho	0.017	0.014	0.020	0.022	0.056	0.016	0.058	0.020	0.045
Er	0.027	0.019	0.040	0.052	0.117	0.026	0.123	0.040	0.101
Tm	0.004	0.003	0.008	0.005	0.018	0.008	0.017	0.008	0.009
Yb	0.018	0.021	0.029	0.032	0.072	0.035	0.087	0.031	0.044
Lu	0.002	0.006	0.005	0.005	0.009	0.005	0.010	0.010	0.005
Eu/Eu*	1.87	1.66	1.42	1.45	1.31	1.45	1.34	1.28	1.13

Eu/Eu* is the same as in Table 3.

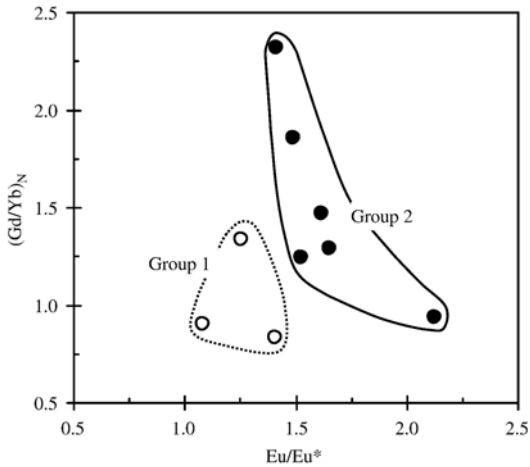


Fig. 7. $(Gd/Yb)_N$ versus Eu/Eu^* ratios in the studied eclogites.

similar pattern to the cumulate gabbros from Zhang et al. (1995a) for most of incompatible elements. The clear peaks for Nb–Ta and Ti in group 2 suggest higher modal rutile, corresponding to higher modal Fe–Ti oxides in the protolith, in this group than in group 1 and the cumulate gabbros. This feature is in good agreement with petrographic observation (Table 1). A strong positive Pb anomaly with respect to Ce and Sr in group 2 is also observed, most likely resulting from plagioclase cumulation in its protolith.

4.2. Garnets and clinopyroxenes

The major and trace element compositions are given in Table 4 for garnets and Table 5 for clinopyroxenes. Some trace elements are below detection limits in these minerals, and so REEs are mainly emphasized in this study.

Garnet and clinopyroxene are the major minerals in eclogites. Zhang et al. (1996) demonstrated that the mineral chemistry of these minerals in the eclogites from the Dabie–Sulu terrane is largely controlled by bulk chemistry and metamorphic P – T condition. Correspondingly, garnet and clinopyroxene, in this study, have relatively restricted compositions (Tables 4 and 5) due to limited variation in bulk composition of the eclogites and their metamorphic conditions. The average components calculated from the mineral chemistry for garnets are Grs: 25 mol%, Prp: 25 mol%, and Alm+Sps: 49 mol%, and for clinopyroxenes Jd: 31 mol%, Aug: 53 mol%, and Aeg: 16 mol%. In this study all garnets and clinopyroxenes are plotted in the fields summarized by Zhang et al. (1996) for the eclogites within gneiss and ultramafic rocks. The clinopyroxenes are omphacites in terms of their Jd component (Jd_{19-48}). They were formed by the associated $NaAlCa_{-1}Mg_{-1}$ substitution.

The chondrite normalized REE patterns for the garnets and clinopyroxenes are shown in Fig. 4. The garnets of group 1 have smooth LREE-depletion and

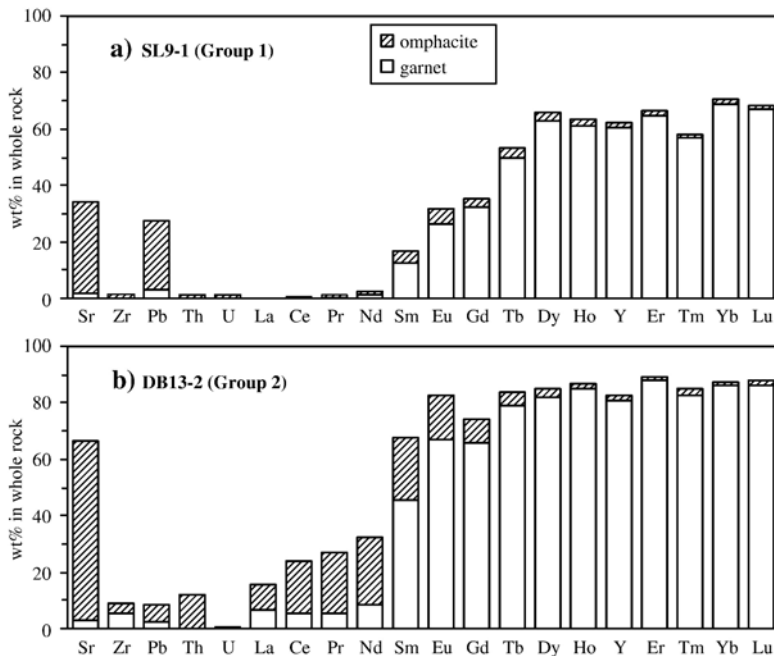


Fig. 8. Bar graphs showing the percentage of trace elements in the major minerals, garnet and clinopyroxene, for the eclogites. The mass balance calculation is based on the estimated modal abundances in Table 1 (symplectite was regarded as clinopyroxene due to its retrograded formation after the latter) and the trace element data for whole rock, garnet, and clinopyroxene in Tables 3–5.

HREE-enrichment patterns (Fig. 4c), which are commonly observed in garnets from many geological occurrences such as phenocrysts (e.g. Sisson and Bacon, 1992) and megacrysts (e.g. Liu et al., 1992) in magmatic systems. In contrast to group 1, the garnets of group 2 show distinct LREE depletion, strong positive Eu anomalies, and flat HREE patterns (Fig. 4d). Fig. 7 clearly shows the difference in garnet REE signature between two groups. The garnets in group 2 generally have higher Eu/Eu^* and $(\text{Gd}/\text{Yb})_{\text{N}}$ ratio than those in group 1. The unique garnet REE pattern observed in group 2 has been recognized in gabbroic rocks (Mazzucchelli et al., 1992), meta-anorthosites (Seifert and Chadima, 1989), and mantle xenolithic eclogites (Jacob et al., 2003). The clinopyroxenes from both group 1 and group 2 have generally coherent REE patterns with slight Ce–Gd enrichment and La and HREE depletion (Fig. 4e and f), but group 2 has a stronger positive Eu anomaly than group 1.

By using the trace element data of whole rock and minerals (garnet and clinopyroxene) coupled with the mineral modal abundance estimated in Table 1, we can obtain the contribution of garnet and clinopyroxene to the trace element budget in the eclogites from mass balance calculation. The results for both group 1 and group 2 demonstrate that major minerals, garnet and clinopyroxene, in the eclogites contain only a fraction of the whole rock trace elements (Fig. 8), in accordance with research on other eclogites (Tribuzio et al., 1996; Hermann, 2002).

Generally, 70–90% of whole rock HREEs and Y are in garnet, with up to 10% in clinopyroxene, suggesting that the main phases host the majority of HREEs and Y. In contrast, these minerals only contain small amounts of LREEs, in agreement with Hermann (2002), who showed allanite to be the main host for LREEs and Th in eclogite facies rocks. About 5–25% of total Pb and 30–60% of Sr are contained in clinopyroxene. Other trace elements, including Th, U, and Zr, are negligible in both garnet and clinopyroxene. They must be incorporated into minor and accessory phases such as allanite, zoisite, apatite, and zircon.

5. Discussion

5.1. Nature of the eclogite protoliths

Chemical compositions of the studied eclogites, such as SiO_2 content, high MgO , the abundances of V, Cr, and Ni, plus mineral assemblage lead us to conclude that the protoliths for our samples are either basalts or gabbros. The isotope studies showed almost all the Dabie–Sulu

eclogites to have negative $\varepsilon_{\text{Nd}}(t)$ values, mainly in the range from -20 to -10 (Zheng et al., 2003). Positive $\varepsilon_{\text{Nd}}(t)$ values were found for only two localities of eclogites. One is the Xiongdian eclogite with $\varepsilon_{\text{Nd}}(t)$ values from -1.9 to $+5.8$, pointing to an oceanic basalt protolith (Fu et al., 2002), but this is from northwestern Dabie, outside our study area (Fig. 1). The other is the Weihai eclogite with extremely high positive $\varepsilon_{\text{Nd}}(t)$ values from 148.2 to 226.5, resulting from severe metasomatism (Jahn, 1998). The Nd isotope data strongly suggest that the basaltic magma forming the protoliths of eclogites in the area of this study originated from subcontinental lithospheric mantle (Jahn, 1998). As shown in Fig. 3, our samples have a whole rock major composition similar to those with continental affinity (Jahn, 1998). Moreover, in a Ti/Y–Nb/Y covariance diagram (Fig. 9), our samples plotted within the same field as those of Jahn (1998) and close to the continental cumulate gabbros of Zhang et al. (1995a), but much different from the gabbros with oceanic setting (Bach et al., 2001). We thus conclude that the protoliths of these eclogites were formed within a continental setting.

Strong positive Eu anomalies, the same whole rock REE patterns as continental cumulate gabbros (Zhang et al., 1995a), and garnet REE features similar to the xenolithic eclogites with gabbroic protoliths (Jacob et al., 2003), indicate a gabbroic protolith for group 2 eclogites. Because garnet in eclogites is formed by a metamorphic reaction involving plagioclase, it seems that there was high modal plagioclase in the igneous

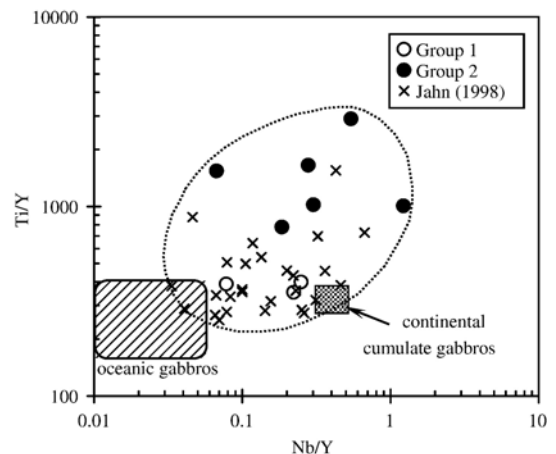


Fig. 9. Ti/Y vs. Nb/Y plots for the eclogites from the Dabie–Sulu terrane in this study and those analyzed by Jahn (1998). All the plotted Type I and III eclogites from Jahn (1998) have continental affinity in terms of their Nd–Sr isotope composition. Note the difference between the eclogites and the oceanic gabbros from Bach et al. (2001) and the similarity between the eclogites and the continental cumulate gabbros (Zhang et al., 1995a).

assemblage of group 2 (i.e. plagioclase cumulates), and the protoliths are cumulate gabbros. Previous research showed that ilmenite is the high temperature and low-pressure Ti phase, and rutile the high-pressure Ti phase (Frost, 1991). Under UHP conditions in a basic system, rutile is metamorphosed from ilmenite, and so the high modal rutile in group 2 corresponds to high modal ilmenite in the gabbro protoliths. Recent trace element measurements show that ilmenite can have highly variable concentrations of Nb and Ta (Barth et al., 2002), even higher than rutile (Barth et al., 2001). Therefore, most Nb, Ta and Ti in these eclogites were primarily incorporated into the Fe–Ti oxide ilmenite in their protoliths.

The eclogites in group 1, except the sample of SL9-1 with anomalously high Zr and Hf contents due to the inclusions of inherited zircon (Fig. 2f), have consistent REE and HFSE patterns (Figs. 4a and 6a), and they should have a similar protolith. The higher LILE concentrations in sample SL9-1 probably represent the primary composition with little LILE mobility and loss during UHP metamorphism. Although the possibility that group 1 has a similar protolith to group 2 cannot be completely excluded, we suggest that the protoliths of group 1 eclogites are basalts instead of gabbros by taking into account that there are (1) no positive Eu anomalies in either whole rock or garnet, (2) much higher whole rock LREE concentrations and slightly higher HREE patterns, and (3) no peaks for whole rock Nb–Ta and Ti corresponding to lower modal Fe–Ti oxides in their igneous protoliths. These features indicate that the magma forming the protoliths of group 1 could have evolved by fractional crystallization that produced crystals for the cumulate gabbros of group 2. Sample SL7-1 is placed in group 2 based on it having the same whole rock HREE and HFSE and garnet REE pattern as other eclogites in this group. However its whole rock LREE pattern is like the eclogites of group 1. SL7-1 is therefore transitional between the two groups but its low HREE content and Nb–Ta and Ti peaks show its protolith to be still a cumulate gabbro that probably trapped some of the evolved LREE-rich melt being responsible for its high LREE content.

Previous studies have shown that Type I and III UHP eclogites in the Dabie–Sulu terrane were metamorphosed from Neoproterozoic igneous rocks occurring in the northern margin of the Yangtze craton (Liou et al., 1996; Zheng et al., 2003). So it is significant to identify the exact nature of the protolith to explore tectonic process, a currently fascinating and controversial issue, in the Yangtze craton during the Neoproterozoic. Several researchers have argued that the breakup of

Rodinian supercontinent actually occurred in the Yangtze craton (Li et al., 2003 and references therein). The important evidence to support their conclusion is from the identification of widespread Neoproterozoic rift magmatism marked by bimodal volcanic and plutonic rocks in the western and southeastern margins of the Yangtze craton. However, in the Dabie–Sulu area on the northern margin of the Yangtze craton possible bimodal igneous rocks were destroyed by UHP metamorphism associated with subduction during the Mesozoic. It is now widely accepted, that in a rifting event, bimodal plutonic complexes are commonly observed, and the basic plutonic component is generally gabbro with a cumulate texture. As summarized in Zheng et al. (2003) and partly shown in Table 1, the ages of the protoliths for both the eclogites and granitic gneisses in the Dabie–Sulu terrane have been well determined, and are in a range from 620 to 880 Ma, with a mode range from 700 to 800 Ma. These ages imply bimodal magmatic activity during Neoproterozoic in the

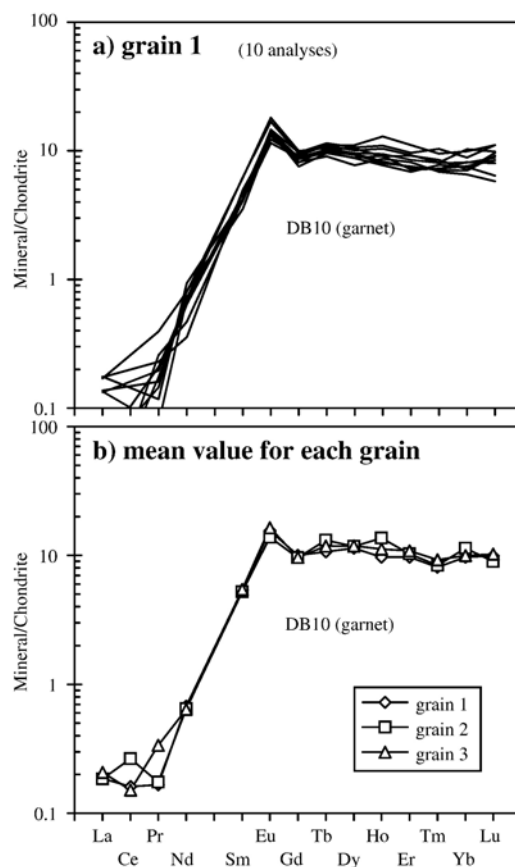


Fig. 10. Chondrite normalized REE patterns of the garnet in sample DB10 for 10 analyses traverse grain 1 (a), and mean results of three grains. Normalizing values are from Sun and McDonough (1989).

studied area. If the granitic rocks hosting the eclogites are considered to be the acidic component of the bimodal plutonic complex, then we should identify the corresponding basic component from the eclogites. In addition, magmatic underplating that likely results in the occurrence of cumulate gabbros associated with ultramafic rocks is a common process in rift magmatism. The geochemical data in this study confirm the occurrence of cumulate gabbros and hence provide evidence for Neoproterozoic rift magmatism in the northern margin of the Yangtze craton.

5.2. Trace element behaviour during UHP metamorphism

The equilibrium status of trace element distribution among phases in a metamorphic assemblage has been an interesting geochemical issue for several decades. Under amphibole facies conditions of relatively low temperature and moderate pressure, the distribution is usually in disequilibrium as characterized by major and trace element zonation in metamorphic phases (e.g. Hickmott et al., 1987), but in a granulitic system with high metamorphic temperature, distribution equilibrium is commonly approached. For UHP metamorphism, equilibrium status depends on individual conditions due to the wide temperature range. For example, Griffin and Brueckner (1985) reported that most Norwegian eclogites that have a high metamorphic temperature ($T > 700$ °C) show equilibrium distribution of REE between garnet and clinopyroxene, but in lower-T eclogites

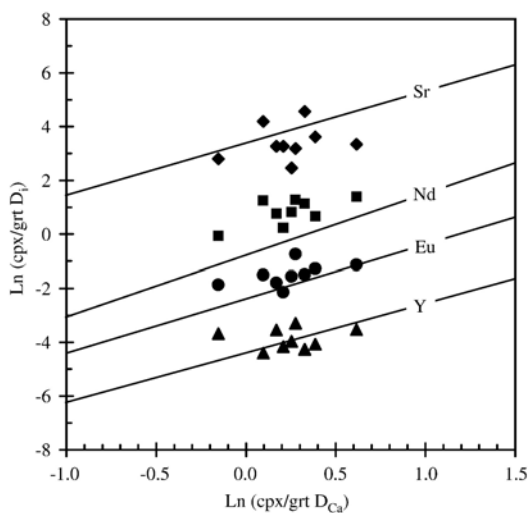


Fig. 11. Natural logs of clinopyroxene/garnet partition coefficients for Sr (diamonds), Nd (squares), Eu (circles), and Y (triangles) plotted against natural logs of molar partition coefficients for the major cation Ca. The regression lines labeled with element symbols after Harte and Kirkley (1997) for xenolithic eclogites from South Africa.

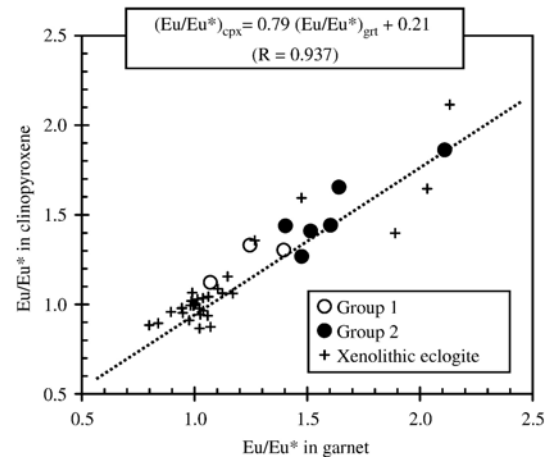


Fig. 12. Plots of Eu/Eu^* in garnet against the same ratio in clinopyroxene for both the eclogites in this study and xenolithic eclogites from South Africa (Barth et al., 2001, 2002; Jacob et al., 2003).

(~ 600 °C) they have not equilibrated between the two mineral phases.

For the eclogites in this study, the metamorphic temperatures are in the range from 700 to 800 °C (Table 1). Their garnet and clinopyroxene grains are homogeneous for major and trace elements. For example ten REE values measured across one grain of garnet in sample DB10 are similar except for La–Pr (Fig. 10a) that are in lower concentration and hence have a relatively large analytical error. The mean values for three garnet grains also have similar REE contents (Fig. 10b). The clinopyroxene in this sample has the same features as the associated garnet. Therefore, the REEs in garnet and clinopyroxene have approached equilibrium on a grain scale. The UHP eclogites from the Dabie–Sulu terrane fit the linear trends of $D^{\text{cpx/grt}}$ versus D_{Ca} for Y, Eu, Nd, and Sr (Fig. 11) from the data of the xenolithic eclogites that have an equilibrium distribution of trace elements between garnet and clinopyroxene (Harte and Kirkley, 1997). We therefore consider that the eclogites in this study have also an equilibrated distribution of trace element between garnet and clinopyroxene. This is further confirmed by the linear correlation for Eu/Eu^* ratios between garnet and clinopyroxene for our samples (Fig. 12) similar to that for the equilibrated xenolithic eclogites (Barth et al., 2001, 2002; Jacob et al., 2003).

Trace element mobility is another significant but controversial issue for UHP metamorphism since this process frequently occurs in subduction zones, which are important tectonic environments for exploring the recycling of elements between Earth's mantle and crust. Some experimental and field-based researches (e.g.

Kogiso et al., 1997; Becker et al., 2000) suggest that LILEs, LREEs, and Pb have varied mobility during metamorphic dehydration under eclogite facies conditions, but recent investigations showed no significant element transfer during subduction (Chalot-Prat et al., 2003; Spandler et al., 2003, 2004). It is almost impossible to probe into element mobility during metamorphism because the geochemical composition of a protolith exactly corresponding to the metamorphosed rock is difficult to determine. However, it is widely accepted that HFSEs and HREEs are immobile during metamorphism including at UHP conditions. Here, the eclogites in each group have similar HREE and HFSE contents, suggesting that the protoliths for each group have the similar geochemical compositions. In contrast, LILE contents are very different among samples in both group 1 and group 2 (Table 3 and Fig. 6). Compared to the cumulate gabbros of Zhang et al. (1995a) all the members in group 2 have strong enrichment in U, and sample DB10 has additional enrichment in Rb (Fig. 6b). Considering that the retrograde alteration is almost negligible in these samples, we infer that UHP metamorphism is probably responsible for the variation in LILE abundances. During this process, most of LILEs were lost but U in group 2 and Rb in sample DB10 probably gained to some extent. Therefore, LILEs are mobile during the UHP metamorphism in the Dabie–Sulu terrane. By reviewing experimental data and observations in natural rocks, Hermann et al. (2006) recently note that the mobility of LILE is highly sensitive to temperature. In fact, for the cases studied by Chalot-Prat et al. (2003) and Spandler et al. (2003, 2004) the metamorphic temperatures are 600 °C or less, and the fluid phase released by dehydration during HP or UHP metamorphism would be aqueous fluid, a dilute and water-rich one. This nature of fluid phase was responsible for less or no LILE mobility. However, the peak metamorphic temperatures, in a range from 700 to 850 °C much higher than those in above cases, together with the granitic hosts, determined that the fluid phase liberated during UHP metamorphism in the Dabie–Sulu terrane should have high dissolved solutes (Hermann et al., *in press*). Consequently, the dehydration in this case resulted in the observed LILE mobility. It is worth noting that LREE abundances in these eclogites, except sample SL7-1 with higher LREE content than others in group 2 due to possibly trapped melt, are constant within each group, suggesting there was no LREE transfer or mobility. The partitioning experiments of Keppler (1996) show that $D^{\text{fluid/cpx}}$ for K, Rb, Ba, and Th are 370, 1300, 460, and 7.7 times respectively higher than $D^{\text{fluid/cpx}}$ for La (1.0), and more recent experimental data of Green and Adam (2003) also reveal that at conditions of 650–700 °C and 3.0 GPa

the fluid released through dehydration of subducted mafic crust has strong enrichment in LILEs with respect to REEs. These experimental results imply that the LILEs are more compatible than LREEs in a clinopyroxene-bearing aqueous fluid system, and a decoupling between LREE and LILE during dehydration at UHP conditions, being most likely responsible for the relatively constant LREE contents in our samples. We therefore conclude that LREEs are also immobile during UHP metamorphism in the Dabie–Sulu terrane. This decoupling behaviour between LILE and LREE in dehydration-related fluid systems under HP or UHP conditions has also observed in several other nature rocks (e. g. Becker et al., 2000; Breeding et al., 2004; Hermann et al., 2006). The mobility difference between LILE and LREE could be well explained by their various behaviour during metamorphic dehydration in which LILEs are easily transported into the released fluid due to their high dissolution in fluid phases, but most of LREEs can be directly transferred from minerals within a protolith into newly formed accessory phases such as allanite, a significant LREE carrier in subducted crust (Hermann, 2002).

6. Conclusions

Based on the geochemical data presented in this study, and previous research for the eclogites from the Dabie–Sulu terrane, the following conclusions are derived.

- (1) The eclogites are the metamorphic products of basaltic igneous rocks in terms of mineral assemblages, and major and transition element compositions. Isotopic data from the literature and discrimination diagrams using some immobile elements show that their igneous protoliths were formed in a continental setting.
- (2) The analyzed eclogites can be roughly divided into two groups. Group 1 has LREE enrichment with no Eu anomaly for whole rock, and smooth LREE depletion but HREE enrichment pattern for garnet, whereas group 2 has depletion of LREE with a pronounced positive Eu anomaly and flat HREE pattern for both whole rock and garnet. The consistency between group 2 and fresh cumulate gabbros for whole rock REE, and eclogites with gabbroic protoliths for both whole rock and garnet REE strongly suggests that the protoliths for group 2 are Fe–Ti–gabbros with relatively high cumulus phases of plagioclase and ilmenite. The unusual garnet REE pattern observed in group 2 can hence be considered as an important signature

for identifying gabbro protoliths for eclogites. The rocks of group 1 were possibly metamorphosed from basalts.

- (3) The major phases garnet and clinopyroxene are the main hosts for HREEs and Y, and clinopyroxene is a significant host for Sr. Minor and accessory minerals account for predominant LREEs, Th, U, Zr, Nb, and Ta. During UHP metamorphism in the Dabie–Sulu terrane, LILEs had high mobility, whereas REEs and HFSEs were immobile. Trace element distribution between garnet and clinopyroxene in these eclogites was close to or approached equilibrium.

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