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Micro-area Chemical Composition and Preserved *P-T* Evolution Trace of Phengite in Albite Gneiss from the Donghai Ultrahigh-Pressure Metamorphic Area, East China

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Abstract Study of micro-area chemical compositions indicates that phengite in albite gneiss from hole ZK2304 of the Donghai region has evident compositional zoning. SiO_2 and tetrahedrally coordinated Si contents decrease, and Al_2O_3, Al^{IV} and Al^{VI} contents increase gradually from core to rim. However, K_2O, MgO and FeO contents basically remain unchanged from core to rim. According to *P-T* estimates obtained from geothermometers and barometers, combined with previous experimental data, the core belt (micro-area I) of phengite was formed at T=637–672°C and P=1.55–1.73 GPa, and the transitional belt (micro-area II) of the phengite were formed at T=594–654°C and P=1.35–1.45 GPa. Towards the rim belt (micro-area III), the temperature decreased slightly, but the pressure decreased rapidly with T=542–630°C and P=1.12–1.19 GPa. The *P-T* evolution path recorded by the compositional zoning of phengite is characterized by significant near-isothermal decompression, revealing that the gneiss has undergone high-pressure-ultrahigh-pressure metamorphism. The compositional zoning of the phengite in the albite gneiss may have formed in the geodynamic process of rapid exhumation in the Sulu ultrahigh-pressure metamorphic belt.

Key words: phengite, compositional zoning, gneiss, genetic mechanism, Donghai, drill hole

1 Introduction

The Sulu terrane, located in the Qinling-Dabie collsion zone of East China, is one of the most important ultrahigh-pressure metamorphic terranes in the world (Liu Xiaochun et al., 1994; Liu Fulai et al., 1994, 1999; Zhang Zeming et al., 1995, 1999; Hu et al., 1997; Zhang Changhou et al., 1998; Li et al., 2000). In recent years, the study of ultrahigh-pressure metamorphism (UHPM) of the Sulu terrane has attracted a great deal of attention. The Sulu UHPM belt, lying east of the Tanlu fault, extends from Donghai county of northern Jiangsu province to Weihai of northeastern Shandong province for about 320 km. It is separated from the Sino-Korean craton by the Yantai-Qingdao-Wulan fault (YQWF) on the north and from the Yangtze craton by the Jiashan-Xiangshui fault (JXF) on the south (Fig. 1). The Donghai area, located at the southwestern end of the Sulu UHP belt, is one of the most typical UHPM areas in the belt. In this area, the UHPM belt consists mainly of gneisses and related granitic gneisses (making up 70%–80% of the whole outcrops), with intercalations of kyanite quartzite, jadeite-mica quartzite and marble. Some gneisses and granitic gneisses contain many eclogite layers or lenses of varying sizes and sporadical ultramafic bodies or blocks (Fig. 1).

Up to now, many geologists have studied the petrology, genetic characteristics, *P-T-t* paths of eclogites in the Sulu UHPM belt (Enami and Zang, 1990; Hirajima et al., 1990; Zhao et al., 1993; Kato et al., 1997; Zhang et al., 1995). However, divergent views have long existed as to whether various types of extensively exposed gneisses and related granitic gneisses were subjected to UHPM. Some geologists advocate tectonic emplaçement of UHPM eclogite into low-*P* gneisses (Smith, 1988; Zhao et al., 1992), while others propose that both eclogites and country rocks (gneisses) underwent UHP metamorphism (Okay et al., 1992; Zhang et al., 1995). However, both views lack

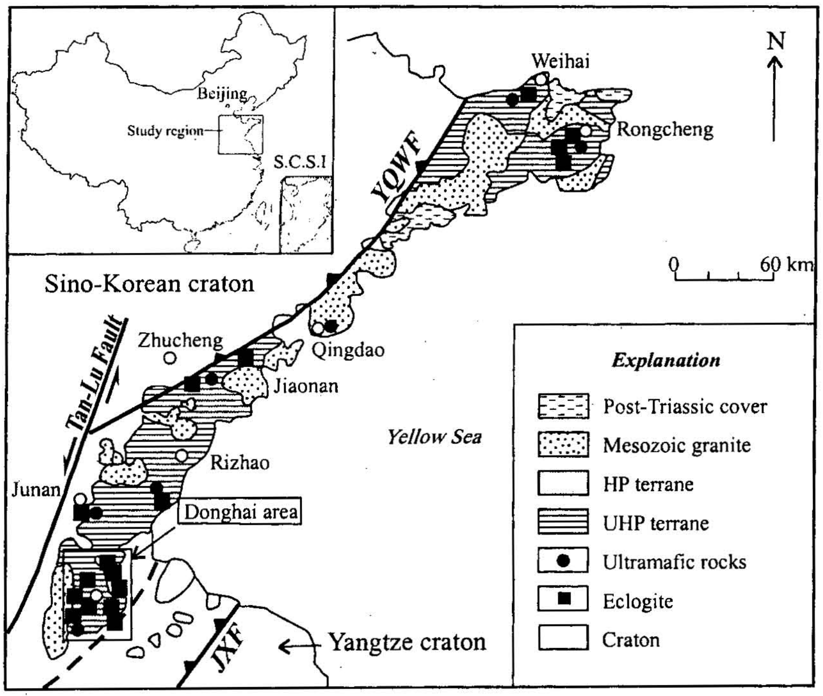

Fig. 1. Geological sketch map of the Sulu UHPM belt showing the tectonic units and distribution characteristics of metamorphic rocks.

sufficient evidence. Therefore, according to the data from hole ZK2304 cores in the Donghai area, an attempt has been made to study the characteristics of the change of the micro-area chemical composition of the characteristic metamorphic mineral phengite in albite gneiss and *P-T* evolution and determine the genetic mechanism of gneiss and its relationship with UHP metamorphism.

2 Lithology and Mineral Assemblage of the Studied Gneiss Sample

Hole ZK2304 is located at longitude 118°40′E and latitude 34°24′, near Maobei village, about 16 km SW of Donghai county. The hole was drilled to a depth of 602.26 m. The rock types revealed by this hole consist mainly of eclogites, gneisses and ultramafic rocks. Garnet-amphibole-two-mica-albite gneiss is one of the most important gneisses and occurs at depths of 178.8–183.48 m of hole ZK2304. Its contacts with its overlying and underlying rutile eclogites are sharp. The studied gneiss sample (ZK2304-44) was collected from the depth of ca. 179.83 m, and its main composition is as follows: SiO_2=58.99%; Al_2O_3=16.50%; Fe_2O_3=2.41%; FeO=6.14%; MgO=1.72%; CaO= 4.06%; Na_2O=5.92%; K_2O=1.66% with Na_2O/K_2O= 3.57. The protolith of this gneiss is intermediate sodium-rich volcanic tuff (Liu Fulai et al., 1999).

The garnet-amphibole-two-mica- albite gneiss (ZK2304-44) is comprised mainly of garnet (13%) + phengite (12%) + amphibole (5%) + biotite (9%) + albite (25%) + K-feldspar (5%) + quartz (28%) ± epidote (2%) ± rutile (1%). In this gneiss, the relict garnet shows an irregular shape with grain size 0.5–1.5 mm. Around its margins, the garnet commonly becomes fine-grained or vermicular amphibole symplectite. The flaky phengite with a grain size of 0.5–3.1 mm tends to retrograde to scaly biotite and fine-grained epidote along edges (Fig. 2).

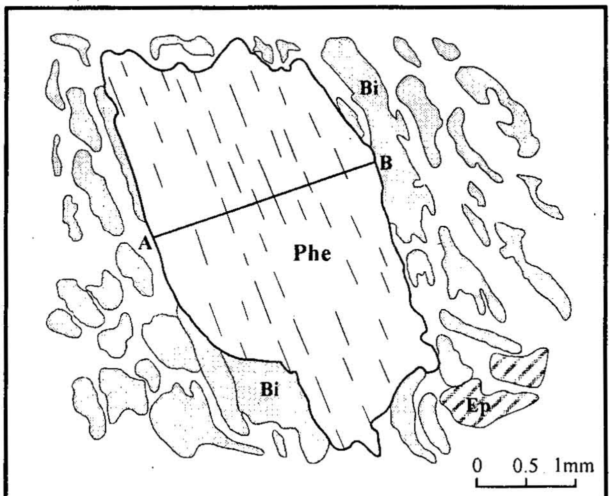

Fig. 2. Microtextures of phengite in gneiss (ZK2304-44). A-B–profile line of chemical analysis; Phe–phengite; Bi–botite; Ep–epidote.

3 Conditions for Analyzing the Micro-area Chemical Composition of Phengite and Characteristics of Its Compositional Zoning

3.1 Analyzed conditions of the micro-area chemical composition of phengite

The analyzed phengite is flaky in shape with a grain size of 3.1×2.1 mm. The crystal is surrounded by finely scaly biotite and fine-grained epidote (Fig. 2). In order to analyze precisely the change of the micro-area chemical composition in phengite, the profile line of the compositional analysis is near-vertical to the cleavage cracks of the phengite (line A-B in Fig. 2). The length of line A–B is 2.1 mm and the distance of analyzed spots is 0.16 mm. All the compositional spots of the phengite were analyzed using a Sx50 microprobe of the Mineral Institute of Heildberg University, Germany. Analytical conditions were: accelerating voltage 15 kV, beam current 10 nA, beam diameter 10 μm and counting time 200 s. All analyses presented were single-spot analyses with an analytical error (major elements) of ±0.20 wt%.

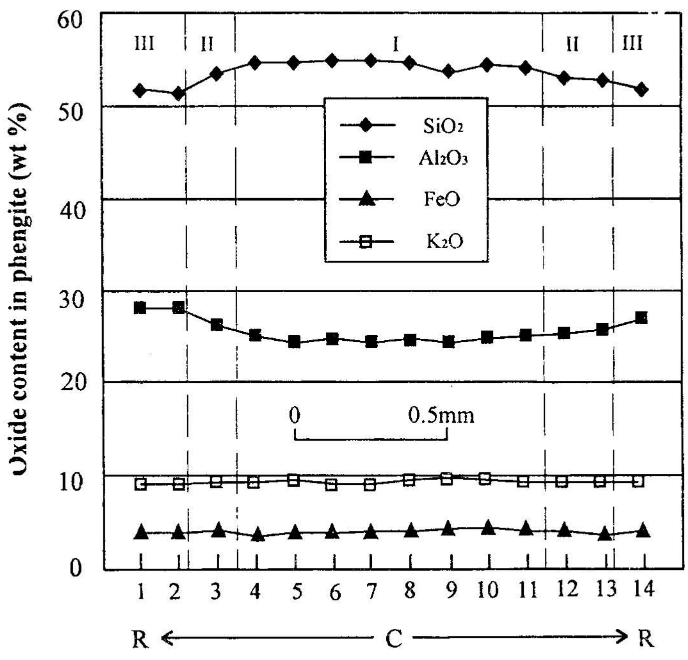

Fig. 3. Chemical compositional zoning of micro-areas in phengite (Phe). C–core, R–rim, 1–14–analyzed spot number.

3.2 Micro-area chemical composition and compositional zoning characteristics of phengite

The chemical compositions of 14 spots on profile line A-B were analyzed. The analyzed results are listed in Table 1, and the characteristics of the change of major element contents are shown in Fig. 3. According to the data of the chemical composition of the phengite, SiO_2 (wt%) decreases and Al_2O_3 (wt%) increases gradually from core to rim, showing an evident negative correlation between SiO_2 and Al_2O_3. From the variation ranges of SiO_2 and Al_2O_3 contents, the compositional profiles of the phengite may be divided into three micro-areas (Table 1, Fig. 3). Micro-area I is the widest with a width of 1.12 mm (analyzed spots 4–11). In this micro-area, the SiO_2 content is highest, ranging from 54.222 to 54.836%, with an average value of 54.580%. The related tetrahedrally coordinated Si ranges from 3.533 to 3.573 (except for spot 9) with average value 3.555. The Al_2O_3 content ranges from 24.377 to 25.031% with an average value of about 24.669%. The related tetrahedrally coordinated Al^{IV} and hexahedrally coordinated Al^{VI} are about 0.427–0.497 and 1.440–1.481, respectively. Compared with micro-area I, the width of micro-area II is narrow, only about 0.16–0.32 mm. The SiO_2 content ranges from 52.879 to 53.405%, with average value 53.116%. The related tetrahedrally coordinated Si is about 3.486–3.503 with average value 3.493. The Al_2O_3 content ranges from 25.328 to 26.283% with average value 25.793%. The related tetrahedrally coordinated Al^{IV} and hexahedrally coordinated Al^{VI} are about 0.497–0.514 and 1.472–1.505, respectively. Compared with micro-area I, SiO_2 (wt%) in micro-area II decreases and Al_2O_3 (wt%) increases. The width of micro-area III is similar to that of micro-area II, only about 0.16–0.32 mm. Its SiO_2 content is the lowest, but the Al_2O_3 content is the highest among the three micro-areas of the phengite. The SiO_2 content ranges from 51.476 to 51.787% with average value 51.679%. The related tetrahedrally coordinated Si is about 3.396–3.422 with average value 3.40. The Al_2O_3 content ranges from 26.893 to 28.005% with average value 27.632%. The related tetrahedrally coordinated Al^{IV} and hexahedrally coordinated Al^{VI} are about 0.578–0.604 and 1.515–1.574, respectively.

Table 1 Chemical compositions (wt%) of micro-area in phengite (ZK2304-44)

Micro-area	III		II			I	
Number	1	2	3	4	5	6	7
Zone	R ◀	———	———	———	———	———	C
SiO_2	51.773	51.476	53.405	54.657	54.550	54.836	54.825
TiO_2	0.489	0.493	0.532	0.462	0.492	0.619	0.512
Al_2O_3	28.005	27.998	26.263	24.973	24.381	24.672	24.396
Cr_2O_3	0.039	0.041	0.003	0.031	0.016	0.066	0.061
<FeO>	3.872	3.869	4.097	3.740	4.131	4.254	4.244
MnO	0.076	0.083	0.118	0.120	0.061	0.063	0.058
MgO	2.781	2.785	3.190	3.484	3.721	3.709	3.689
CaO	0.007	0.008	0.000	0.011	0.015	0.021	0.015
Na_2O	0.154	0.147	0.186	0.158	0.124	0.173	0.181
K_2O	9.110	9.212	9.380	9.285	9.539	9.189	9.176
Total	96.306	96.112	97.174	96.921	97.030	97.602	97.157
Si	3.405	3.396	3.486	3.564	3.567	3.559	3.573
Al^{IV}	0.595	0.604	0.514	0.436	0.433	0.441	0.427
Al^{VI}	1.574	1.571	1.505	1.481	1.444	1.445	1.446
Ti	0.024	0.024	0.026	0.023	0.024	0.030	0.025
Fe^{2+}	0.213	0.213	0.224	0.204	0.226	0.231	0.231
Cr	0.002	0.002	0.000	0.002	0.001	0.003	0.003
Mn	0.004	0.005	0.007	0.007	0.003	0.003	0.003
Mg	0.273	0.274	0.310	0.339	0.363	0.359	0.358
Ca	0.000	0.001	0.000	0.001	0.001	0.001	0.001
Na	0.020	0.019	0.024	0.020	0.016	0.022	0.023
K	0.764	0.775	0.781	0.772	0.796	0.761	0.763
X_{Mg}	0.560	0.560	0.580	0.620	0.620	0.610	0.610

Micro-area			I			II	III
Number	8	9	10	11	12	13	14
Zone	C	———	———	———	———	———	▶ R
SiO_2	54.597	53.373	54.370	54.222	53.063	52.879	51.787
TiO_2	0.524	0.509	0.497	0.520	0.532	0.547	0.533
Al_2O_3	24.863	24.377	24.659	25.031	25.328	25.789	26.893
Cr_2O_3	0.012	0.019	0.075	0.063	0.048	0.048	0.042
<FeO>	4.061	4.423	4.234	4.334	4.145	3.762	3.962
MnO	0.019	0.054	0.019	0.079	0.092	0.107	0.091
MgO	3.615	3.535	3.658	3.600	3.465	3.376	3.342
CaO	0.008	0.000	0.006	0.022	0.021	0.034	0.031
Na_2O	0.106	0.131	0.127	0.178	0.123	0.171	0.179
K_2O	9.558	9.715	9.541	9.403	9.382	9.350	9.279
Total	97.363	96.136	97.186	97.452	96.199	96.063	96.139
Si	3.554	3.537	3.551	3.533	3.503	3.490	3.422
Al^{IV}	0.446	0.463	0.449	0.467	0.497	0.510	0.578
Al^{VI}	1.460	1.440	1.448	1.454	1.472	1.494	1.515
Ti	0.026	0.025	0.024	0.025	0.026	0.027	0.026
Fe^{2+}	0.221	0.245	0.231	0.236	0.229	0.208	0.219
Cr	0.001	0.001	0.004	0.003	0.003	0.003	0.002
Mn	0.001	0.003	0.001	0.004	0.005	0.006	0.005
Mg	0.351	0.349	0.356	0.350	0.341	0.332	0.329
Ca	0.001	0.000	0.000	0.002	0.001	0.002	0.002
Na	0.013	0.017	0.016	0.022	0.016	0.022	0.023
K	0.794	0.821	0.795	0.782	0.790	0.787	0.782
X_{Mg}	0.610	0.590	0.610	0.600	0.600	0.610	0.600

Note: Analyzed by the Institute of Mineralogy, Heildberg University, Germany; C–core; R–rim; X_{Mg}=Mg/(Mg+Fe).

In addition, K_2O (9.110–9.715%), <FeO> (3.762–4.254%) and MgO (2.781–3.721%) contents show slight changes from core to rim of phengite (Fig. 3).

4 Genetic Relationship between Micro-area Chemical Compositional Zoning of Phengite and Preserved *P-T* Evolution Trace

4.1 Temperature conditions for forming micro-area compositional zoning of phengite

As mentioned above, phengite shows evident compositional zoning. In the same sample (ZK2304-44), Mg and Fe^{2+} of garnet also exhibit weak compositional zoning. From the core to the rim, Mg content decreases and Fe^{2+} content increases gradually. Therefore, according to the chemical compositions of garnet and phengite in different micro-areas, Fe^{2+}-Mg exchange thermometers of coexisting garnet and phengite calibrated by Krogh and Raheim (1978) and Green and Hellman (1982) were used for calculating the stable temperature conditions for forming different micro-areas of the phengite.

The stable temperature condition of micro-area I in the phengite: Micro-area I is located in the core of the phengite (Fig. 3). Using the chemical compositions of the cores of garent and phengite, the calculated temperature after Krogh and Raheim (1978) and Green and Hellman (1982) range from 637 to 672°C (Table 2), representing the stable temperature condition of micro-area I in the phengite.

The stable temperature condition of micro-area II in the phengite: Micro-area II is located in the transitional zone between the core and the rim of the phengite (Fig. 3). Therefore, using the chemical compositions of the transitional zones of the garnet and phengite, the temperature estimates obtained from the thermometers mentioned above range from 594 to 654°C (Table 2), representing the stable temperature condition of micro-area II in the phengite. The temperature of micro-area II is slightly lower than that of micro-area I with a decrease range of about 18°C–43°C.

The stable temperature condition of micro-area III in the phengite: Micro-area III is located on the rim of the phengite (Fig. 3). Using the chemical compositions of rims of the garnet and phengite, the temperature estimates obtained from the same thermometers range from 542 to 630°C, indicating the stable temperature condition of micro-area III. Compared with the temperature of micro-area II of the phengite, the temperature of micro-area III decreases about 24°C–52°C.

4.2 Pressure conditions for forming compositional zoning of phengite

Massonne and Schreyer (1987) made a high-*P* and high-*T* experiment about the genetic mechanism of phengite in gneisses. The experimental results indicated that the tetrahedrally coordinated Si content of phengite increases gradually with rising pressure. On the basis of the experimental data, a *P-T* diagram of Si content isoleths (Fig. 4) was drawn by Massonne and Schreyer (1987). The Si content of the phengite of the gneiss (ZK2304-44) has evident compositional zoning. In micro-area I of the phengite, the average Si content is about 3.555, the highest value being up to 3.6 (Table 3). According to Massonne and Schreyer (1987), in the temperature interval of 637–672°C, the stable pressure condition of micro-area I in the phengite ranges from 1.55 to 1.73 GPa (Fig. 4), indicating that

Table 2 Calculated results of garnet-phengite geothermometers

Sam.No.	Micro-area	Mineral pair	Gt Fe^{2+}	Gt Mg	Phe Fe^{2+}	Phe Mg	LnK_1	LnK_2	T_1 (°C)	T_2 (°C)
6		Gt(C)-Phe(C)	1.680	0.348	0.231	0.359	2.0169	2.0152	640	670
7	I	Gt(C)-Phe(C)	1.680	0.348	0.231	0.358	2.0140	2.0078	641	672
8		Gt(C)-Phe(C)	1.680	0.348	0.222	0.351	2.0377	2.0324	637	668
3	II	Gt(T)-Phe(R)	1.667	0.344	0.224	0.310	1.9057	1.9030	602	654
12		Gt(T)-Phe(T)	1.667	0.344	0.229	0.341	1.9767	1.9762	594	643
1	III	Gt(R)-Phe(R)	1.696	0.331	0.213	0.273	1.8814	1.8821	566	630
14		Gt(R)-Phe(R)	1.696	0.331	0.219	0.329	2.0422	2.0408	542	623

T_1=Krogh and Raheim (1978) thermometer; T_2=Green and Hellman (1982) thermometer; $K_1=(FeO/MgO)_{Gt}/(FeO/MgO)_{Phe}$; $K_2=(X_{Fe}/X_{Mg})_{Gt}/(X_{Fe}/X_{Mg})_{Phe}$; X_{Fe}–Fe/(Fe+Mg); X_{Mg}–Mg/(Fe+Mg); Gt(C)-Phe(C) represent the composition of the core; Gt (T)-Phe (T) represent the composition of the transitional zone; Gt(R)-Phe(R) represent the composition of the rim.

the core of the phengite formed by high or ultrahigh-pressure metamorphism. In micro-area II of the phengite, the Si content of the phengite ranges from 3.486 to 3.503. When the temperature is about 594–654°C, the stable pressure condition of the micro-area ranges from 1.35 to 1.45 GPa (Fig. 4). The pressure decrease about 0.20–0.28 GPa from micro-area I to micro-area II. The tetrahedrally coordinated Si of micro-area III ranges from 3.396 to 3.422 with average value 3.40. In the temperature interval of 542 to 630°C, the stable pressure condition ranges from 1.12 to 1.19 GPa. The metamorphic pressure decreases rapidly from micro-areas II to III with a decompression range of 0.23–0.26 GPa.

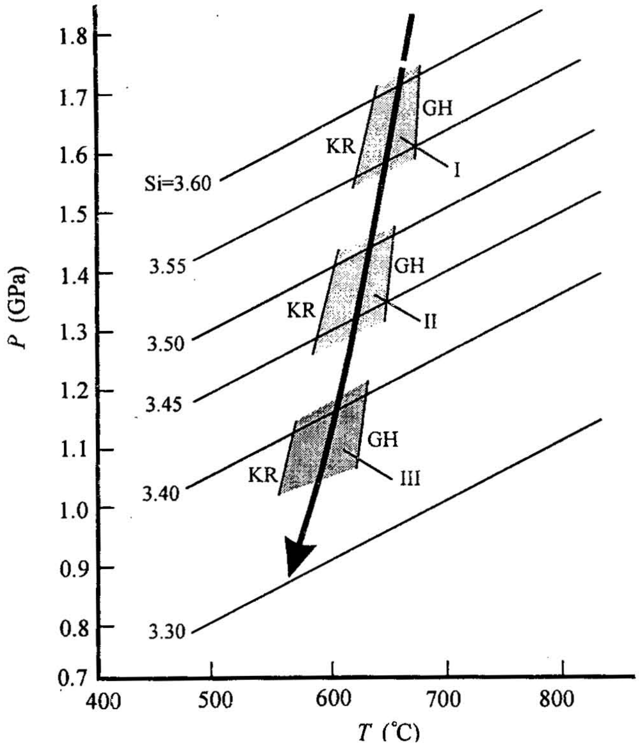

Fig. 4. *P-T* conditions and evolution of the micro-area compositional zoning of phengite in gneiss.

KR, GH represent the garnet-phengite geothermometers calibrated by Krogh and Raheim (1978) and Green and Hellman (1982), respectively; Si content isopleths represent the phengite geobarometer calibrated by Massonne and Schreyer (1987).

4.3 Genetic mechanism of the micro-area compositional zoning of the phengite and *P-T* evolution

According to the *P-T* estimates, combined with the previous experimental data, the *P-T* path of the micro-area compositional zoning of the phengite in gneiss is shown in Fig. 4. This *P-T* path is characterized by substantial near-isothermal decompression. The temperature decreases about 42–95°C, but the decompression range is up to 0.61 GPa. The *P-T* path of the phengite in the gneiss is similar to that of the Sulu UHPM belt (Zhang et al., 1995). These features indicate that the compositional zoning of the phengite was closely related to substantial decompression and was formed by the rapid exhumation and uplift process of the Sulu UHP belt. In addition, the 1.73 GPa pressure information preserved in the core of the phengite of gneiss collaterally support the idea that the gneisses occurring as intercalated layers in eclogites experienced high- and ultrahigh-pressure metamorphism.

5 Discussion and Conclusions

Study of the micro-area chemical compositions of phengite from drill hole ZK2304 of the Maibei area, near Donghai county, indicate that the phengite of the gneiss, occurring as intercalated layers in eclogite bodies, shows evident compositional zoning. SiO_2 and tetrahedrally coordinated Si contents of the phengite decrease, and Al_2O_3, Al^{IV} and Al^{VI} contents increase gradually from core to rim. However, K_2O, MgO and FeO contents basically remain unchanged from core to rim.

According to the calculated data of the geothermometer and barometers, combined with previous experimental data, the stable *P-T* conditions of the core belt (micro-area I) of the phengite were 1.55–1.73 GPa and 637–672°C, and the stable *P-T* conditions of the transitional belt (micro-area II) and rim belt (micro-area III) of the phengite were 1.35–1.45 GPa and 594–654°C, and 1.12–1.19 GPa and 542–630°C, respectively.

The *P-T* evolution path recorded by the compositional zoning of the phengite is characterized by substantial near-isothermal decompression. The data mentioned above collaterally demonstrate that the gneisses, occurring as intercalated layers in the eclogites, experienced high- and ultrahigh-pressure metamorphism. The compositional zoning of the phengite was formed in the geodynamic process of rapid exhumation in the Sulu UHPM belt.

According to the data of the micro-area chemical compositions of the phengite, combined with previous experimental data, the compositional zoning of the phengite of the gneiss in the study area only recorded the *P-T* evolution trace of the near-isothermal decompression stage. Therefore, it is not advisable for many a geologist to use the garnet-phengite geothermometes and barometers in the determination of the *P-T* conditions of the peak metamorphic stage, especially for eclogite bodies in the Sulu UHPM belt.

Acknowledgements

This study was supported by the Ministry of Land and Resources of China Projects "1:250000 Regional Geological Survey of the Lianyugang Sheet (I50C002004) of P. R. China" and "Geological Research for Selecting a Drillhole in the Donghai Target Area of the Chinese Continental Scientific Drilling Programme". The rock samples of hole ZK2304 were provided by the No. 6 Geological Party of Jiangsu Province. The authors also sincerely thank senior engineer Lu Yongzheng and Xu Zhongxin for their help during the field work.

Manuscript received Nov. 1999
edited by Fei Zhenbi and Hao Ziguo

References

Enami, M., and Zang, Q., 1990. Quartz pseudomorphs after coesite in eclogites from Shandong province, east China. *Am. Mineral.*, 75: 381–386.

Green, T.H., and Hellman, P.L., 1982. Fe-Mg partitioning between coexisting garnet and phengite at high pressure, and comments on a garnet-phengite geothermometer: *Lithos*, 15: 253–265.

Hirajima, T., Ishiwatari, A., Cong, B. L., Zhang, R. Y., Banno, S., and Nozaka, T., 1990. Identification of coesite in Mengzhong eclogite from Donghai country, northeastern Jiangsu province, China. *Mineral. Mag.*, 54: 579–584.

Hu Shouxi, Zhao Yiying, Xu Bing et al., 1997. Evidence for the Jiangsu-Shandong ultra-high-pressure metamorphic belt returns from the upper mantle to the earth surface in the Mesozoic-Cenozoic. *Acta Geological Sinica*, 71(3): 245–253 (in Chinese with English abstract).

Kato, T., Enami, M., and Zhai, M., 1997. Ultra-high-pressure (UHP) marble and eclogite in the Su-lu UHP terrane, eastern China. *J. Metamorphic Geol.*, 15: 169–182.

Krogh, E.J., Raheim, A., 1978. Temperature and pressure dependence of Fe-Mg partitioning between garnet and phengite, with particular reference to eclogite. *Contrib. Mineral. Petrol.*, 66: 75–80.

Li Yanhe, Li Jincheng, Song Hebin and Liu Xiaochun, 2000. Helium isotope geochemistry of ultrahigh-pressure metamorphic eclogites from the Dabie-Sulu terrane in East China. *Acta Geological Sinica* (Eng. ed.), 74(1): 14–18.

Liu Fulai, Xu Zhiqin and Xu Huifen, 1999. Petrology and genetic mechanism of granitic gneiss in Donghai ultrahigh-pressure metamorphic belt. *Geological Review*, 45 (Sup.): 636–644 (in Chinese with English abstract).

Liu Fulai, Xu Zhiqin, Xu Huifen and Yang Jingsui, 1999. High- and ultrahigh-pressure metamorphism and retrogressive textures of gneiss in the Donghai area. *Acta Geological Sinica* (Eng. ed.), 73(3): 300–315.

Liu Xiaochun, Hu Ke, Li Xuexie and Kang Weiguo, 1994. The diversity and origin of eclogites from the Dabie-Sulu high-pressure metamorphic belt. *Geological Review*, 40(6): 494–501 (in Chinese with English abstract).

Massonne, H.J., and Schreyer, W., 1987. Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz. *Contrib. Mineral. Petrol.*, 96: 212–224.

Okay, A.I., and Sengor, A.M.C., 1992. Evidence for intracontinental thrust related exhumation of the ultra-high pressure rocks in China. *Geology*, 20: 411–414.

Smith, D.C., 1998. A review of the peculiar mineralogy of the "Norwegian coesite-eclogite province", with crystal-chemical, petrological, geochemical and geodynamical notes and an extensive biblography. In: Smith, D.C. (ed.), Eclogite and Eclogite-facies Rocks. Amesterdam: Elsevier, 1–126.

Wang, Q., Ishiwatari, A., Zhao, Z., Hirajima, T., Enami, M., Zhai, M., Li, J., and Cong, B.L., 1993. Coesite-bearing granulite retrograded from eclogite in Weihai, eastern China: a preliminary study. *European J. Mineral.*, 5: 141–152.

Zhang Changhou, Chai Yucheng, Song Honglin and Wu Zhengwen, 1998. The role of extensional tectonics in the exhumation of high-and Ultrahigh-pressure rocks in northern Jiangsu and southeastern Shandong. *Geological Review*, 44(3): 225–232 (in Chinese with English abstract).

Zhang Zeming, Xu Zhiqin and Xu Huifen, 1999. Metamorphism of the eclogites from the ZK703 drillhole in Donghai, south Sulu (Jiangsu-Shandong) ultrahigh-pressure metamorphic belt, eastern China. *Acta Geological Sinica*, 73(4): 321–333 (in Chinese with English abstract).

Zhang Zeming, You Zhendong, Han Yujing and Sang Longkang, 1996. Petrology, metamorphic process and genesis of the Dabie-Sulu eclogite belt, eastern-central China. *Acta Geological Sinica* (Eng. ed.), 93(2): 134–156.Zhang, R.Y., Hirajima, T., Banno, S., Cong, B.L., Liou, J.G., 1995. Petrology of ultrahigh-pressure rocks from the sourthern Sulu region, eastern China. *J. Metamorphic Geol.*, 13: 659–675.

Zhao, Z.Y., Wang, Q.C., and Cong, B.L., 1992. Coesite-bearing ultramafic pressure metamorphic rocks from Donghai, northern Jiangsu province, eastern China: "foreign or in situ"? *Scientica Geologica Sinica*, 1: 43–58.

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