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Komatiites from west Shandong, North China craton: Implications for plume tectonics

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Abstract

The Mengyin komatiites are located at the base of the Taishan Complex (~2.7 Ga), in the western Shandong greenstone belt of the eastern block of North China craton. The Mengyin komatiites have high-magnesian, low-titanium, and aluminum-undepleted chemical characteristics. Although the ultramafic rocks underwent amphibolite to greenschist facies metamorphism, they preserve remnant igneous spinifex textures. Some komatiite samples even preserve rare fresh olivine. According to the mass equilibrium between the olivine and melt, the potential eruption temperature of the Mengyin komatiites at 1 atm is about 1270 °C which might indicate a plume tectonic setting. It is inferred that komatiites in Mengyin, west Shandong may be part of a plume-related global magmatic event related to the break-up of a supercontinent that included the eastern block of the North China craton.

Keywords: Komatiites; Mengyin; North China craton; Archean

1. Introduction

Komatiites are high-temperature, ultramafic volcanic rocks containing more than 18 wt.% MgO (Arndt and Nisbet, 1982). Although the tectonic setting in which komatiites form is still uncertain, most investigators agree that their high liquidus temperatures require an anomalously hot mantle plume source (Campbell et al., 1989; Xie and Kerrich, 1994; Herzberg, 1995; Grove and Parman, 2004). As such, they provide important constraints on the composition and thermal structure of the Archean mantle (Sproule et al., 2002).

It has been debated whether or not there are komatiites in the North China craton (NCC) for many years (Cheng and Shen, 1964; Cheng et al., 1982; Cheng and Xu, 1991). The first komatiites in the eastern NCC were reported from the base of Yanlingguan Formation in 1982 (Cheng et al., 1982). However, no spinifex texture was found in the field at that time, although spinifex textures were later discovered at this location by the Shandong Geological Bureau (Zhang et al., 1998). Previous studies focused on textures, petrography and major element geochemistry (Zhang et al., 1998; Yang, 2000; Zhang et al., 2001). Recently, the trace element geochemistry of this area has been discussed in detail (Polat et al., 2006). This paper presents new geochemical data and petrological evidence about the komatiites, focusing on mineral chemistry and their implications for plume tectonics.

2. Regional setting

Most tectonic models for the North China craton (NCC) divide the craton into western and eastern blocks, separated by the Central Orogenic belt (Trans-North China Orogen) (Fig. 1a). However, there is still some debate about the time and direction of the collision. There are mainly two views. Kusky and Li (2003) suggest that the collision occurred about 2.5 Ga and the

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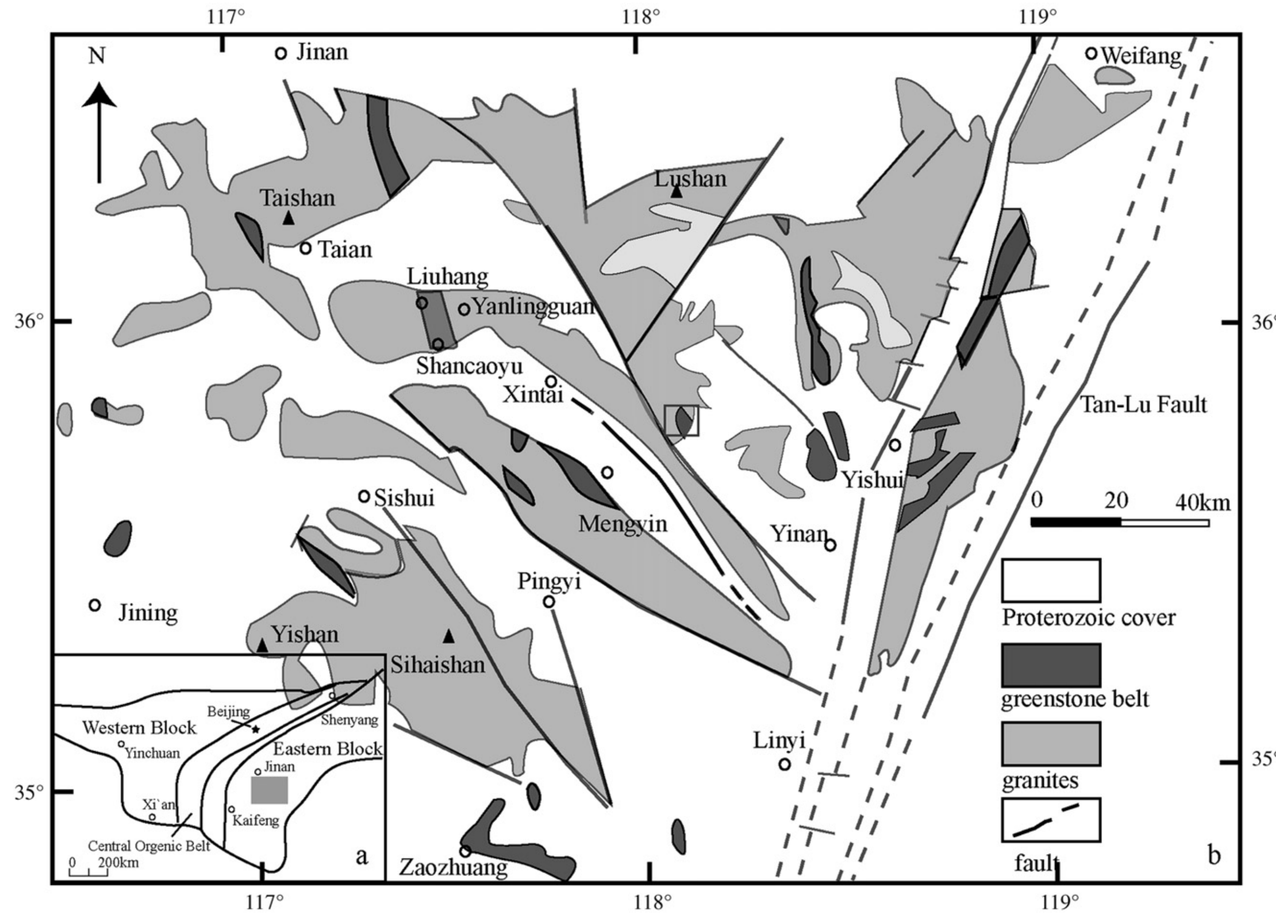

Fig. 1. Geological sketch of Mengyin komatiites in Shandong (after Cao, 1996) a—The location of working area in the NCC; b—Gray rectangle part in a, rectangle in b refers to komatiite outcrop.

eastern block subducted below the Central Orogenic belt, whereas Zhao et al. (2001, 2003, 2005) hold that the subduction was in the opposite direction and the collision may not have occurred until 1.8 Ga.

Our field area is located in the western Shandong greenstone belt, eastern block of the NCC (Fig. 1b), which underwent regional amphibolite to greenschist facies metamorphism and deformation. The strongest and pervasive fabric is S_1, which did not affect the later (circa 2.5–2.4 Ga) granite, so it is suggested that the deformation and synchronous metamorphism took place before 2.5 Ga (Cao, 1996). Rocks of the greenstone belt are well preserved in the Liuhang, Shancaoyu, and Yanlingguan Formations (Fig. 1b). The rocks in Liuhang Formation include meta-conglomerate and associated lithologies (Fig. 2a); The Shancaoyu Formation is characterized by abundant feldspar and clastic texture with common crossbedding and inclined bedding. Basic to ultrabasic lavas including pillow lavas (Fig. 2b), meta-basalts (now amphibolite) (Fig. 2c) and komatiites (Fig. 2d) are exposed in the Yanlingguan Formation. The contact between the three formations is conformable. The outcrop of Mengyin komatiites lies at the base of the Yanlingguan Formation, and is about 450 m long, 118 m wide, inclined to southwest with foliation direction similar to that of the host rocks (Zhang et al., 2001) (Fig. 3). In the upper and middle parts of the section are serpentine komatiites, which can be divided into spinifex, massive and cumulate textures in terms of the characteristics in the field. Tremolite schist is light yellow and green, mainly composed of tremolite, and is about 0.89 m thick. Biotite–actinolite schist is about 1.3–1.9 m thick with two layers, which is mainly composed of actinolite and biotite, with accessory minerals including magnetite. There are magnetite quartzites in the amphibolite bearing granulite. The amphibolites with abundant plagioclase show relatively little deformation. The wall rock of the greenstone belts is granite.

No precise ages for the komatiites from the present area have yet been determined, but the regional data (Jahn et al., 1988; Cheng and Xu, 1991) show that Mengyin komatiites erupted in Neoarchean (see also Polat et al., 2006).

3. Petrography and mineralogy

The samples were collected from the Mengyin area (area marked within rectangle in Fig. 1b). The komatiites are heavily altered, yellow on weathered surfaces but are gray on fresh faces. However, typical spinifex texture is preserved in some places. Most of the rocks are altered to chlorite–tremolite serpentine schist, which exhibits crystalloblastic texture. Most minerals are oriented in the same direction defining a strong

Fig. 2. Field photos of the greenstone belts in Western Shandong a—meta-conglomerate; b—pillow lava; c—meta-basalt (amphibolite); d—komatiite.

foliation. The crystalloblasts include serpentine, olivine (30%), chlorite, tremolite and actinolite. Magnetite is also abundant, derived from the alteration of olivine to serpentine. Previous studies reported that there is also primary pyroxene in the Mengyin komatiites (Xu and Dong, 1992), but we did not observe these in our samples. If there was pyroxene in the original komatiites, it may have been replaced by secondary hydrous minerals such as tremolite. In fact, in our study, the only primary mineral preserved is olivine, which has undergone significant recrystallization. However, fresh olivine was found in the thin sections. The Fo content increases from the rim to the core. Some olivines (now serpentine) are dendritic (Fig. 4a), whereas other olivines occur as aggregates (Fig. 4b, c), and still others form long plates up to several centimeters in length. (Fig. 4d). Others form small grains only several millimeters in diameter. Generally olivine forms rounded grains in typical cumulate dunites. Therefore we infer that the long platy olivines might be related to rapid cooling and could be a remnant of spinifex texture (Fig. 4d).

4. Analytical methods and results

Major elements and some trace elements (Cr, Ni and V) were analysed by the X-ray fluorescence spectrometer (XRF-1500) at the Geological and Geophysical Institute of the Chinese Academy of Sciences in 2002. The rock powder (0.6 g) and

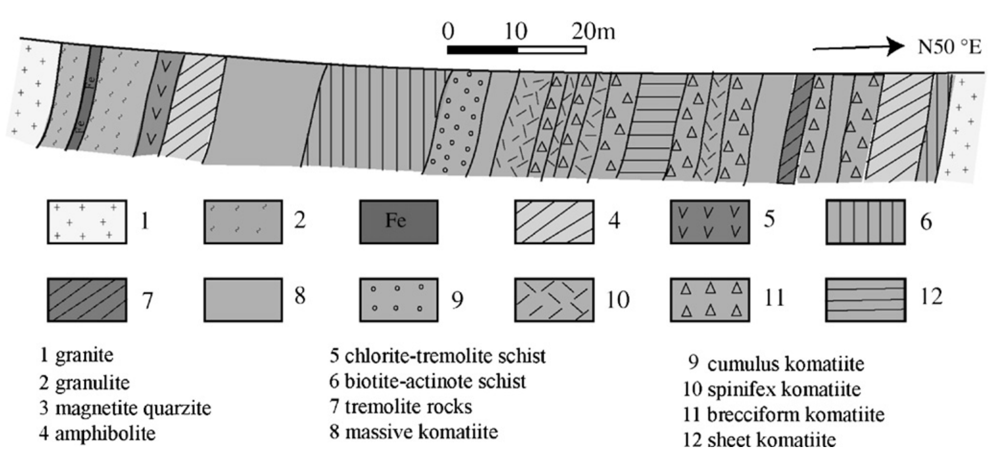

Fig. 3. Cross section of the komatiites in Mengyin, Shandong (after Zhang et al., 1998).

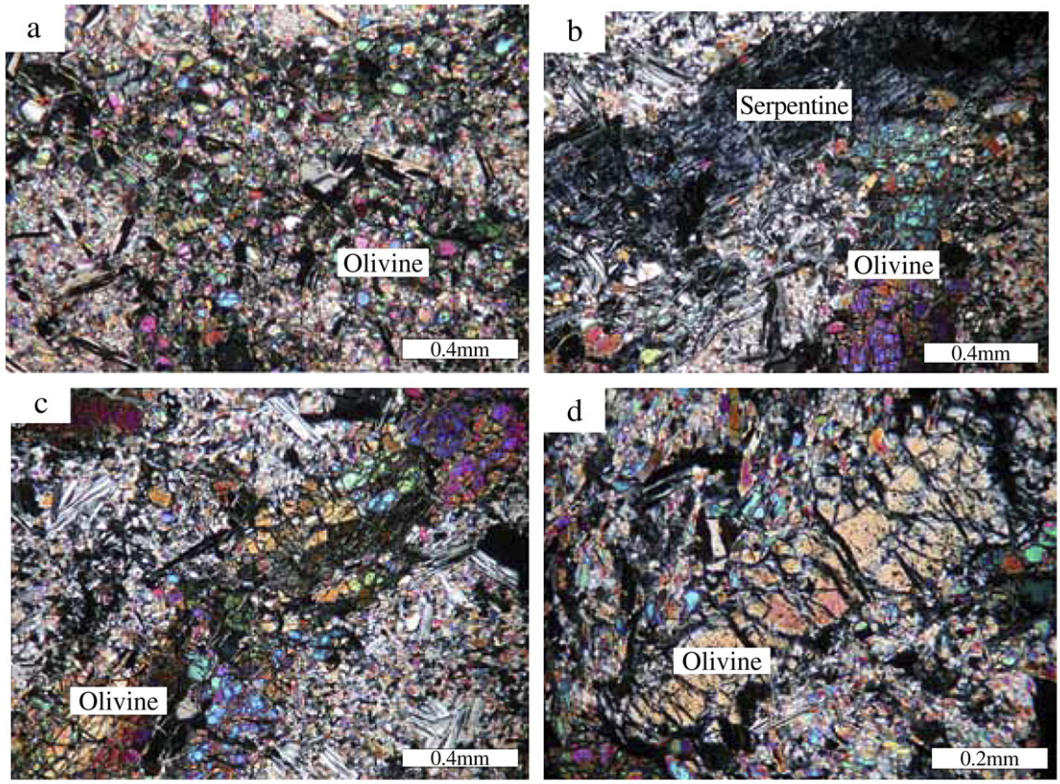

Fig. 4. Spinifex textures of Mengyin komatiites a—dendritic texture; b—c aggregates olivines; d—Plate spinifex texture.

$Li_2B_4O_7$ (1.2 g) were mixed and then were melted at 1100° for 10 min. The precisions are listed in Table 1. To gain LOI, we placed the rock powder (0.6 g) in a pot that was heated to 1000° and continued heating at this temperature for an hour, then put the sample in an airer, and cooled it to room temperature (about 25 min). We then weighed the samples including the pot, and then heated the sample again to constant temperature.

Mineral compositions were conducted by EPMA (JXA-8100) at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, China. The analyses were performed under an accelerating voltage of 15 kV and a beam current of 10 nA with a bind spot of 1 μm.

The komatiites have high-MgO (27.92–29.65 wt.%), Ni (1422–1633 ppm) and Cr (2200–2600 ppm), with low-TiO_2 (0.14–0.18 wt.%) as well as $Al_2O_3/TiO_2=25.50–30.00$, which is a little higher than that of chondrite ($Al_2O_3/TiO_2=22$). According to the reclassification of high-Mg volcanic rocks by Le Bas (2000), our samples belong to komatiites ($SiO_2<52\%$, $Na_2O+K_2O<2\%$, $TiO_2<1\%$, $MgO>18\%$, Table 1). The Mg# of the samples ranges from 0.83 to 0.85, and most are 0.84. The

Table 1
Representative bulk compositions of the komatiites from Mengyin, Shandong (wt%)

Sample	K-15	K-20	K-21	K-24	K-26	K-28	K-31	K-35	K-18	K-25	Precision
SiO_2	43.28	43.2	44.04	43.87	43.66	43.77	42.95	42.43	44.02	42.52	±0.20
TiO_2	0.16	0.16	0.14	0.16	0.17	0.17	0.17	0.16	0.18	0.16	±0.01
Al_2O_3	4.70	5.00	4.42	4.56	4.43	4.38	5.15	4.61	4.82	3.82	±0.10
FeOt	9.78	9.29	9.97	9.57	9.63	9.52	9.47	9.64	9.37	10.68	
MnO	0.14	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.14	0.14	±0.01
MgO	28.74	29.51	28.67	28.36	28.29	27.92	28.87	29.65	28.49	29.44	±0.10
CaO	5.03	4.89	5.33	5.17	5.56	5.64	4.93	4.55	5.34	4.27	±0.10
Na_2O	0.42	0.34	0.41	0.36	0.39	0.38	0.36	0.29	0.44	0.37	±0.10
K_2O	0.04	0.05	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	±0.05
P_2O_5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	±0.01
LOI	7.72	7.43	6.76	7.47	7.60	7.44	7.84	8.24	6.97	8.28	±0.20
Total	100.02	100.02	99.92	99.7	99.91	99.4	99.91	99.73	99.81	99.72	
Mg#	0.84	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.85	0.84	0.83
Cr (ppm)	2500	2500	2200	2400	2300	2300	2600	2400	2400	2200	±10
Ni (ppm)	1472	1481	1428	1441	1447	1432	1459	1555	1422	1633	±10

* The data were analysed in the Geological and Geophysical Department of the Academy of Sciences Institute of China using XRF-1500 Sequential X-RAY Fluorescence Spectrometer. Mg#=Mg/(Mg+Fe).

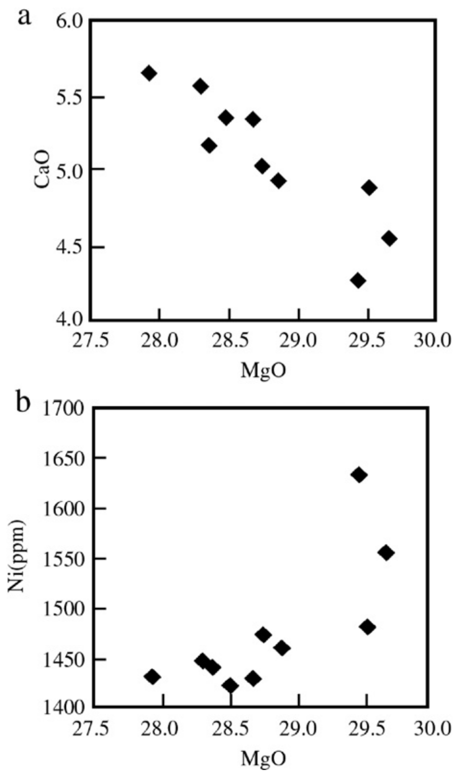

Fig. 5. Covariant diagram of the komatiites in Mengyin Shandong.

LOI is as much as 6.76–8.28 wt.%. So the Mengyin komatiites are low-Ti, Al-undepleted and high-MgO lavas. In the MgO covariant diagrams, only CaO and Ni show linear correlation (Fig. 5a, b). Mg-numbers in the relic olivine are from 0.80–0.86. Cr abundance in the olivine is 0–0.15 wt.%, Ni = 0.23–0.39 wt.%, CaO = 0–0.18 wt.% and Ti = 0–0.04 wt.% (Table 2). Most of the Cr is below 0.1 wt.%, but in some cases it goes up to 0.15 wt.%; CaO is generally 0.01%, but in some cases up to 0.18 wt.%.

5. Discussion

The data presented in this study shows that even though the Mengyin Komatiites underwent significant metamorphism and alteration, some relic spinifex textures and igneous olivine grains are still preserved. As such, it is important to know the primitive MgO abundance, which was in equilibrium with the melt to infer the potential eruption temperature of the rocks.

5.1. Alteration

High Loss on Ignition indicates that there are many hydrous minerals in the rocks, which is consistent with the large amount of serpentine, tremolite, chlorite and talc suggesting strong secondary alteration. Such minerals tend to occur where there are plenty of fluids. Some serpentine forms bands near tremolite, some near relict olivine. Many magnetite grains in the matrix also indicate the transformation from olivine to serpentine. The Mg-number decreases from the center to the margin of the olivine. In most cases, the CaO abundance is 0.01%, but some olivines have up to 0.18 wt.%. Obviously CaO in our samples is much lower than igneous komatiite olivine (CaO > 0.2 wt.%, Arndt et al., 1977). Moreover, there is no sample with intermediate CaO content. This indicates the possibility that the high-CaO olivine sample K-35 may be contaminated with tiny Ca-bearing minerals such as tremolite or calcite. The K-35 olivine is the highest in Al_2O_3 and K_2O, and this also suggests contamination. This sample is also the highest in MnO, although the FeO content is relatively low, suggesting a metamorphic recrystallization origin for this olivine. We suggest that most olivines from Mengyin were recrystallized during metamorphic processes (Trommsdorff et al., 1998).

5.2. Whole-rock characteristics

The Mengyin komatiites have low-Ti, which results in the ratio of Al_2O_3/TiO_2 being a little higher than that of chondrite. Condie (2001) give a good review of Ti content in flood basalts. Foder (1987) proposed that low-Ti magmas are produced near a plume axis by high degrees of melting and that high-Ti magmas are produced by low degrees of melting around the margin of the plume. Arndt et al. (1993) proposed a similar model in which the high-Ti group is produced in a plume beneath thick lithosphere and the low-Ti group beneath thin lithosphere. These melting models, however cannot explain isotopic differences between high- and low-Ti basalts (Peate, 1997). Others have addressed the problem with models that involve different sources. Because the low-Ti group is not found in plume-related basalts from oceanic areas, some investigators have been led to suggest they come from the subcontinental lithosphere or that they are produced by crustal contamination (Hergt et al., 1991; Turner and Hawkesworth, 1995).

Ji et al. (1994) regarded that the western Shandong greenstone belt represents a continental environment based on the bimodal character of the volcanic rocks with respect to SiO_2 contents. Nd isotope data indicate assimilation of 2–6% LREE-enriched older continental crust or sediments (Polat et al., 2006).

Table 2
Representative microprobe data of the olivine in the komatiites from Mengyin, Shandong

Sample	11-5	K-15	K-21	K-25	K-24	K-35
SiO_2	39.03	39.28	39.60	39.37	38.97	39.13
TiO_2	0.00	0.04	0.00	0.02	0.01	0.00
Al_2O_3	0.00	0.02	0.00	0.01	0.02	0.03
FeOt	13.43	17.81	18.77	17.96	18.73	17.2
MnO	0.11	0.26	0.29	0.28	0.24	0.36
MgO	47.35	42.32	41.73	42.24	41.78	42.43
CaO	0.01	0.01	0.01	0.01	0.00	0.18
Na_2O	0.00	0.01	0.01	0.00	0.02	0.00
K_2O	0.00	0.00	0.00	0.00	0.01	0.03
Cr_2O_3	0.15	0.00	0.00	0.05	0.00	0.02
NiO	0.37	0.24	0.23	0.39	0.26	0.32
Total	100.45	99.99	100.64	100.33	100.04	99.70
Mg-number	0.86	0.81	0.80	0.81	0.80	0.81

Analyses of olivines in polished thin sections were conducted by EPMA (JXA-8100) at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, China. The analyses were performed under an accelerating voltage of 15 kV and a beam current of 10 nA with a bind spot of 1 μm.

So the low-Ti komatiite might come from the subcontinental lithosphere, rather than produced by crustal contamination.

Although the origin of high-and low-Ti flood basalts is not resolved, most trace element and isotopic data demand two sources for the two groups (Sharma, 1997). High-Ti magmas appear to have been generated by low degrees of garnet lherzolite, leaving garnet in the resitite, whereas low-Ti magmas reflect a high degree of melting of a different mantle source in which garnet is not left in the resitite (Condie, 2001). As such, the Mengyin komatiites might indicate the latter case.

Ni is positively correlated with MgO, indicating that it is controlled by the crystallization of olivine since Ni is a compatible element for olivine. In the case of progressive magmatic fractionation, Ni must display a sympathetic variation with MgO (Fig. 5b). Other major elements are mobile in the metamorphism and late alteration.

5.3. Potential eruption temperature

Experimental results show that the partition coefficient of the Fe/Mg ratio between olivine and coexisting melt is constant (0.3–0.34), and will increase with pressure (Thompson and Gibson, 2000). As mentioned in the last section, the Mengyin komatiites were not derived from a low-pressure source, so we take the partition factor K_D between olivine and the coexisting melt as 0.33.

Most of the Fo in the residual olivine is about 0.81, the maximum Fo is about 0.86, which is equilibrated with 12% MgO in the primitive melt. We thus identify excess olivine in the melt and compute the eruption temperature of Mengyin komatiites to be about 1270° at 1 atm (Nisbet, 1982; Smith and Erlank, 1982). Such high eruption temperatures are indicative of a plume source. However, this temperature is based on the assumption of dry melting conditions, and if there was water present in the melt the actual eruption temperature would be lower (e.g., Parman and Grove, 2004).

5.4. Tectonic setting

Although there are some debates surrounding the tectonic setting of komatiites, most geologists agree that komatiites formed in an anomalously hot plume environment (Campbell et al., 1989; Xie and Kerrich, 1994; Herzberg, 1995; Parman and Grove, 2004). Mainly four tectonic settings are proposed: oceanic plateau, continental hot spot, arc and rift (Kusky and Polat, 1999).

Previous studies suggested that the Mengyin komatiites formed in an arc, continental margin (Xu and Dong, 1992) or a continental environment (Ji et al., 1994). Considering the potential eruption temperature and Nd isotopic data, it is inferred that komatiites of present study may have been related to a plume source in subcontinental lithospheric setting.

U/Pb zircon and Nd isotopic age show that 2.7 Ga is a peak of continental crust growth and the eruption of komatiites worldwide (Condie, 1998). Therefore, the eruption of komatiites in Shandong may be part of the continental growth in Neoarchean and reflect part of a global superplume komatiite event.

The tectonic model for the evolution of the North China craton outlined by Kusky and Li (2003) and Kusky et al. (2004) sheds some light on the tectonic setting of the Mengyin komatiites that is consistent with our data. In their model, a major ocean between the eastern and western blocks closed at 2.5 billion years ago, deforming the western margin of the eastern block where the Mengyin komatiites and the Shandong greenstone belt are preserved. The 2.7 billion year age and probable plume source for the Mengyin komatiites suggests that the komatiites may have been erupted during plume-related magmatism related to the initial break-up of an older continental land mass now preserved as the eastern block of the NCC, and that the ocean between the eastern and western blocks may have been active and open from 2.7–2.5 Ga. Further, the correlation of the Mengyin komatiites with the widespread global komatiite event at 2.7 Ga suggests that this may have been a global period of supercontinent break up.

6. Conclusion

Komatiites in Mengyin, Shandong Province have typical spinifex textures with high-Mg, low-Ti, and undepleted Al. Recent Sm–Nd isotopic data show that ε_{Nd} ranges from $-0.6 \sim +3.6$, but in general lie around +3.3 for fresh samples, which suggests long-term depleted event with little (if any) contamination by old continent crust. According to the mass equilibrium, we get an eruption temperature for the Mengyin Komatiites of about 1270 °C. It is inferred that komatiites in Mengyin, west Shandong may be part of a plume-related global magmatic event related to the break up of a supercontinent that included the eastern block of the North China craton.

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References

Arndt, N.T., Nisbet, E.G., 1982. Geochemistry of Munro township basalts. In: Arndt, N.T., Nisbet, E.G. (Eds.), Komatiites. Allen and Unwin, London, pp. 309–329.

Arndt, N.T., Naldrett, A.T., Pyke, D.R., 1977. Komatiitic and iron-rich tholeiitic lavas of Munro township, northeast Ontario. Journal of Petrology 18, 319–369.

Arndt, N.T., Czamanske, G.K., Wooden, J.L., Fedorenko, V.A., 1993. Mantle and crustal contributions to continental flood volcanism. Tectonophys 223, 39–52.

Cao, G.Q., 1996. Early Precambrian Geology of Western Shandong. Geological Press, Beijing, pp. 112–117 (in Chinese with English abstract).

Campbell, I.H., Griffith, E.W., Hill, R.I., 1989. Melting in an Archean mantle plume: heads it's basalts, tails it's komatiites. Nature 339, 697–699.

Cheng, Y.Q., Shen, Q.H., 1964. Geochronology study on Taishan metamorphic rocks and magmatic rocks in Xintai, Shandong province. Geology Review 22, 198–202 (in Chinese with English abstract).

Cheng, Y.Q, Xu, H.F., 1991. Some new ideas on the komatiite in Archean Yanlingguan group in Xintai, Shandong. Regional Geology of China 135, 31–32 (in Chinese with English abstract).

Cheng, Y.Q., Shen, Q.H., Wang, Z.J., 1982. Shandong Archean Yanlingguan Metavolcanic-Sedimentary Rocks. Geological Press, Beijing, pp. 70–74 (in Chinese).

Condie, K.C., 1998. Episodic continental growth and supercontinents, a mantle avalanche connection? Earth and Planetary Science letters 193, 97–108.

Condie, K.C., 2001. Plumes as tracers of mantle processes. In: Condie, K.C. (Ed.), Mantle Plumes and Their Record in Earth History. Cambridge University Press, p. 162.

Foder, R.V., 1987. Low- and high-TiO_2 flood basalts of southern Brazil: origin from picritic parent age and a common mantle source. Earth and Planetary Science Letters 84, 423–430.

Grove, T.L., Parman, S.W., 2004. Thermal evolution of the earth as recorded by komatiites. Earth and Planetary Science Letters 219, 173–187.

Hergt, J.M., Peate, D.W., Hawkesworth, C.J., 1991. The petrogenesis of Mesozoic Gondwana low-Ti flood basalts. Earth and Planetary Science Letters 105, 134–148.

Herzberg, C., 1995. Generation of plume magmas through time, an experimental approach. Chemical Geology 126, 1–16.

Jahn, B.M., Auray, B., Shen, Q.H., Liu, D.Y., Zhang, Z.Q., Dong, Y.J., Ye, X.J., Zhang, Q.Z., Cornichet, J., Mace, J., 1988. Archean crustal evolution in China: the Taishan Complex, and evidence for juvenile crustal addition from long-term depleted mantle. Precambrian Research 38, 381–403.

Ji, H.Z., Shimazaki, H., Hu, S.H., Zhao, Y.Y., 1994. Two types of greenstone belts in Shandong province, eastern China. Resource Geology 44, 101–110.

Kusky, T.M., Li, J.H., 2003. Paleoproterozoic tectonic evolution of the North China craton. Journal of Asian Earth Sciences 22, 383–397.

Kusky, T.M., Polat, Ali, 1999. Growth of granite–greenstone terranes at convergent margins, and stabilization of Archean craton. Tectonophysics 305, 43–73.

Kusky, T.M., Li, J.H., Glass, A., Huang, X.N., 2004. Origin and emplacement of Archean ophiolites of the central orogenic belt, North China craton. In: Kusky, T.M. (Ed.), Precambrian Ophiolites and Related Rocks. Developments in Precambrian Geology, vol. 13, pp. 223–274.

Le Bas, M.J., 2000. IUGS reclassification of the high-Mg and picritic volcanic rocks. Journal of Petrology 41, 1467–1470.

Nisbet, E.G., 1982. The tectonic setting and petrogenesis of komatiites. In: Ardnt, A.T., Nisbet, E.G. (Eds.), Komatiites. Allen and Unwin, London, pp. 501–520.

Parman, S.W., Grove, T.L., 2004. Petrology and geochemistry of Barberton komatiites and basaltic komatiites: evidence of Archean fore-arc magmatism. In: Kusky, T.M. (Ed.), Precambrian Ophiolites and Related Rocks. Developments in Precambrian Geology, vol. 13, pp. 539–565.

Peate, D.W., 1997. The Parana-Etendeka province. American Geophysical Union, Mon, vol. 100, pp. 217–245.

Polat, A., Li, J., Fryer, B., Kusky, T., Gagnon, J., Zhang, S., 2006. Geochemical characteristics of the Neoarchean (2800–2700 Ma) Taishan greenstone belt, North China craton: evidence for plume–craton interaction. Chemical Geology 230, 60–87.

Sharma, M., 1997. Siberian traps. American Geophysical Union, Mon, vol. 100, pp. 273–295.

Smith, H.S., Erlank, A.J., 1982. Geochemistry and petrogenesis of komatiites from the Barberton greenstone belt, South Africa. In: Ardnt, N.T, Nisbet, E.G. (Eds.), Komatiites. Allen and Unwin, London, pp. 347–398.

Sproule, R.A., Lesher, C.M., Ayer, J.A., Thurston, P.C., Herzberg, C., 2002. Spatial and temporal variations in the geochemistry of komatiites and komatiitic basalts in the Abitibi greenstone belt. Precambrian Research 115, 153–186.

Trommsdorff, V., Lopes Sanchez-Vizcaino, V., Gomez-Pugnaire, M.T., Muntener, O., 1998. High pressure breakdown of antigorite to spinifex-textured olivine and orthopyroxene, SE Spain. Contribution to Mineral Petrology 132, 139–148.

Thompson, R.N., Gibson, S.A., 2000. Transient high temperatures in mantle plume heads inferred from magnesian olivines in Phanerozoic picrites. Nature 407, 502–506.

Turner, S.P., Hawkesworth, C.J., 1995. The nature of the subcontinental mantle: constraints from the major element composition of continental flood basalts. Chemical Geology 120, 295–341.

Xie, Q., Kerrich, R., 1994. Silicate-perovskite and majorite signature komatiites from the Archean Abitibi greenstone belt: implications for early mantle differentiation and stratification. Journal of Geophysical Research 99, 799–812.

Xu, H., Dong, Y., 1992. Granite-Greenstone Belt in West Shandong. Geological Press, Beijing.

Yang, Q., 2000. The petrological characteristics of Sujiagou komatiite in Mengyin. Shandong Rock and Mineral Analysis 19, 58–62 (in Chinese with English abstract).

Zhang, R., Si, R., Song, B., 1998. Komatiite in Sujiagou village of Mengyin country. Shandong Geology 14, 26–33 (in Chinese with English abstract).

Zhang, R.S., Tang, H.S., Kong, L.G., Gan, Y.J., Song, B.Z., 2001. Characteristics and significance of the Sujiagou komatiite at Mengyin. Shandong Regional Geology of China 20, 236–24 (in Chinese with English abstract).

Zhao, G., Wilde, S.A., Cawood, P.A., Sun, M., 2001. Archean blocks and their boundaries in the North China craton: lithological, geochemical, structural and P-T path constraints and tectonic evolution. Precambrian Research 107, 45–73.

Zhao, G., Sun, M., Wilde, S.A., 2003. Correlations between the eastern block of the North China craton and the south indian block of the Indian Shield: an Achaean to Palaeoproterozoic link. Precambrian Research 122, 201–233.

Zhao, G., Sun, M., Wilde, S.A., Li, S., 2005. Late Archean to Paleoproterozoic evolution of the North China craton: key issues revisited. Precambrian Research 136, 177–202.