Pergamon

Geochimica et Cosmochimica Acta, Vol. 64, No. 6, pp. 1077–1093, 2000

0016-7037/00 $20.00 + .00

PII S00167037(99)00319-1

Sm–Nd and Rb–Sr isotopic chronology and cooling history of ultrahigh pressure metamorphic rocks and their country rocks at Shuanghe in the Dabie Mountains, Central China

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(*Received November* 11, 1998; *accepted in revised form July* 20, 1999)

Abstract—Ultrahigh pressure metamorphic (UHPM) rocks at Shuanghe area in the Dabie Mountains occur as a UHPM block within the regional granitic gneiss. A Sm–Nd isochron defined by garnet + omphacite + rutile from coesite-bearing eclogite yield an age of 226.3 ± 3.2 Ma. Another Sm–Nd isochron defined by garnet + two phengites form UHP gneiss yield a similar age of 226.5 ± 2.3 Ma. The two consistent Sm–Nd ages defined by three UHPM minerals suggest that Nd isotopic equilibrium between UHPM minerals in these rocks during UHP metamorphism has been achieved. This may correspond to the age of peak metamorphism with an average metamorphic temperature of 800°C. It is demonstrated that the retrograde metamorphism of UHPM rocks occurred in an open chemical system, whereas the Nd and Sr isotopic systematics of UHPM minerals may have remained closed. Nd and Sr isotopic disequilibrium between UHPM minerals and retrograde metamorphic minerals has been observed; therefore, the tie line of garnet or phengite and whole rock containing retrograde metamorphic minerals gives an old Sm–Nd age and a young Rb–Sr age, respectively, with no geologic significance. However, a Rb–Sr ages of 219.0 ± 6.6 Ma defined by phengite + garnet from a UHPM gneiss indicates that the UHPM rocks at Shuanghe cooled down to 500°C at that time. It suggests that the UHPM rocks at Shuanghe experienced the first rapid cooling during 226–219 Ma. On the other hand, the Rb–Sr ages of 174 ± 7.8 to 169.2 ± 3.3 Ma defined by retrograde minerals (amphibole or biotite) with closure temperature ranging from 450° to 300°C and intensely retrograded metamorphic rocks reflect a second rapid cooling during this time interval. This is consistent with the "rapid cooling" time of 190–170 Ma of the orthogneiss in the Dabie–Su–Lu UHPM belt obtained by Ar–Ar dating method. In contrast to UHPM rocks, the Nd isotopic composition of the garnet in granitic gneiss has been reset during retrograde metamorphism and is in equilibrium with those of retrograde epidote and biotite, which yields a Sm–Nd isochron age of 213 ± 5 Ma indicating the retrometamorphic time corresponding to amphibolite facies. In addition, the biotites from the granitic gneiss yield Rb–Sr ages of 171–173 Ma similar to those of the UHPM rocks. These data suggest that the country rocks (granitic gneiss) may have a similar cooling history to the UHPM rocks at Shuanghe. Two stages of rapid cooling of UHPM rocks at Shuanghe may correspond two stages of fast uplift: the initial rapid uplifting and cooling of UHPM rocks during 226–219 Ma may be caused by compression tectonics during subducting time of the continental crust; whereas the later rapid cooling may reflect the exhumation of the entire subducted continental crust by extension during the early–middle Jurassic. *Copyright © 2000 Elsevier Science Ltd*

1. INTRODUCTION

The occurrence of ultrahigh pressure (UHP) minerals, such as coesite and diamond, in crustal rocks in orogenic belts suggests that a huge amount of continental crust can be subducted to mantle depth during the continent–continent collision (Chopin, 1984; Smith, 1984; Okey et al., 1989; Wang et al., 1989; Sobolev and Shatsky, 1990; Xue et al., 1992). This has raised an intriguing question about how the ultrahigh pressure metamorphic (UHPM) rocks were exhumed from the depth of >100 km to the surface, and in the process the UHP minerals were preserved during decompression and cooling rather than being destroyed. Cooling history study of UHPM rocks is the most direct means to give constraint on tectonic process of the exhumation.

The Dabie mountains and Su–Lu terrane in central China (Fig. 1) is the largest known UHPM belt on Earth. Abundant Sm–Nd mineral isochron and U–Pb zircon ages of UHPM rocks from this belt have documented the Triassic event of ultrahigh pressure metamorphism (e.g., Li et al., 1992, 1993, 1994, 1996, 1997; Ames et al., 1993, 1996; Chavagnac and Jahn, 1996; Rowley et al., 1997; Hacker et al., 1998). $^{40}Ar/^{39}Ar$ thermochronology of the gneiss in the Dabie Mountains and Su–Lu terrane has also been studied to reveal cooling history (Chen et al., 1992; Eide et al., 1994; Chen et al., 1995; Hacker and Wang, 1995; Li Q. et al., 1995). However, presence of excess Ar in phengite and biotite from UHPM rocks cast doubt about their suitability for $^{40}Ar/^{39}Ar$ thermochronologic studies of UHP rocks (Li et al., 1994; Arnaud and Kelley, 1995; Hacker and Wang, 1995; Ruffet et al., 1995; Scailete, 1996). In fact, except for blueschist, most samples used for the $^{40}Ar/^{39}Ar$ thermochronologic studies in the Dabie–Su–Lu terrane are from granitic gneisses. They can only reveal cooling history of the country rocks of UHPM units in the Dabie–Su–Lu terrane,

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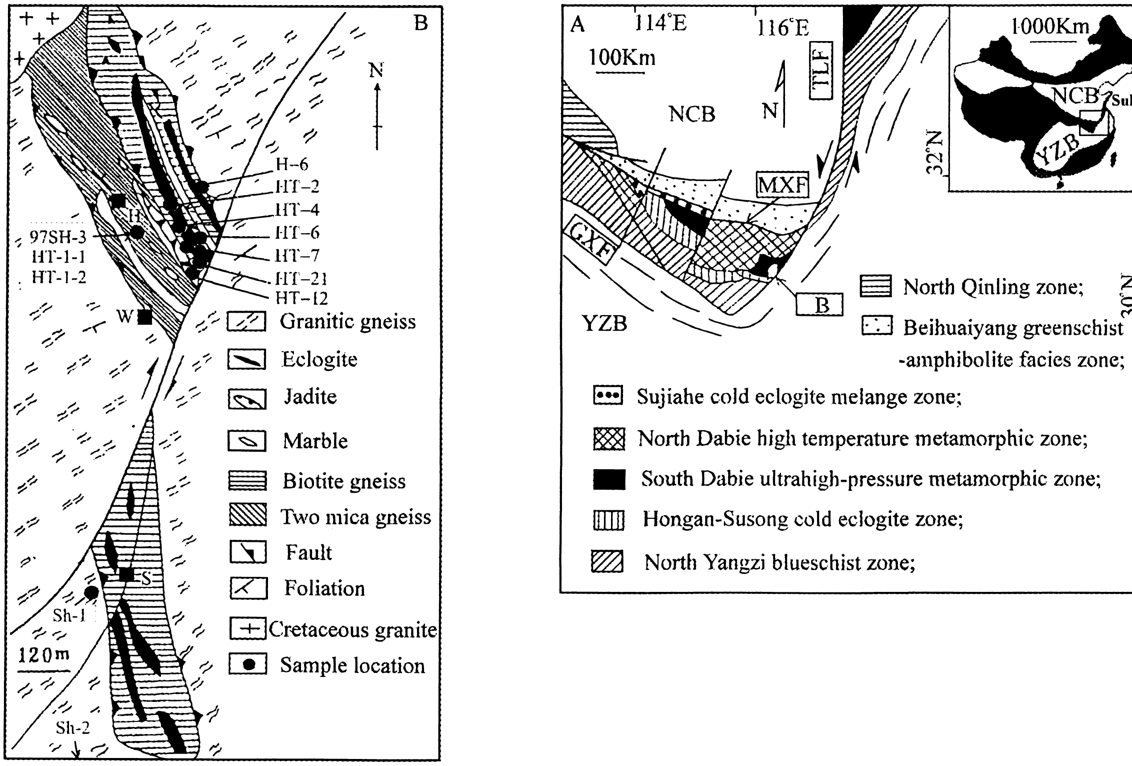

Fig. 1. (A) Tectonic map of Dabie Mountains and its location in China (modified after Xue et al., 1996). (B) Geologic map of the Shuanghe UHPM slab and its country rocks (after Cong et al., 1995) and sample locations.

but cannot directly reveal the cooling history of UHPM units. These studies indicate that the country rocks (granitic gneisses) of UHPM units in the Dabie–Su–Lu terrane have experienced fast cooling between 190 and 170 Ma (Chen et al., 1992; Li Q. et al., 1995; Chen et al., 1995).

To define the cooling history of the UHPM rocks in the Dabie Mountains, Rb–Sr isotopic dating method in addition to Sm–Nd method has been chosen to date phengite and biotite from UHPM rocks. A high rate of initial cooling (≈40°C/Ma) between 220 and 210 Ma for the UHPM rocks from Bixiling, Dabie Mountains, has been determined by using Sm–Nd and Rb–Sr isotopic dating methods (Chavagnac and Jahn, 1996). Similar Sm–Nd and Rb–Sr isotopic dating results for the UHPM rocks from the Qinglongshan in the Su–Lu terrane (Li et al., 1994) revealed a rapid cooling (≈50°C/Ma) between 226 and 219 Ma. However, there are some important questions concerning the cooling history of UHPM rocks in the Dabie–Su–Lu terrane that remain to be answered.

1. The reported Sm–Nd isochron ages have a large variation (from 246 to 210 Ma) (Li et al., 1993, 1994, 1996; Okey and Sengör, 1993; Chavagnac and Jahn, 1996) resulting in an uncertainty in the peak metamorphic age of the UHPM rocks. Most of the Sm–Nd ages were defined by two minerals (garnet + omphacite). Therefore, we cannot judge whether Nd isotopic equilibrium between the two minerals was achieved during UHPM.
2. Phengite Rb–Sr ages have been widely used to determine the cooling time corresponding to closure temperature of 500°C (e.g., Cliff, 1985). However, the reported phengite Rb–Sr ages show considerable variation even for samples from the same UHPM unit. For example, four phengite samples from the Bixiling eclogite body yield Rb–Sr ages ranging from 223 to 198 Ma (Chavagnac and Jahn, 1996). The major influence upon this age uncertainty is still unknown. Thus, the possible Sr isotopic disequilibrium between phengite and other minerals during cooling or retrograde metamorphism should be investigated.
3. As mentioned, previous studies have revealed that the initial rapid cooling of UHPM rocks between 226 and 210 Ma in the Dabie–Su–Lu terrane is much earlier than that (190–170 Ma) of their country rocks (granitic gneiss). If true, these data support the "foreign" relationship between UHPM rocks and their country rocks (e.g., Cong et al., 1995). However, if the UHPM rocks and their country rocks have "in situ" relationships as suggested by other investigators (e.g., Wang and Liu, 1991; Rowley et al., 1997; Carswell et al., 1998; Hacker et al., 1998), they should have a similar cooling history, that is, the UHPM rocks in the Dabie–Su–Lu terrane should have experienced another rapid cooling between 190 and 170 Ma, as well as their country rocks, and the granitic gneiss should also have experienced the earlier rapid cooling between 226 and 210 Ma. Finding the evidence for these cooling events is critical to evaluate this controversy.

These problems indicate that we need to improve our understanding of the isotopic systematics of UHPM rocks during

UHP or retrograde metamorphism. In this article, we report a Rb–Sr and Sm–Nd isotopic study of an UHPM unit and its country rocks at Shuanghe, Dabie Mountains, and try to answer the above questions. On the basis of the cooling T–t path obtained in this study, the exhumation mechanisms of the UHPM rocks in the Dabie Mountains will be discussed.

2. GEOLOGIC SETTING AND METAMORPHIC HISTORY

The Qinling–Dabie orogenic belt is a complex collision zone of the North China Block (NCB), Yangtze Block (YB), and some microcontinents located between the NCB and YB (e.g., Li S. et al., 1995, 1998; Zhang et al., 1995; Li and Sun, 1996). The Dabie Mountains represent the eastern section of the belt and can be subdivided into seven metamorphic zones from the north to the south (Fig. 1A); they are (1) North Qinling zone; (2) Beihuaiyang green schist–amphibolite facies zone; (3) Sujiahe cold eclogite melange zone; (4) Northern Dabie high-temperature metamorphic zone; (5) Southern Dabie ultrahigh pressure metamorphic zone; (6) Hongan–Susong cold eclogite zone; and (7) Northern Yangtze blueschist zone. Petrologic, geochemical, chronologic, and geologic studies suggest that zone 1 is a Paleozoic island arc of the NCB; zone 2 could be a forearc complex of the NCB; zone 3 is a tectonic melange related to the collision between the NCB and a microcontinent; and zones 4, 5, 6, and 7 represent the subducted continental crust of the YB (e.g., Li S. et al., 1995, 1998; Li and Sun, 1996; Xu et al., 1999). The UHPM rocks, including coesite or diamond-bearing eclogite associated with jadeite quartzite, garnet–epidote–micaceous paragneiss and marble with eclogite boudins are restricted within in zone 5. They are encased in amphibolite facies orthogneisses. The relationships between the UHPM units and the country rocks are still a controversial issue. Cong et al. (1995) suggested a model of foreign relationship between them based on the detailed mapping and petrologic studies at the Shuanghe area. On the basis of the more detail petrologic study in the same area, Carswell et al. (1998) suggested an in situ model relationship and emphasized that it is necessary to resort to models of tectonic juxtaposition to explain the spatial association of the granitic gneiss with the undoubted UHP schists and eclogites within the Dabie Mountains.

Figure 1B shows that the elongated UHPM unit with north northwest–south southeast trend outcrops over an area of about 1 km^2 at Shuanghe, and is surrounded mostly by orthogneiss. This UHPM unit is offset by a dextral strike–slip fault, and intruded by a younger granitic body to the northwest. This UHPM unit is mainly composed of fine-grained and homogeneous coesite-bearing eclogite, garnet–epidote–two mica gneiss, garnet–biotite gneiss, jadeite quartzite, and marble with or without eclogite nodules or boudins. The compositional layering within the UHPM unit is more evident in the northern outcrop (Fig. 1B). A few tectonic fragments of actinolitite and serpentinite (several meters long) occur along the eastern boundary fault of the northern UHPM unit. Abundant eclogite lenses and boudins are interlayered or interleaved with garnet–epidote–two mica gneiss and minor garnet–biotite gneiss and marble in the eastern part of the northern unit. Abundant garnet–biotite gneiss are interlayered with marble, jadeite–quartzite, and minor eclogite lenses in the western part of the northern unit.

Mineral paragenesis and chemistry of the UHPM rocks and their country rocks at Shuanghe have been reported by Cong et al. (1995) and Carswell et al. (1998), and five metamorphic stages were recognized (modified after Cong et al., 1995):

1. Pre-eclogite stage (PE): This is recorded by phengite and barroisite inclusions within garnet porphyroblasts. This mineral assemblage may have been formed before coesite at pressures of 6 to 8 kbar.
2. Peak UHP coesite–eclogite stage (CE): It is recorded by coesite and Jd-rich (Jd60) omphacite inclusions in garnet. The metamorphic temperatures ranging from 720 to 880°C (with an average of 800°C) in this stage has been estimated (Cong et al., 1995). The presence of coesite during this stage indicates pressures $>$ 29 kb at 800°C. All UHP minerals have been formed in this stage.
3. Quartz–eclogite stage (QE): This is represented by the coexisting garnet and omphacite porphyroblasts. Pressure and temperature conditions of the mineral pair were estimated to be 13–16 kbar and 630° –760°C (with an average of 695°C) (Cong et al., 1995). The garnet and omphacite could continue growth by recrystallization during this stage.
4. Symplectite stage (Smp): This is represented by various symplectite replacement assemblages, for example, the omphacite and garnet have been partly replaced by symplectitic assemblages of augite $+$ sodic plagioclase and of amphibole $+$ sodic plagioclase, respectively. The pressure and temperature conditions for this stage have been estimated to be 6–8 kbar at 470° –570°C (Cong et al., 1995).
5. Post-symplectic stage (PS): This is represented by various retrograde minerals formed after symplectite, such as actinolitic amphibole, biotite, and chlorite. The pressure and temperature conditions of this stage correspond to the green schist facies (Cong et al., 1995).

3. SAMPLE DESCRIPTION

Ten UHPM rock samples and two country rock samples were collected from the Shuanghe area. Sample locations are shown in Figure 1B. Their major and trace element compositions are listed in Table 1.

3.1. Petrography

Samples HT–2, HT–4, HT–7, and HT–21 were massive, fine-grained eclogites. They are mainly composed of garnet, omphacite, rutile, quartz, and minor retrometamorphic minerals, such as symplectite and amphibole. Relict coesite or quartz pseudomorphs after coesite have been found in these samples as inclusion in garnet. In addition, garnet and Jd-rich omphacite inclusions have been observed in omphacite and garnet, respectively. The retrometamorphism in sample HT–2 is much stronger than other samples. Garnet, omphacite, and rutile from the sample HT–4 were separated for isotopic dating.

Sample HT–12, a strongly retrograded eclogite occurred as nodule in the marble (Fig. 1B). Except omphacite inclusions in garnet, all omphacites were retrograded to amphibole, but no biotite has been observed. It suggests that the retrometamorphism corresponds to the amphibolite facies. Titanite is another

Table 1. Major element (in wt%) and trace element (in ppm) compositions of the UHPM rocks and their country rock from Shuanghe in Dabie Mountains.

Sample no. rock type	92HT–1–1-UHP gneiss	92HT–6-UHP gneiss	92HT–2-Retrograde quartz eclogite	92HT–4-Quartz eclogite	92HT–7-Quartz eclogite	92HT–21-Quartz eclogite	92HT–12-Retrograde eclogite in marble	SH–1-Granite gneiss	SH–2-Granite gneiss
SiO_2	60.71	62.99	53.37	50.97	48.82	50.78	41.13	72.75	74.65
Al_2O_3	17.42	14.34	16.39	12.58	13.85	13.36	16.73	13.87	13.74
Fe_2O_3	1.19	1.59	1.44	2.39	1.21	1.43	1.10	0.86	0.95
FeO	4.99	5.03	8.19	13.54	10.44	13.59	20.12	1.15	0.74
MgO	2.87	2.73	5.30	5.75	6.89	5.01	3.62	0.26	0.37
CaO	2.93	5.01	8.88	9.40	11.64	8.98	10.43	0.98	0.64
Na_2O	1.98	3.45	4.22	2.24	3.79	2.67	1.91	5.66	5.92
K_2O	4.40	2.34	0.42	0.01	0.05	0.01	0.27	2.96	1.86
TiO_2	0.59	0.72	0.94	2.65	1.26	2.36	2.72	0.35	0.35
P_2O_5	0.04	0.11	0.20	0.15	0.12	0.36	0.06	0.06	0.05
MnO	0.12	0.10	0.17	0.23	0.17	0.20	0.40	0.12	0.04
H_2O^+	1.75	0.88	0.06	0.07	0.04	0.05	0.85	0.57	0.22
CO_2	0.64	0.07	0.34	0.09	1.46	0.84	0.58	0.33	0.32
Total	99.63	99.36	99.92	100.07	99.74	99.64	99.92	99.93	99.88
La	106.30	7.93	4.13	7.81	7.35	9.39	1.30	40.50	45.22
Ce	206.00	15.57	13.39	22.12	18.25	24.30	3.79	81.28	94.94
Pr	23.48	1.95	2.04	3.13	2.70	3.61	0.55	11.37	11.31
Nd	83.43	8.60	10.24	14.27	12.15	15.75	3.20	42.14	44.24
Sm	12.81	2.22	3.20	3.72	3.24	4.32	1.82	8.12	8.35
Eu	1.96	0.82	0.90	0.37	1.11	1.48	1.06	1.78	1.67
Gd	7.84	0.50	4.39	4.90	3.72	5.53	5.52	7.13	7.13
Tb	0.94	0.40	0.72	0.85	0.57	0.91	1.27	1.24	1.15
Dy	6.00	2.52	4.68	5.77	3.77	5.81	9.97	7.54	7.55
Ho	1.24	0.48	0.91	1.13	0.71	1.15	2.07	1.50	1.52
Er	3.38	1.33	2.46	3.18	1.85	3.18	6.10	4.68	4.50
Tm	0.53	0.19	0.36	0.51	0.27	0.48	0.92	0.75	0.72
Yb	3.21	1.16	1.97	2.98	1.56	2.71	5.68	4.97	4.45
Lu	0.50	0.18	0.30	0.47	0.23	0.45	0.90	0.72	0.71
Rb	153	49	8	2.2	2	0	7	56	40.2
Sr	77	171	93	80	106	184	254	107	210
Ba	1589	1091	210	20	44	21	223	1392	784
V	88	119	178	419	334	346	361		8
Cr	91	88	59	90	82	44	76	3	8
Ni	41	34	54	49	92	70	45	0	5
Y	32.90	13.41	25.25	31.31	19.12	32.19	58.35	24	35.4
Zr	162	85	140	104	86	177	245	243	325
Nb	15	8	13	11.6	9	20	19	12	11.5
Th	15	2	4	2.0	2	5	5	4	2.5
Pb	6	6	10	5.0	8	9	15		5.2
U	5	2	2	0.4	1	0	0	2	0.5
Nb/La	0.14	1.01	3.15	1.49	1.22	2.13	14.6	0.30	0.25

The REE data were obtained by inductively coupled plasma spectrometry at the analytical center of Geological Bureau, Hubei Province, P. R. C. The other data were obtained at the Institute of Geophysical and Geochemical Exploratory Techniques, Chinese Academy of Geological Sciences, by x-ray fluorescence analysis except for CO_2 and H_2O, which were obtained by nonaqueous titration and gravimetric analysis, respectively.

common retrograde mineral, and occurs as corona around ilmenite, which contains relict of rutile. Recrystallized quartz and apatite coexisting with amphibole and titanite are also common in this sample. The retrograde assemblage of quartz + apatite + amphibole + titanite forms in a vein around the garnets. Garnet, amphibole, titanite, and apatite were separated from this sample for isotopic dating.

Sample HT–6 is a garnet–epidote–biotite gneiss collected from a thin (1 m) gneiss layer interbeded with thick eclogite layers. It mainly consists of quartz, biotite, and epidote, together with minor garnet, phengite, rutile, titanite, and thin amphibole as symplectite intergrowth with sodic plagioclase. Most of phengites are partly replaced by biotite, and some titanites occur as corona around rutiles. These observations indicate that the biotite and titanite are retrograde metamorphic products. Only biotite was separated from this sample for Rb–Sr dating.

Samples HT–1–1, HT–1–2, and 97SH–3 are garnet–epidote–two mica gneiss collected from the one outcrop in the western part of the UHPM unit (Fig. 1B). The gneiss is interbeded with marble containing eclogite nodules. It mainly consists of quartz, garnet, phengite, clinozoisite/epidote, biotite, plagioclase with minor rutile, and titanite. The sample HT–1–2 contains much less biotite than other two samples. Most phengites are developed along foliations, but a few phengite inclusions in garnet have been observed. Phengite is partly replaced by biotites and rutile by titanite, which suggest that the biotites and titanite were formed during retrograde metamorphism. Carswell et al. (1998) also indicated that clinozoisite grains in this UHP gneiss are zoned toward later more pistacite-rich epidote and sometimes cored by early allanites, which suggests a retrograde origin for the epidote in these samples. Garnet, phengite, epidote, and biotite were separated from these samples for isotopic dating.

Sample H–6 is a biotite gneiss from the eastern margin of the UHPM unit (Fig. 1B). This sample is strongly sheared and retrograded. It consist of quartz, plagioclase, biotite, and minor garnet. Biotite was separated from this sample for Rb–Sr dating.

Samples Sh–1 and Sh–2 are fine-grained granitic gneisses from the country rock of the UHPM unit. These gneiss samples consist of quartz, K-feldspar, plagioclase, biotite, garnet, epidote, and clinozoisite. Contents of both phengite and garnet are lower than in the UHP gneiss, whereas K-feldspar is conspicuously abundant. There is no obvious petrographic evidence that coesite was ever stable. On the basis of this mineral assemblage together with the high spessartine contents (18.6–34.9 mol%) and very low pyrope contents (1.0–3.8 mol%) of the garnet, Cong et al. (1995) suggest that the granitic gneiss has only experienced amphibolite facies metamorphism with temperature estimated to be 530 $\pm$ 20°C at 4 kbar by using garnet–biotite geothermometers (Ferry and Spear, 1978). However, recently, Carswell et al. (1998) argue that the granitic gneiss also witnessed UHP conditions based on the discoveries of UHPM mineral relicts, such as rutile, phengites with Si contents as high as 3.49, and more calcic Mn-poor garnet, in the granitic gneiss at Shuanghe. Biotite and phengitic white mica (Si = 3.2–3.3) appear to coexist in the late foliation but phengite grains with higher Si contents breakdown to secondary biotite and plagioclase (Carswell et al., 1998). The clinozoisite/epidote grains are often cored by allanite and show zonation from early clinozoisite toward late more Fe-rich epidote (Carswell et al., 1998). These observations suggests that the biotite and epidote in granitic gneiss are late-stage products during retrograde metamorphism corresponding to 450°C and 6 kbar (Carswell et al., 1998). It is also important to emphasize that the limited amount of garnet occurred in a skeletal or even atoll form around plagioclase have been observed by Carswell et al. (1998) and Xu et al. (1998), which suggests the strong influence of retrograde metamorphism on the garnet. Garnet, biotite, and epidote were separated for isotopic dating.

3.2. Major and Trace Element Geochemistry

The chemical compositions of the four eclogites (HT–2, HT–4, HT–7, HT–21; Table 1) with SiO_2 range from 48.8% to 53.4% and $K_2O + Na_2O$ range from 2.25% to 4.64%; this suggests that their protoliths are subalkaline basalts. The mobility of Rb, Ba, and K during retrograde metamorphism can be observed in the primitive mantle normalized spider diagram (Fig. 2b) by comparing the strongly retrograded eclogite samples HT–2 and HT–12 with other unretrograded eclogite samples. High contents of Rb, Ba, and K in samples HT–2 and HT–12 suggest that the retrograde metamorphism in eclogite occurred in a open chemical system. The retrometamorphic fluid may have introduced a large quantity of iron lithophile elements into eclogite, which may potentially influence the Sr isotopic composition of retrograde metamorphic minerals and whole rock. Most of eclogite samples from Shuanghe display slight LREE-enriched patterns at 10 to 30 times the chondritic abundance without positive Eu anomaly, suggesting that they are not of cumulate origin (Fig. 2a). Unlike the eclogites from Bixiling, these do not show any negative Nb anomaly; they show positive anomalies in the primitive mantle-normalized spider diagrams (Fig. 2b), especially for retrograde eclogites (samples HT–2 and HT–12) with Nb/La ratios as high as 3.15–14.6 (see Table 1). The high Nb contents in some eclogites samples, for example, 20 ppm for sample HT–21 (see Table 1), could be caused by enrichment of rutile in these samples. However, the high Nb/La ratio could also be caused by loss of LREE through devolatilization during HP or UHP metamorphism or through retrograde metamorphic fluid. The loss of LREE during UHP or retrograde metamorphism can be observed more clearly from sample HT–12.

The retrograded eclogite (HT–12) in marble shows an unusual chemical composition with low MgO (3.62%) and SiO_2 (41.13%) and very high FeO (20.12%) and Zr (245 ppm) contents (Table 1). These features with relative higher Al_2O_3 and CaO contents suggest that the protolith of this sample is similar to iron-rich para-amphibolite, but not highly fractionated basalt because of its low SiO_2 content. It is interesting to note that the retrograded eclogite is strongly LREE depleted (Fig. 2a), but has very low initial ε_{Nd} value (-10) at retrograde time (200 Ma) (see Fig. 5A). It suggests that the protolith of sample HT–12 should be LREE enriched and the LREE depletion is caused by a recent loss of LREE during UHP or retrograde metamorphism. In view of the higher Nb/La ratios of retrograde eclogites (e.g., samples HT–2 and HT–12) than those of unretrograde eclogite (Table 1), the mobilization of LREE during retrograde metamorphism is more likely to be responsible for the loss of LREE. This may potentially influence the Nd isotopic composition of retrograde metamorphic minerals and whole rock.

Two UHP gneiss samples (HT–1–1 and HT–6) display different geochemical characters. Sample HT–1–1 has a high K_2O content with a high K_2O/Na_2O (2.22) ratio and a strong LREE-enriched pattern with high REE abundances as well as abundant detrital zircons suggesting a sedimentary origin. However, the relative lower K_2O content with low K_2O/Na_2O (0.68) of sample HT–6 and its REE pattern similar to those of eclogites (Fig. 2d) suggests that the protolith of sample HT–6 is more like to be an intermediate volcanic rock interbeded within basaltic eclogite.

According to the petrologic and geochemical features of the UHPM rocks discussed, protoliths of the UHPM unit at Shuanghe are volcanic–sedimentary rocks deposited in a shallow marine basin. Large variation in $\delta^{18}O$ values (-2.6 to $+7.0$ ‰) of garnet and omphacite associated with a small range in δD value (-83 to -73‰) of phengite from eclogite at Shuanghe suggest a characteristic ^{18}O shift to lower $\delta^{18}O$ values as a result of isotopic exchange with ^{18}O-depleted meteoric water before the UHPM (Zheng et al., 1998). Thus, these hydrothermal-altered volcanic–sedimentary rocks are expected to contain more water than deep mafic–ultramafic intrusions, such as the protoliths of the Bixiling eclogite (Chavagnac and Jahn, 1996). This difference in wet versus dry system could have an important effect on the Nd isotopic equilibrium between minerals during UHPM. This will be discussed in a later section.

The granitic gneiss sample (Sh–1,2) are of trondhjemitic

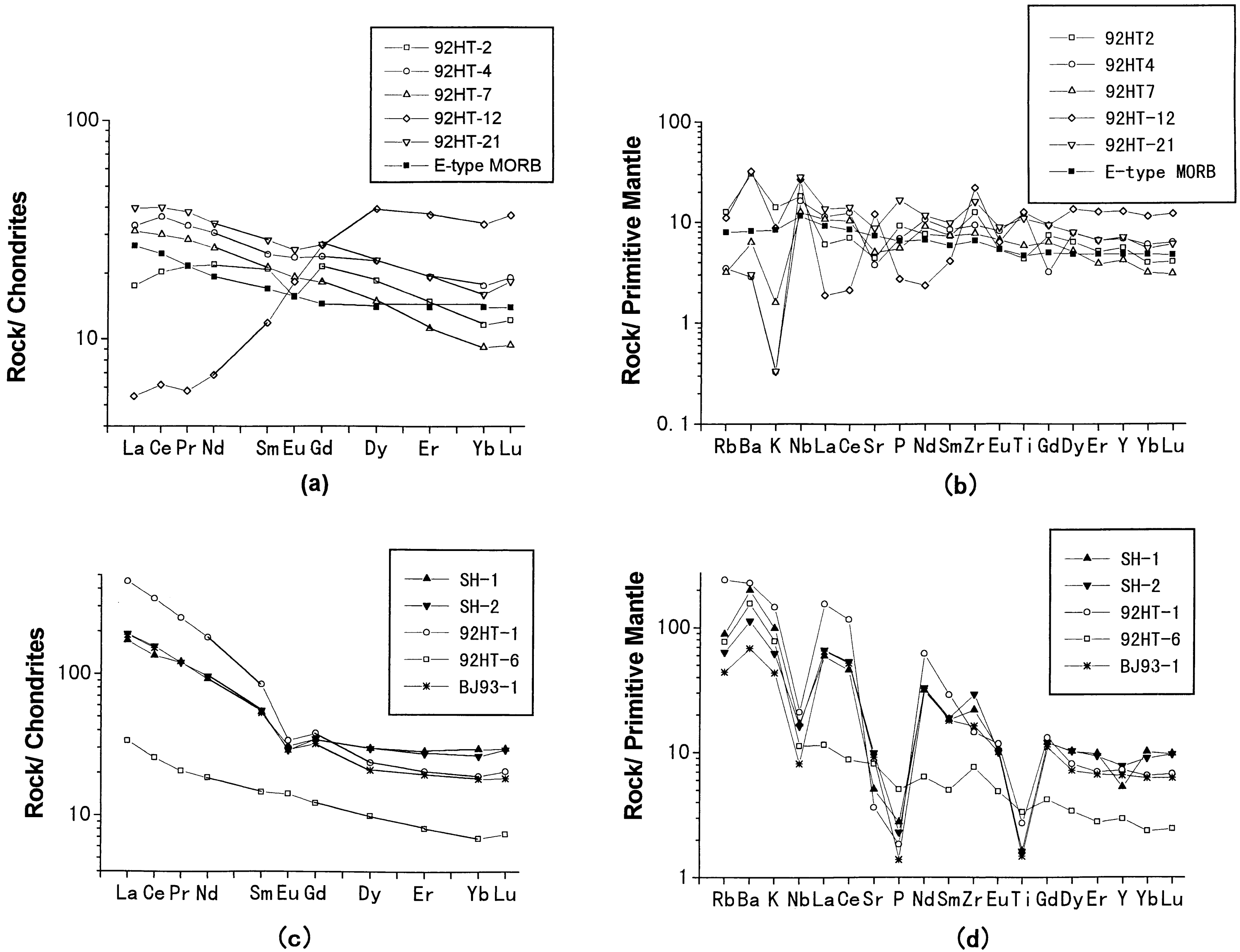

Fig. 2. REE distribution patterns and primitive mantle-normalized spiderdiagrams for the UHPM rocks and their country rock (granitic gneiss) from Shuanghe; (a, b), eclogites, Data of E-type MORB are based on Sun and McDonough (1989); (c, d), UHP gneiss and granitic gneiss, sample BJ 93–1 is granitic gneiss from Bixiling for comparison (Chavagnac and Jahn, 1996).

Table 2. Sm, Nd comcentrations and Nd isotope ratios for ultrahigh-pressure metamorphic rocks and their country rock from Shuanghe in the Dabie Mountains.[a]

Sample no.	Rock or mineral	Sm (ppm)	Nd (ppm)	$^{14}Sm/^{144}Nd$	$^{143}Sm/^{144}Nd \pm 2\sigma$
Ht–1–1 W	UHPM gneiss	11.59	71.72	0.1041	0.511236 ± 15
HT–1–1 gar	Garnet	3.231	1.034	1.887	0.514107 ± 13
Ht–1–1 phen 1	Phengite	0.01481	0.1285	0.06982	0.511424 ± 60
HT–1–1 phen 2	Phengite	0.007349	0.02850	0.1559	0.511539 ± 21
HT–1–1 bi	Biotite	0.01828	0.04015	0.2752	0.511561 ± 3
HT–1–1 epid	Epidote	17.07	32.40	0.3184	0.511525 ± 18
HT–4 W	Coesite-bearing Eclogite	3.612	12.31	0.1773	0.511940 ± 17
HT–4 gar	Garnet	2.529	1.263	1.210	0.513526 ± 18
HT–4 omph	Omphacite	1.208	3.021	0.2418	0.512096 ± 13
HT–4 rut	Rutile	0.8092	4.569	0.1070	0.511891 ± 13
HT–12 W	Retrograded eclogite	1.448	2.289	0.3824	0.512372 ± 13
HT–12 gar	Garnet	1.611	0.6713	1.451	0.514064 ± 15
HT–12 amph	Amphibole	0.6028	1.056	0.3450	0.512308 ± 14
HT–12 sphen	Sphene	26.59	62.04	0.2591	0.512197 ± 20
HT–12 apt	Apatite	202.5	761.0	0.1523	0.512055 ± 27
Sh–1 W	Granitic gneiss	6.635	33.99	0.1180	0.512040 ± 10
Sh–1 gar	Garnet	3.105	2.891	0.6491	0.512778 ± 15
Sh–1 bi	Biotite	0.07847	0.2574	0.1843	0.512137 ± 13
Sh–1 epid	Epidotite	122.4	651.8	0.1135	0.512027 ± 9

[a] The Sm–Nd data were obtained at MPI.

composition with high Na_2O (5.66–5.92%) and Na_2O/K_2O (1.91–3.25%) contents. Their trace element characters are similar to those of the granitic gneiss from Bixiling (Chavagnac and Jahn, 1996). They show a typical post-Archean granite REE pattern with enriched LREE, nearly flat HREE, and negative Eu anomaly (Fig. 2c). Negative anomalies of Nb, P, and Ti in spiderdiagrams are commonly observed for granitic or upper continental crust (Fig. 2d). It suggests that the Shuanghe UHPM unit and the Bixiling eclogite body are both encased in similar granitic gneiss.

4. ANALYTICAL PROCEDURES

After careful hand-picking under a binocular microscope, all mineral separates are 100% pure without any altered grain. Except for micas, mineral separates were leached by 2.5 N HCl at about 70°–80°C for 1 hr and then for 15 min in cold 5% HF to remove any surface contamination. We have observed that micas lost their Rb after acid leaching; hence, the micas were only ultrasonically cleaned in H_2O.

All Sm and Nd and part of Rb, Sr isotope data were obtained at the Max Plank Institute für Chemie, Germany, following procedures described elsewhere (Jagoutz, 1988; Thöni and Jagoutz, 1992). Rb and Sr isotope data of biotite, some phengite, and whole rock samples were obtained at the isotope laboratory of the Modern Analysis Center, Nanjing University, China (see Table 3). Blanks for the whole chemical procedures are <50 pg for Sm and Nd, 0.2 ng for Sr at the Max Plank Institute, and 1 ng for Sr at the Nanjing University. $^{143}Nd/^{144}Nd$ ratios were normalized against the value of $^{146}Nd/^{144}Nd$ = 0.7219. All Nd and Sr isotope ratios reported in this article are relative to values of 0.511878 ± 14 for the LaJolla Nd standard and 0.707987 ± 28 for the E&A Sr standard. Ages are calculated using the ISOPLOT software of Ludwig (1994) and given with 2σ error. The uncertainty, including all sources of error, of Rb/Sr ratios is ±2% and that of Sm/Nd ratios ±0.5%. The Sm–Nd data and Rb–Sr data are listed in Tables 2 and 3, respectively.

5. CHRONOLOGIC RESULTS

5.1. Sm–Nd Age of Eclogite HT–4

Figure 3 shows that the data points of three UHPM minerals (garnet + omphacite + rutile) of sample HT–4 define a perfect isochron, which gives an age of 226.3 ± 3.2 Ma with initial $^{143}Nd/^{144}Nd = 0.511735 \pm 11$, $\varepsilon_{Nd} = -11.9$. The whole rock lies below the mineral isochron in Figure 3, which suggests that not analyzed retrograde metamorphic minerals, such as amphibole, should have lower $^{143}Nd/^{144}Nd$ ratios than those of UHPM minerals. Thus, the line connecting garnet and whole rock will give an old age with no geologic significance. The good linear relationship between the three HPM minerals in Figure 3 suggests isotopic equilibrium between the UHPM minerals in eclogite from the Shuanghe area. Fine-grain mineral size of the eclogite and more water content in the precursors of the UHPM rocks at Shuanghe is likely to have facilitated isotopic equilibrium during UHP metamorphism.

5.2. Sm–Nd Age of UHPM Gneiss HT–1–1

Figure 4 shows that the isochron defined by garnet and two phengites of the sample HT–1–1 gives an age of 226.5 ± 2.3 Ma with initial $^{143}Nd/^{144}Nd = 0.511310 \pm 27$, $\varepsilon_{Nd} = -20.2$. This age is consistent with the Sm–Nd age of 226.3 ± 3.2 Ma obtained from eclogite (HT–4). It can be suggested that isotopic equilibrium between garnet and phengite has been achieved in the UHPM gneiss at Shuanghe and they remained a closed system during retrograde metamorphism. Retrograded biotite, epidote, and whole rock plot below this isochron (Fig. 4). These results suggest that the Nd isotopic system of the whole rock sample was open during retrograde metamorphism and Nd isotopic disequilibrium between UHPM minerals and retrograde metamorphic minerals. Similar to the case in sample HT–4, the data from sample HT–1–1 also indicates relative lower $^{143}Nd/^{144}Nd$ ratios of the retrograde metamorphic min-

Table 3. Rb, Sr concentrations and Sr isotope ratios for untrahigh-pressure metamorphic rocks and their country rock from Shuanghe in Dabie Mountains.

Sample no.	Rock or mineral	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$
HT–1–1 W[a]	UHPM gneiss	209.2	92.30	6.574	0.746840 ± 16
HT–1–1 phen[a]	Phengite	547.5	52.51	30.23	0.790577 ± 16
HT–1–1 bi	Biotite	502.1	2.811	518.0	2.011592 ± 26
HT–1–1 gar[a]	Garnet	3.660	1.073	9.892	0.727364 ± 19
HT–1–2 W	UHP gneiss	207.2	91.87	6.541	0.741803 ± 26
HT–1–2 phen	Phengite	471.5	61.26	22.32	0.787061 ± 24
97SH–3 W	UHP gneiss	193.7	102.4	5.548	0.735380 ± 17
97SH–3 phen	Phengite	448.3	53.58	24.26	0.780487 ± 15
97SH–3 epid	Epidote	14.88	1096	0.4008	0.723950 ± 17
HT–6 W[a]	UHP gneiss	55.31	209.2	0.7667	0.712260 ± 20
HT–6 bi	Biotite	257.6	4.893	152.7	1.103687 ± 20
H–6 W	UHP gneiss	108.6	496.3	0.6346	0.715684 ± 12
H–6 bi	Biotite	453.8	5.690	231.3	1.270487 ± 27
HT–12 W[a]	Retrograde eclogite	1.440	221.2	0.01888	0.704760 ± 23
HT–12 sphen[a]	Sphene	0.1653	86.77	0.005525	0.704794 ± 64
HT–12 amph[a]	Amphibole	9.548	74.49	0.3717	0.705632 ± 18
HT–12 gar[a]	Garnet	0.1337	7.577	0.05117	0.704811 ± 13
Sh–1 W[a]	Granitic gneiss	52.18	90.95	1.664	0.721718 ± 11
Sh–1 bi	Biotite	498.9	6.445	224.5	1.262966 ± 26
Sh–2 W	Granitic gneiss	77.04	220.1	1.015	0.712199 ± 23
Sh–2 bi	Biotite	601.7	14.91	117.0	0.997830 ± 22

a These samples were analyzed at MPI, and others were analyzed at the Nanjing University of China.

erals than those of UHPM minerals. Because the whole rock contains many retrograde minerals, the age of 246.0 ± 2.1 Ma given by the line connecting garnet and whole rock has no geologic significance. Figure 4 shows that the retrograde minerals (biotite and epidote) and whole rock cannot fit into a straight line suggesting Nd isotopic disequilibrium between the biotite and the epidote in this sample. Because of the much higher Nd content in epidote than in biotite (see Table 2), however, the line connecting epidote and whole rock gives a reasonable retrometamorphic age of 206 ± 16 Ma, which is consistent with the Sm–Nd age of 200 ± 23 Ma defined by retrograde minerals from sample HT–12 (see below).

5.3. Sm–Nd and Rb–Sr Ages of Retrograde Eclogite HT–12

Sample HT–12 is an intensely retrograded eclogite. All omphacites have been replaced by amphiboles and rutiles by titanite or ilmenites in this sample. Although samples HT–12 and HT–4 occurred in the same UHP unit, Figure 5A shows that the line fitted by garnet + whole rock yields an age of 242.0 ± 3.6 Ma, significantly older than the age of sample HT–4. Obviously, this line is not an isochron, because the amphibole is a retrograde phase and whole rock is basically a mixture of garnet and amphibole. It implies again that the retrograde fluid has a relative lower $^{143}Nd/^{144}Nd$ ratio than that of UHPM rocks at Shuanghe. Figure 5A also shows that the

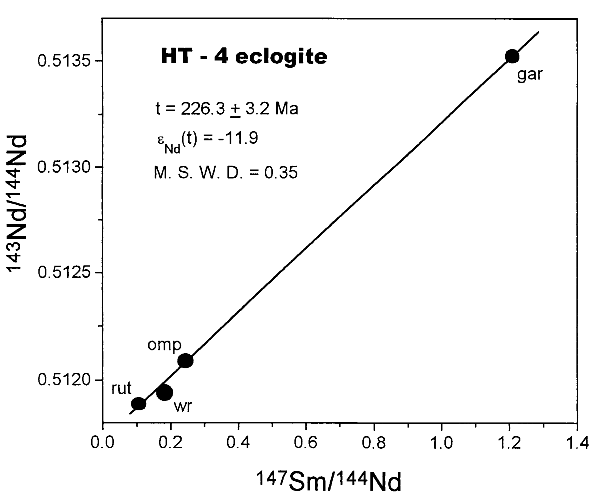

Fig. 3. Sm–Nd isotopic diagram of the coesite-bearing eclogite (HT–4) from Shuanghe.

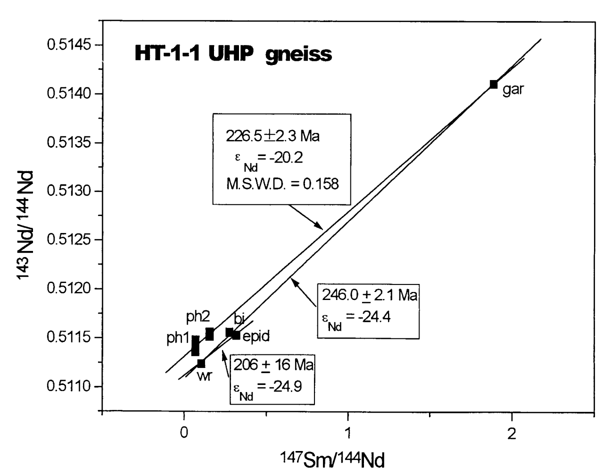

Fig. 4. Sm–Nd isotopic diagram of the UHP gneiss (HT–1–1) from Shuanghe.

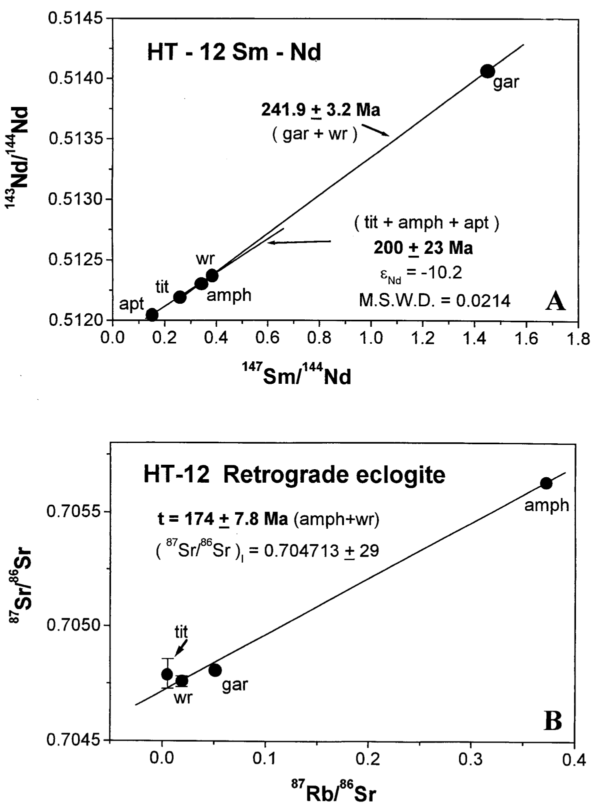

Fig. 5. Sm–Nd (A) and Rb–Sr (B) isotopic diagram of the retrograde eclogite (HT–12) from Shuanghe.

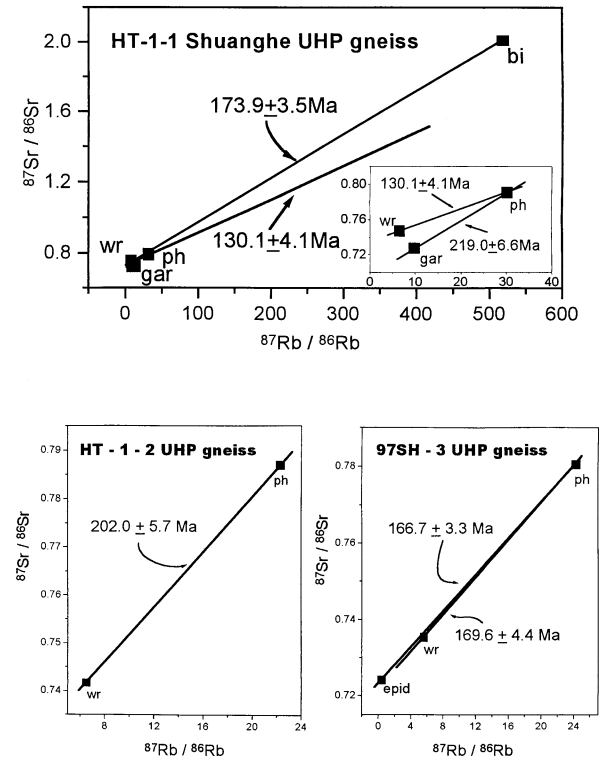

Fig. 6. Rb–Sr isotopic diagrams of the UHP gneisses (HT–1–1, HT–1–2, and 97SH–3) from Shuanghe.

line fitted by three retrograde minerals, amphibole, titanite, and apatite, gives a younger age of 200 ± 23 Ma with $\varepsilon_{Nd} = -10.2$. The good linearity (M.S.W.D. = 0.02) of this isochron suggests the Nd isotopic equilibrium between the three retrograde minerals. The age of 200 ± 23 Ma for the retrograde minerals of sample Ht–12 as well as the age of 206 ± 16 Ma for the epidote of sample HT–1–1 roughly indicates that the recrystallization of retrometamorphic minerals with amphibolite facies in the UHP eclogite could have occurred around 200 Ma. The corresponding pressure–temperature condition of this stage has been estimated to be 450°–500°C at 8 kbar (Carswell et al., 1998).

Figure 5B shows a little scatter of amphibole, whole rocks, and titanite, which may be caused by the large uncertainty of $^{87}Sr/^{86}Sr$ of the titanite. Thus, the Rb–Sr isochron defined by the two retrograde minerals and whole rock gives an unprecise age of 172 ± 84 Ma. The Rb–Sr isochron defined by amphibole + whole rock gives a similar but more precise age of 174 ± 7.8 Ma (Fig. 5B). Garnet falls below this isochron, which suggests that Rb–Sr of the garnet was not reset during retrograde metamorphism. Because the slope of the Rb–Sr isochron is mainly controlled by amphibole, this age may indicate the closure time of the Rb–Sr system in amphibole. Unfortunately, we do not exactly know the closure temperature (Tc) of the Rb–Sr system in amphibole. However, based on our study of the North Qinling belt we know that the Rb–Sr ages of 414 ± 1 to 410 ± 2 Ma defined by amphibole + plagioclase + whole rock for amphibolite are always similar to or only slightly lower than Ar–Ar ages of 426 ± 2 Ma for the amphibole (Sun et al., 1996), but significantly older than the Ar–Ar ages of 351 ± 4 Ma for the biotite (Tc = 300°C) from the same area (Sun et al., 1996; Li et al., unpublished data). These results suggest that the Tc of the Rb–Sr system in amphibole is similar or slightly lower than the Tc (500°C) of Ar in amphibole (Harrison, 1981). Hence, we chose 450 ± 50°C as the Tc of the Rb–Sr system in amphibole for the following T–t path plotting.

5.4. Rb–Sr Ages of Phengite and Biotite From UHP Gneisses

Figure 6 shows that phengite from samples HT–1–1, HT–1–2, and 97 SH–3 gives a large variation in Rb –Sr ages. The lines connecting phengite and garnet for sample HT–1–1 gives an age of 219.0 ± 6.6 Ma, whereas the line connecting phengite and whole rock for these three samples give ages of 130.1 ± 4.1 Ma, 202.0 ± 5.7 Ma, and 169.6 ± 4.4 Ma, respectively. The age of 130.1 ± 4.1 Ma for phengite from sample HT–1–1 is much younger than the Rb–Sr age of biotite from the same sample (see Fig. 6), although the closure temperature of phengite is 200°C higher than that of biotite. We suggest that the open system during retrograde metamorphism of UHPM rocks and the Sr isotopic disequilibrium between UHPM minerals and retrograde metamorphic minerals are responsible for the large uncertainty and the reversal of phengite and biotite ages. We will discuss this later in detail.

Biotites + whole rocks from samples HT–1–1, HT–6, and H–6 yield ages of 173.9 ± 3.5 Ma, 181.2 ± 3.5 Ma, and

Table 4. Rb–Sr ages defined by biotite + whole rock from the Shuanghe area.

Rock	Sample no.	Age (Ma)	Data source
UHP fneiss	HT-1-1	173.9 ± 3.5	This work
	H-6	169.2 ± 3.3	This work
	HT-6	181.2 ± 3.5	This work
Granitic gneiss	Sh-1	170.8 ± 3.4	This work
	Sh-2	173.2 ± 3.4	This work
	—	181	Jahn et al., 1994

169.2 ± 3.3 Ma, respectively (Table 4). These ages are consistent with the Rb–Sr age of 179 ± 4 Ma defined by biotite + whole rock for the Bixiling eclogite within error limits (Chavagnac and Jahn, 1996). The age variation of about 10 Ma for biotite is much less than that of phengite from the same UHP unit. It suggests that retrograde biotite + whole rock may yield a meaningful Rb–Sr age. Because biotite is high in Rb/Sr ratio, these isochron ages could be considered to indicate the time of the rock cooling through the closure temperature of biotite, which is about 300°C (Dodson, 1973). The potential causes for the spread in ages will be discussed later in the discussion section.

5.5. Sm–Nd Age of Granitic Gneiss

Figure 7 shows that garnet, biotite, epidote, and whole rock from sample Sh–1 define an isochron that gives an age of 213.3 ± 4.8 Ma with $\varepsilon_{Nd}(t) = -9.5$. The good linearity of the three minerals in Figure 7 suggests the Nd isotopic equilibrium within garnet, biotite, and epidote. Because biotite and epidote are retrograde minerals as indicated by Carswell et al. (1998), the Nd isotopic equilibrium between garnet and retrograde minerals must be reached during retrograde metamorphism. Thus, the age of 213.3 ± 4.8 Ma may be interpreted as the retrograde metamorphic age corresponding to amphibolite facies with metamorphic temperature of 530 ± 20°C (Cong et al., 1995) or 450°C (Carswell et al., 1998). If it is true and in view of the Rb–Sr cooling age of 219.0 ± 6.6 Ma for the phengite from the UHP paragneiss (sample HT–1–1), our data suggest that both UHPM rocks and their country rock (granitic gneiss) had been cooled down to about 500°C at about the same time.

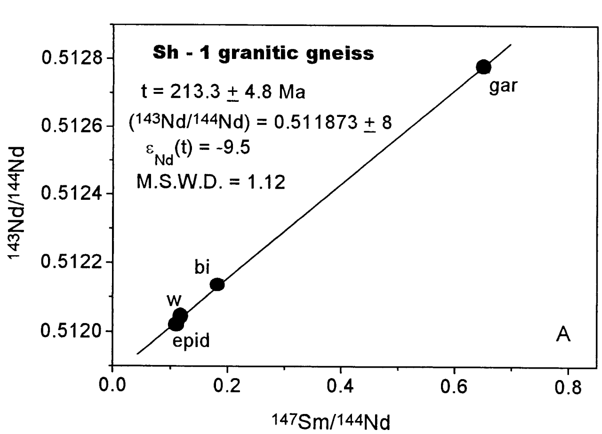

Fig. 7. Sm–Nd isotopic diagram of the granitic gneisses (Sh–1) from Shuanghe.

Now, we have observed that the Sm–Nd isotopic systematics of garnets from the UHP paragneiss and granitic gneiss at Shuanghe are different. The garnet in UHP paragneiss keeps closed and is in disequilibrium with the retrograde minerals during retrograde metamorphism, whereas the garnet in granitic gneiss can be reequilibrated with the retrograde minerals during retrograde metamorphism. It is still unknown why the garnet in granitic gneiss is more easily influenced by retrograde metamorphism than garnet in UHP paragneiss. Perhaps the high Mn garnet in granitic gneiss is of retrograde origin. This is indeed a challenge to metamorphic petrology.

5.6. Rb–Sr Age of Biotite From Granitic Gneiss

Two biotite samples + whole rocks from the granitic gneiss give two consistent Rb–Sr ages of 170.8 ± 3.4 Ma and 173.2 ± 3.4 Ma (Table 4), which are consistent with their $^{40}Ar/^{39}Ar$ ages of 170–177 Ma (Li and Lo, 2000). These ages are also consistent with the Rb–Sr ages of the biotite from the UHPM rocks. It suggests that both UHPM rocks and their country rocks (granitic orthogneiss) were cooled down to 300°C at the same time.

6. DISCUSSION

6.1. Peak Metamorphic Age of the UHPM Rocks in Dabie Mountains

A correct estimate of the time of peak metamorphism of the UHPM rocks is very important to the calculation of the initial cooling rate. We have reported two consistent Sm–Nd ages of 226.3 ± 3.2 Ma and 226.5 ± 2.3 Ma for eclogite and UHP paragneiss from Shuanghe, respectively. Nd isotopic equilibrium between UHPM minerals during UHP metamorphism in these samples has been demonstrated by the perfect isochron defined by three UHP minerals. Another reported Sm–Nd age of 225 ± 2 Ma for eclogite (sample 92HSH–4) from the same area is consistent with our present results (Ge et al., 1995). What is the significance of these Sm–Nd ages? Do they indicate the time of UHP peak metamorphism at Shuanghe or do they only represent a cooling age? The significance of these Sm–Nd ages depends on peak metamorphic temperature of the eclogite, closure temperatures of the major HPM minerals, i.e., garnet and omphacite and diffusion of Nd isotopes during recrystallization of HPM minerals.

Closure temperatures (Tc) of the Sm–Nd system in garnet are not well defined and controversial. On the basis of the Sm diffusion coefficient in garnet, Humphries and Cliff (1982) calculated the Tc of pyrope close to 500°C and grossular up to 700°C for typical metamorphic grain sized (1 mm) and orogenic cooling rate (10°C/Ma). Mezger et al. (1992) concluded that the Tc of Sm–Nd system in garnet is 600 ± 30°C for slow cooling rate (2–4°C/Ma) by comparing the garnet + whole rock Sm–Nd age with other geochronologic data and temperatures estimated on the same geologic unit. Other lines of evidence, however, suggest that Sm–Nd diffusion in garnet may be significantly slower than that suggested by these results. On the basis of the study of the Sm–Nd system in an eclogite xenolith from kimberlite, Jagoutz (1988) proposed a high Tc of

850°C for garnet under dry condition. Hensen and Zhou (1995) also suggests that the closure temperature for the Sm–Nd system in garnet must be >700–750°C in an dry mafic granulite. Actually, the closure temperature for any given element in garnet is dependent on a number of factors, including grain size, availability of pore fluid, major element composition, the nature of coexisting phases, initial temperature, and the cooling rate experienced by each individual sample (Dodson, 1973; Burton et al., 1995; Ganguly et al., 1998). Therefore, garnet is unlikely to possess a unique closure temperature for Nd, but may has a range from 500° to 850°C, depending on variable conditions. We have to consider all factors mentioned previously to estimate the closure temperature for a specific sample.

A Tc range of 1040°–1090°C for clinopyroxene with a radius of 1 mm and cooling rates of 10°–40°C/Ma can be calculated using the Sm diffusion coefficient of diopside under high-pressure condition (Sneeringer et al., 1984). It is significantly higher than all the possible Tc (500°–850°C) of garnet. Burton et al. (1995) also observed that the diffusion rates of Sm and Nd in clinopyroxene are lower than those in garnet. Because eclogite is basically a bimineral rock, garnets cannot exchange Sm–Nd after the pyroxene has closed to diffusion. Because the average peak metamorphic temperatures (800°C) of the eclogites at Shuanghe is lower than the Tc of clinopyroxene, the equilibrium of Nd isotopes between garnet and pyroxene is difficult to be achieved by diffusion. There are three possible ways to interpret the isotopic equilibration between UHP minerals:

1. Nd isotopic equilibration may be achieved by decomposition of preexisting minerals, such as plageoclase and amphibole, under UPH condition. Decomposition of preexisting minerals and formation of garnet and omphacite could be completed during progressive eclogitic metamorphism, but not necessarily at the peak UHP metamorphic stage. If the following recrystallization during whole HP and UHP metamorphic stages could not affect the Nd isotopic equilibration between garnet and omphacite because of high Tc of clinopyroxene, the Sm–Nd mineral isochron age of 226.2 ± 3.2 Ma for eclogite (HT–4) may indicate the progressive metamorphic time. However, this interpretation is inconsistent with the result of the UHP geiss sample HT–1–1, in which the absence of clinopyroxene do not affect any change of the Sm–Nd ages defined by garnet and two phengites. The consistence between the age of 226.3 ± 3.2 Ma for eclogite and age of 226.5 ± 2.3 Ma for UHP gneiss suggests that the high Tc of clinopyroxene is not an important factor for the isotopic equilibrium between UHPM minerals.
2. Villa (1998) has indicated that the isotopic diffusion during fluid-assisted recrystallization is orders of magnitude faster than the thermal-only volume diffusion in the absence of any recrystallization. Hence, recrystallization of garnet and omphacite could be an important factor for the isotopic equilibrium between them. As a extreme case, if the Nd isotopic compositions were completely reset during recrystallization (no isotopic zoning in a mineral grain), the Sm–Nd age of 226 Ma for the eclogite and UHP gneiss at Shuanghe should indicate the time of the final stage in recrystallization process that corresponded to the quartz–eclogite stage (pressure 13–16 kbar, temperature 630°–760°C) (Cong et al., 1995). However, this extreme case is unlikely because preservation of Ar isotopic zoning in phengites from Alpine and Dabie–Su–Lu eclogites (Scaillet 1996; M. Cosca, personal communication, 1999) suggests that isotopes is difficult to be completely equilibrated in a rapid cooling UHPM mineral grain by volume diffusion. In addition, this age interpretation is in contradiction with the U–Pb zircon ≈ 225 Ma ages of UHPM rocks (see below).
3. Because boundary diffusion is much faster than volume diffusion, isotopic equilibration could be easily achieved along the boundary layers of the growing minerals during recrystallization. However, when these older boundary layers were covered by new overgrowth zone, it is hard to be reequilibrated by volume diffusion. The real isotopic equilibrium between UHPM minerals is only surface equilibration, which is in between the above two extreme cases. In this case, the Sm–Nd mineral isochron age of 226 ± 3 Ma may indicate the average age of recrystallization time. If the growth of garnet and omphacite were continued during the whole HP and UHP metamorphic stage, the average of recrystallization time may close to the peak metamorphic time.

The third interpretation is favoured by us as it is supported by the ages obtained by other independent studies using different isotopic systems. For example, the Sm–Nd isochron of the coesite-bearing eclogite (QL–1) from Qinglongshan, located in the Su–Lu terrane, defined by three UHPM minerals (garnet + omphacite + phengite) + whole rock gives an age of 226.3 ± 4.5 Ma, which is almost the same to the Sm–Nd ages of the sample HT–4 and HT–1–1 from Shuanghe (Li et al., 1994). Rowley et al. (1997) reported one U–Pb zircon lower intercept age of 225.5 + 2.9/−6.3 Ma for eclogite (sample MW03) from Maowu in the Dabie Mountains. This U–Pb age is consistent with our Sm–Nd ages. The SHRIMP ages of 225 ± 4 Ma on zircon from a UHPM gneiss in the Dabie Mountains is also consistent with our Sm–Nd ages (Hacker et al., 1998). Therefore, the Sm–Nd age of 226 ± 3 Ma for eclogite from Shuanghe is more likely to be true peak metamorphic time of eclogite in the Dabie Mountains.

Chavagnac and Jahn (1996) reported seven slightly younger Sm–Nd ages ranging from 210 ± 7 Ma to 218 ± 4 Ma for the Bixiling eclogite block. Because all of these ages are given by two UHPM minerals (i.e., garnet and omphacite) isochrons, the possibility of Nd isotopic disequilibrium between UHPM minerals, which could lower the slop of tie-line between garnet and omphacite (Jagoutz, 1994), cannot be rule out.

Okay and Sengör (1993) reported an older garnet + whole rock Sm–Nd age of 246 ± 8 Ma. According to their description, however, this sample is an intense retrograde eclogite in marbles as an enclave in the Wuhe area. All omphacites have been replaced by amphiboles. As mentioned above, this old age is caused by abundant retrograde minerals in the whole rock sample.

6.2. Sr–Nd Isotopic Systematics of UHPM Rocks During Retrograde Metamorphism

Data presented in this article have shown that the Nd isotopic systems of the most UHPM minerals (e.g., garnet, omphacite,

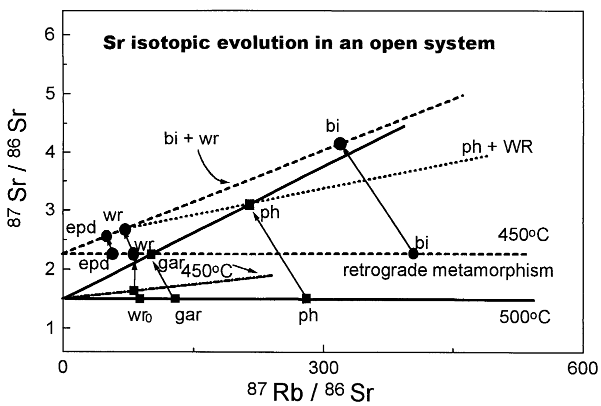

Fig. 8. Sr isotope evolution diagram of UHP minerals (phengite + garnet) and retrograde minerals (epidote + biotite) as well as whole rock in an open system (see text for explanation). wr_0 shows initial isotopic composition of whole rock before retrograde metamorphism; wr shows the whole rock isotopic composition after retrograde metamorphism.

rutile, and phengite) remain closed, whereas the Nd isotopic system of the whole rock containing retrograde minerals was open during retrograde metamorphism. In general, the retrograde metamorphic fluid has relative lower ^{143}Nd to ^{144}Nd ratios than that of eclogite. Hence, the tie-line of garnet and whole rock containing retrograde minerals may give a relative older Sm–Nd age than the peak metamorphic age (see Figs. 3 and 4).

Similarly, Rb–Sr data of sample HT–1–1 (Fig. 6) suggest that the Sr isotopic compositions of phengite and garnet were not reset during retrograde metamorphism, whereas ^{87}Sr/^{86}Sr of whole rock containing epidote and biotite was modified to higher value by fluids introducing higher Rb/Sr or more radiogenic Sr during retrograde metamorphism. Because Sr closure temperature of clinopyroxene and garnet are similar to those of Sm–Nd in the same minerals (Sneeringer et al., 1984; Burton et al., 1995) it may be reasonable to assume that the Sr isotopic systems of garnet, omphacite, and phengite remain closed. Although the later generation mineral phases (e.g., biotite and epidote) grew during the retrograde metamorphism in an open chemical system. Due to the relative higher ^{87}Sr to ^{86}Sr ratio of retrograde metamorphic fluid, the later generation phases would have a higher initial ^{87}Sr/^{86}Sr value (Fig. 8). Thus, the whole rock isotopic composition is also modified to have a higher ^{87}Sr to ^{86}Sr ratio by retrograde metamorphism (see Fig. 8). As time went on, these two Rb–Sr isotopic systems would evolve independently (shown as the solid and dash line in Fig. 8, respectively). In this case regressions of data for these two isotopic systems separately will yield two different isochron ages that may closely represent the cooling ages after metamorphic events. However, any linear regression involving two generation phases or the line connecting phengite and retrograde whole rock (shown as the dotted line in Fig. 8) should be considered as a "mixing line" or an "errochron" rather as an "isochron." The age inferred by the tie-line of phengite + whole rock will be geologically meaningless, even it could be much younger than the biotite cooling age (see Fig. 8).

Because the Sr closure temperature of garnet is ≈750°C (Burton et al., 1995), which is much higher than the Sr closure temperature (500°C) of phengite (Cliff, 1985), the line connecting phengite and garnet from a slow cooling rock may introduce a large error in the closure temperature age of phengite. However, because the UHPM rock cools rapidly above 500°C (Li et al., 1994; Chavagnac and Jahn, 1996; Gebauer et al., 1997), much lower Rb/Sr ratios of garnet and omphacite than that of phengite and the whole rock system of some unretrograde eclogites remains closed, the phengite and garnet (or amphacite) with different closure temperatures and unretrograde whole rock are likely to fall on a straight line in a Rb–Sr isochron diagram. The slope of that line can be taken to represent the cooling age of phengite. For example, the isochrons defined by phengite + garnet (or + omphacite) + whole rock of the samples QL–1 and ZB–4 from the Su–Lu terrane (Li et al., 1994) and the samples BJ93–05 and BJ93–07 from Bixiling in the Dabie Mountains (Chavagnac and Jahn, 1996) yield the Rb–Sr ages of 220 ± 2, 224 ± 2, 214 ± 6, and 223 ± 13 Ma, respectively, which are consistent with each other within error limits. All these ages suggest that the most UHPM rocks in the Dabie–Su–Lu terranes may have cooled down to 500°C at 219 ± 5 Ma.

In light of the above discussion, the Rb–Sr age of 219.0 ± 6.6 Ma defined by phengite + garnet for sample HT–1–1 from Shuanghe can be taken to represent the closure age of phengite at 500°C. This age is consistent with the above mentioned phengite Rb–Sr ages for unretrograde eclogite. Other younger Rb–Sr ages of 130.1 ± 4.1, 169.6 ± 4.4, and 202.0 ± 5.7 Ma defined by phengite + whole rock for sample HT–1–1, 97SH–3, and HT–1–2 (see Fig. 6) have no geologic significance. The samples HT–1–1 and 97SH–3 contain more abundant biotite than sample HT–1–2, which could be the reason why the phengite–whole rock Rb–Sr ages of the samples HT–1–1 and 97SH–3 are much younger than that of sample HT–1–2.

It should be noted that the Rb–Sr ages defined by phengite + whole rock for the granitic gneiss in the Dabie–Su–Lu terrane range from 194 to 198 Ma (Jahn et al., 1994; Chavagnac and Jahn, 1998), which are significantly younger than the phengite Rb–Sr ages for UHPM rocks. This would not be surprised to us if we considered that the most of phengitic white mica in granitic gneiss have much lower Si contents (Si = 3.2 to 3.3), but are not real UHPM minerals as suggested by Carswell et al. (1998). This kind of white mica coexisting with biotite has been suggested to be formed during retrograde metamorphism at temperature 450°C (Carswell et al., 1998). Therefore, the Rb–Sr ages of 194 to 198 Ma for white micas from the granitic gneiss cannot be taken to represent the closure age at 500°C, but correspond to the retrometamorphic temperature of 450°C.

Biotite and amphibole are retrograde metamorphic minerals in UHPM rocks. Hence only on condition that the Sr isotopic system of whole rock was reset during retrograde metamorphism, the Rb–Sr age given by the line connecting biotite or amphibole and whole rock can be regarded as the best estimation of the closure age of biotite or amphibole. Intensely retrograded metamorphic rocks, such as samples HT–1–1, H–6, and HT–12, may approximately satisfy this condition. Garnet or phengite are the major residual UHPM minerals in intensely retrograded metamorphic rocks. Although the Sr isotopic compositions of garnet and phengite may not be reset during

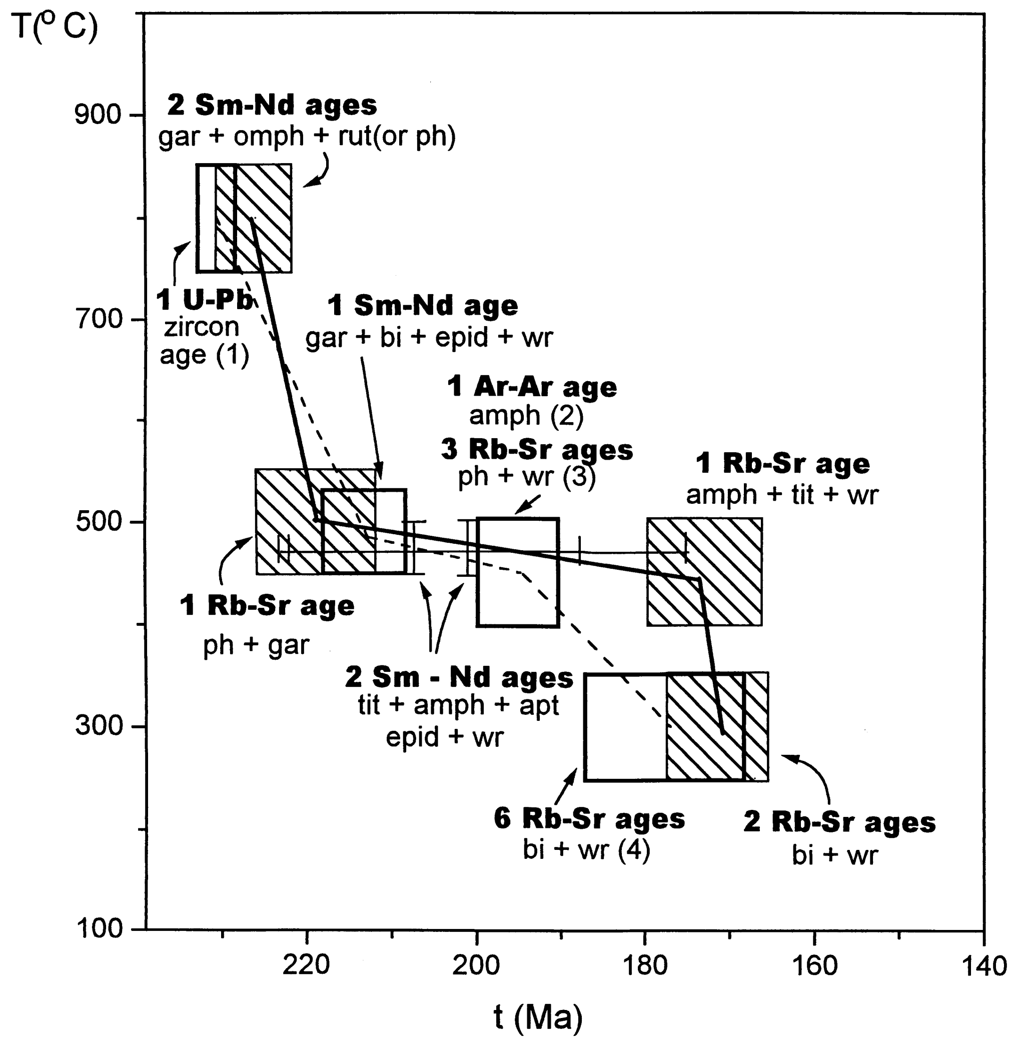

Fig. 9. T–t path of UHPM rocks and their country rocks at Shuanghe. The hatched squares represent UHPM rocks. The open squares represent granitic gneiss. The solid line shows the T–t path of UHPM rocks and the dash line shows the T–t path of granitic gneiss (see text for explanation). Data sources: (1) Hacker et al., 1998; (2) Chen et al., 1995; (3) Jahn et al., 1994; Chavagnac and Jahn, 1998; (4) this work; Jahn et al., 1994; Chavagnac and Jahn, 1998. Other ages are presented in this article.

retrograde metamorphism, because of its small proportion in this kind of rocks and low Sr content, as well as the very high Rb/Sr and $^{87}Sr/^{86}Sr$ ratios of biotite, the Sr isotopic composition of the whole rock may not be influenced significantly by these relict UHPM minerals. However, if there are more abundant residual UHPM minerals, in retrograde UHPM rocks such as sample HT–6, the line connecting biotite or amphibole and whole rock will yield an older Rb–Sr age than its closure age, because the $^{87}Sr/^{86}Sr$ of UHPM minerals, in general, is lower than those of retrograde metamorphic minerals. In addition to the large analytical errors for Rb/Sr this may be the major reason for the spread in biotite + whole rock Rb–Sr ages. In light of the above discussion, we would suggest that Rb–Sr ages of 169.2 ± 3.3 Ma and 173.9 ± 3.5 Ma defined by biotite + whole rock for sample H–6 and HT–1–1 may be the best estimation of the closure age of the biotite from the Shuanghe UHPM paragneiss at 300°C. These ages are also consistent with the Rb–Sr ages of 170.8 ± 3.4 Ma and 173.2 ± 3.4 Ma defined by biotite + whole rock from the Shuanghe granitic gneiss. It is interesting to note that these Rb–Sr cooling ages of biotite are consistent with the Rb–Sr age (174 ± 7.8 Ma) of the amphibole from eclogite, which may suggest a rapid cooling of UHPM rocks in the Dabie Mountains during 180 to 170 Ma.

6.3. Cooling History of UHPM Rocks

On the basis of the above chronology data with corresponding closure or metamorphic temperatures, a T–t path for UHPM rocks at Shuanghe has been obtained (shown as solid line in Fig. 9). Three points in this T–t path (i.e., the peak metamorphic age of 226 ± 3 Ma, Rb–Sr cooling age of 219 ± 7 Ma for phengite, and Rb–Sr cooling age of 172 ± 6 Ma for biotite) are firmly supported by other published chronology data as mentioned above. The Rb–Sr cooling age of 174 ± 7.8 Ma for amphibole is the first time such age for amphibole is reported for the Dabie UHPM rocks. Obviously, this important point on the T–t path should be confirmed by more data in the future. However, the following arguments suggest that this cooling age is plausible: (1) As mentioned, the two Sm–Nd ages of 200 ± 23 Ma and 206 ± 16 Ma for amphibole facies retrograde minerals from samples HT–12 and HT–1–1 indicate their recrystallization time. Thus, their Rb–Sr cooling age should be younger than these ages. (2) A U–Pb age of ≈180 Ma for rutile from the Yangkou eclogite in the Su–Lu terrane also suggests that the UHPM rocks has been cooled down to about 420°C at that time range (Lu, 1998; Li Huimin, personal communication, 1999).

The T–t path in Figure 9 shows that the cooling history of the UHPM rocks from 800° to 300°C can be subdivided into three stages: two rapid cooling stages and one isothermal stage in between them. They may reflect two rapid uplift processes during the exhumation history. Even if the Rb–Sr cooling age of 174 ± 7.8 Ma for amphibole cannot be substantiated by future study, the T–t curve on Figure 9 can still be divided into three stages with a bend around 200 Ma defined by two Sm–Nd ages of retrograde minerals.

The initial rapid cooling with cooling rate of about 40°C/Ma during 226 ± 3 and 219 ± 7 Ma may result from a rapid uplifting or decompression of UHPM rocks after the peak metamorphism. The T–t path shows that the temperature of UHPM rocks at Shuanghe was cooled down to 500°C at 219 ± 7 Ma by the initial rapid cooling, which corresponds to the symplectite stage with pressure condition of about 6–8 kbar (Cong et al., 1995). It implies that the UHPM rocks were uplifted to the middle continental crust level by the first uplifting process. The very high initial cooling rate recorded in the Shuanghe UHPM unit is consistent with those observed on the other UHPM units, such as the Qinglongshan and Zhubian eclogites in the Su–Lu terrane (Li et al., 1994), Bixiling eclogite in the Dabie Mountains (Chavagnac and Jahn, 1996), and Dora Maira massif in western Alps (Gebauer et al., 1997). Hence, it could be a common cooling pattern for UHPM rocks in collisional orogenic belt.

There was a isothermal stage between 219 ± 7 Ma and 174 ± 7.8 Ma for the UHPM rocks at Shuanghe. The pressure and temperature conditions corresponding to amphibolite facies in this stage resulted in recrystallization of the fine-grained symplectite minerals. The Sm–Nd ages of 200 ± 23 Ma and 206 ± 16 Ma for retrograde minerals (e.g., amphibole, titanite, and apatite) from the samples HT–12 and HT–1–1 may indicate their recrystallization time (Fig. 9).

The second rapid cooling from 450° to 300°C during 174 ± 7.8 to 172 ± 6 Ma may be caused by the second uplifting process of UHPM rocks. This is corresponding to the post-symplectite stage suggested by Cong et al. (1995). The UHPM rocks at Shuanghe could be uplifted to the upper crust level after the second rapid cooling.

6.4. Cooling History of the Country Rock

Hacker et al. (1998) reported a precise SHRIMP age of 231 ± 2 Ma for the zircons from a granitic gneiss in the South Dabie UHPM zone. This sample has identical mineralogy to granitic gneiss at Shuanghe. Thus, Hacker et al. (1998) suggest that the peak metamorphic age of the granitic gneiss is indistinguishable from that of the UHPM rocks in the Dabie Mountains. In addition, Carswell et al (1998) indicate that the peak metamorphic temperature of the granitic orthogneiss can be calculated using garnet–phengite geothermometer for the highest Si phengites, which bracket the better constrained temperatures at Pmax recorded in both the UHP paragneiss and eclogites. Therefore, the Sm–Nd cooling age of 213 ± 5 Ma corresponding to amphibolite facies (temperature 530° to 450°C) for the granitic gneiss at Shuanghe suggests that the country rocks also experienced a fast cooling from 800°C to 490° ± 40°C during 231 to 213 Ma (see Fig. 9).

Table 5. Rapid cooling events of the granitic gneiss in Dabie–Sulu belt.

Author	Dating method	Rapid cooling time and rate
Chen Wenji et al. (1992)	Ar–Ar (MDD model)	172–196 Ma (10–40°C/Ma) 105–123 Ma (4–10°C/Ma)
Chen Jiangfang (1995)	Ar–Ar (Hrb. Bi)	193–180 Ma
Li Qi et al. (1995)	Ar–Ar (MDD model)	165–163 Ma(Dabie) 187–180 Ma(Sulu)

Because there is little white mica and no hornblende in the sample SH–1, the second rapid cooling for the granitic gneiss at Shuanghe has not been revealed in this study. However, the rapid cooling from 450° to 300°C during 195 to 165 Ma for the country rocks, granitic gneiss, in the south Dabie zone and Su–Lu terrane has been demonstrated by several $^{39}Ar/^{40}Ar$ thermochronologic studies (see Table 5). In addition, two Rb–Sr ages of 195 Ma and 188 Ma for muscovite and biotite from granitic gneiss at Hushan, which is near Qinglongshan in the Su–Lu terrane, have been reported (Jahn et al., 1994). As mentioned, Carswell et al. (1998) have indicated that this muscovite is formed during retrograde metamorphism at the temperature around 450°C. Thus, the two Rb–Sr ages also suggests a rapid cooling (≈21°C/Ma) of the granitic gneiss in Su–Lu terrane during 195 to 188 Ma. Similar Rb–Sr ages of 194 to 198 Ma for muscovite and 170 to 184 Ma for biotite from the country rocks, tonalitic gneiss, of the Bixiling eclogites in Dabie Mountains have been recently reported by Chavagnac and Jahn (1998). Their new Rb–Sr age data suggest that the country rocks of the Bixiling eclogite have experienced a rapid cooling (8°C/Ma) during 196 to 177 Ma. We believe that the granitic gneiss at Shuanghe should have similar cooling history to other granitic gneiss in the southern Dabie zone (i.e., it underwent a rapid cooling between 190 and 175 Ma below 450°C).

Summarizing the all chronologic data mentioned, a T–t path for the regional granitic gneisses in the Dabie–Su–Lu terrane has been obtained (shown as dash line in Fig. 9). It shows that the country rocks of the UHPM units in the Dabie–Su–Lu terrane have also experienced the two rapid cooling events between 230 and 213 Ma and 195 and 175 Ma. The similarity of the cooling histories between the UHPM units and granitic gneiss in the Dabie Mountains suggests that both the UHPM rocks and their country rocks may have exhumed together from the mantle depth to the upper crustal level.

6.5. Constraints on Exhumation Model of UHPM Rocks

Many exhumation models of UHPM rocks in orogenic belt have been proposed (Anderson et al., 1991; Dobretsov, 1991; Hsü, 1991; Okey and Sengör, 1992; Maruyama et al., 1994; Chemenda et al., 1995, 1996; Davies and Blanekenburg, 1995; Ernst and Liou, 1995; Hacker et al., 1995; Xue et al., 1996). Most of the researchers suggest one initial rapid uplifting process to account for the preservation of coesite in UHPM rocks during their exhumation process, which was followed by a slow uplifting over a long time. Two different exhumation mechanisms for the initial rapid uplifting (i.e., thrusting of UHPM slabs) (e.g., Chemenda et al., 1995, 1996) or breakoff of subducting oceanic lithosphere (e.g., Davies and Blanekenburg, 1995; Ernst and Liou, 1995) have been emphasized by different investigators. However, the two stages of rapid cooling of the UHPM rocks established above most likely correspond to two stages of fast uplift. They call for reconsideration of the exhumation model. The mechanisms of these two uplift events could be different, because they occurred separately at different times, which may correspond two different tectonic regimes in the Dabie–Su–Lu belt.

The Dabie–Su–Lu belt was in a compression regime in the early-to-middle Triassic, which is recorded by the UHP metamorphism in this belt. The extension tectonics in the Dabie–Su–Lu belt could begin at the middle Jurassic (≈180–170 Ma), which is suggested by the middle Jurassic basal molasses-type sediments in the Beihuaiyang terrane, which is the internal basin in the Dabie Mountains during the Jurassic and Cretaceous (Xu et al., 1994). Consequently, we suggest that the earlier rapid cooling may reflect the exhumation of the UHPM rocks including granitic gneiss from mantle depth to the middle crustal level by compression tectonics during the continental subduction (such as thrusting model suggested by Chemenda et al., 1995), whereas the later rapid cooling may reflect the exhumation of the entire subducted continental crust from middle crustal level to the upper crustal level by way of extension tectonics due to the breakoff of subducted slab, as suggested by Davies and Blanckenburg (1995) and Ernst and Liou (1995). On the other hand, if both tectonic thrust and breakoff of the subducted oceanic lithosphere had occurred during the first stage of exhumation, then the second stage of exhumation has to be related to another process of extension tectonics such as post-collisional delamination of the lithospheric mantle. Further research is required to evaluate such alternatives.

After the second rapid uplifting, the UHPM rocks and their country rocks may have shared the same slow cooling history (≈4°C/Ma) from 300° to 100°C between 160 and 110 Ma, which has been revealed by fission track ages of apatite from granitic gneiss in South Dabie terrane (Chen et al., 1995). The magmatic structural dome formed during the Cretaceous (Hacker et al., 1998) and voluminous Cretaceous alkaline volcanics and granites developed along the north side of the Dabie Mountains (Li et al., 1993) suggest the extension in the late Jurassic and Cretaceous, which may have been responsible for the slow cooling and uplift of UHPM rocks and their country rocks during this period.

7. CONCLUSION

1. Neodymium isotopic equilibrium between UHPM minerals has been achieved in fine-grained eclogite at Shuanghe in Dabie Mountains during UHP metamorphism. The best estimate of the peak metamorphic time of UHPM rocks in the Dabie Mountains and Su–Lu terrane is 226 ± 3 Ma. Other younger Sm–Nd ages for UHPM rocks from the Dabie–Su–Lu terrane could be their cooling ages or resulted from Nd isotopic disequilibrium between UHPM minerals or analytical error.
2. Retrograde metamorphism of the UHPM rocks in the Dabie Mountains and Su–Lu terrane occurred in an open chemical system. Retrograde metamorphic fluids with abundant large ion lithophile elements have influenced the isotopic composition of the retrograde metamorphic minerals. The UHPM minerals, such as garnet, omphacite, rutile, and phengite, have their Sr and Nd isotopic systems remained closed during the retrograde metamorphism, whereas Sr and Nd isotopic systematics of the retrograde metamorphic minerals, such as epidote, amphibole, and biotite, growing during the retrograde metamorphism are not in equilibrium with the UHPM minerals. For this reason, the tie-line of garnet and UHPM whole rock containing retrograde metamorphic minerals will give a Sm–Nd "age" generally older than the peak metamorphic age with no geologic significance. Similarly, the tie-line of phengite and whole rock from such retrograde metamorphic UHPM rocks will give a younger Rb–Sr age than the true closure age of phengite. Hence, we will not recommend to use the Rb–Sr isochron defined by phengite + whole rock in thermochronologic studies.
   Meaningful Rb–Sr ages of phengite from UHPM rocks can be obtained by the regression of phengite with other UHPM minerals or unretrograded metamorphic whole rock. The meaningful Rb–Sr ages of biotite or amphibole can be obtained by the regression of biotite or amphibole with other retrograde metamorphic minerals or strongly retrograde whole rock.
3. On the basis of the Sm–Nd and Rb–Sr isochron ages with their corresponding metamorphic and closure temperatures reported in this article, a T–t path with two rapid coolings for the UHPM rocks at Shunaghe can be obtained, as shown in Figure 9. This T–t path shows that after peak metamorphism the UHPM rocks in the Dabie–Su–Lu belt has experienced a rapid cooling to about 500°C at ≈219 Ma. The UHPM rocks then went through a nearly isothermal stage from ≈219 Ma to ≈180 Ma. Starting from ≈180 Ma, the rocks cooled rapidly again to ≈300°C. Considering the change of the tectonic regime in the Dabie–Su–Lu belt during the above cooling times (i.e., a compression regime in the early-to-middle Triassic and an extension regime after 180 Ma), it is plausible that the earlier rapid cooling may reflect the exhumation of the UHPM rocks from mantle depth to the middle crustal level by compression tectonics during the continental subduction, whereas the later rapid cooling may reflect the exhumation of the entire subducted continental crust from middle crust to the upper crustal level via extension tectonics during the early–middle Jurassic.

4. The Nd isotopic composition of the garnet in regional granitic gneiss can be reset during retrograde metamorphism and became equilibrated with the retrograde metamorphic minerals (e.g., epidote and biotite), which is different from that of the garnet in eclogite and UHPM paragneiss. The retrograde metamorphism with amphibolite facies of the granitic gneiss at Shuanghe in the Dabie Mountains occurred at 213 $\pm$ 5 Ma, and then it was cooled down to $\approx$300°C at 172 $\pm$ 4 Ma. These two ages are consistent, respectively, with the Rb–Sr cooling ages of the phengite and biotite from the UHPM rocks in the Dabie–Su–Lu belt. It suggests that the cooling history of the granitic gneiss may be similar to that of the UHPM rocks in the Dabie–Su–Lu belt.

Acknowledgments—We would like to thank Bolin Cong, Qingchen Wang, Mingguo Zhai, Zhongyan Zhao, Huogen Dong, and Xingyun Lai for their friendly help and discussions during field trips. We are also grateful to Michael Ginther and Yohannes D. Vogel for their assistance in laboratory works at MPI and Ge Long, Weili Han for typing the manuscript, Shen–su Sun for spending many hours writing correspondences, offering critical comments, helping in English presentation, and reviewing the draft, and an anonymous reviewer for critical comments. This study is financially supported by the National Natural Science Foundation of China (No. 49132040, 49573190, 49794042), Max–Planck–Institut für Chemie, Germany, and Chinese Academy of Science (No. KZ951-A1-401-05).

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