Geochemical characteristics of basic and ultrabasic metavolcanics from the Proterozoic Kuanping Group in the Qinling orogenic belt, China : petrogenetic and tectonic implications

Ze-Jun ZHANG

Department of Earth Sciences, Kumamoto University, Kumamoto 860, Japan

Department of Geology, Northwest University, Xian 710069, China

The basic and ultrabasic metavolcanics, occurring within the about 1.0 Ga Kuanping Group in the Qinling orogenic belt, China, have been investigated for bulk-rock major and trace-element data. Studied rocks fall into three geochemical categories: (1) komatiites, resembling Barberton-type Al-depleted komatiites; (2) OIB-like basalts, spatially associated with and geochemically similar to komatiites; and (3) MORB-like tholeiites, resembling mid-ocean ridge and back-arc basin basalts. Combining our observations and recent high-pressure experimental data, we accordingly considered an unusual pressure condition at the depth of mantle transition zone and a low-degree critical melting (5–6%) event of a majorite mantle source for the generation of komatiitic initial melt. The OIB-like basaltic melt may have been produced by another low-degree melting event of the komatiite-derived source or by high-pressure segregation of initial komatiitic magma at the depth greater than 300 km, whereas the MORB-like tholeiite by 15–30% partial melting of a depleted shallow spinel-peridotite source. An unusually hot rising plume would have controlled the generation of komatiitic and basaltic magma and the magmatic evolution. This plume magmatism may have occurred either in a marginal ocean basin where the mantle plume would also controlled the development of the marginal basin, or in a major ocean basin which had developed between the North-China and the South-China platform at about 1.2 to 1.0 Ga.

Keywords: Komatiite, Basalt, Geochemistry, Petrogenesis, Proterozoic oceanic lithosphere, Qinling orogenic belt, China

I. Introduction

Basic and ultrabasic metavolcanics form a significant part of the Proterozoic Kuanping Group (986–1142 Ma., Zhang Z.-Q. *et al.*, 1994) in the Qinling orogenic belt, China. As a Proterozoic volcanic-sedimentary formation, the Kuanping Group would provide an important and significant example to study the nature and origin of basic to ultrabasic magmatism in the Precambrian. It will help us better understanding of deep mantle sources, crust growth processes and precambrian plate tectonics, which all are not clear in the region. More

interestingly, the ultrabasic volcanics within the Kuanping Group are inferred to be Barberton-type komatiites on the basis of geochemical characteristics. An interesting model has been proposed recently that the Barberton-type komatiites could be formed by a low degree partial melting at very high pressures (Ohtani, 1984; Takahashi and Scarfe, 1985; Herzberg and Ohtani, 1988; Gruau *et al.*, 1990; Xie and Kerrich, 1994; Riganti and Wilson, 1995). The komatiites within the Kuanping Group would, therefore, be an example to test this hypothesis by investigating the geochemical characteristics of the komatiites.

In this paper, the author summarizes geochemistry of the komatiites and the associated basalts from the Kuanping Group, and then discusses their petrogenesis and tectonic implications.

II. Geological setting

The Qinling Mountains is an E-W trending mountain range that separates the North and South China, extending west-ward to the Qilian and the Kunlun Mountains, and east-ward to the Dabei Mountains (Fig. 1A). Tectonically, the Qinling can be divided into the north and south belt with the Shandan fault. It is commonly agreed that the Qinling Mountains had experienced a multistage development from the early Proterozoic to the late Mesozoic, and the

Shandan fault was a complicated suture of the North China and the South China platform (Zhang G.-W. *et al.*, 1989).

The studied area is located in the south of Luonan county, Shannxi province, and geologically within the Kuanping Group in the north Qinling belt (Fig. 1B). Figure 1B shows the regional relationships and the main litho-tectonic units segmented by several thrusts or ductile faults trending approximately EW of the north Qinling belt. The Songshugou ophiolitic complex and the Danfeng Group, as well as several mafic-ultramafic complexes along the Shandan fault, occupy a similar structural position, representing the southern structural Proterozoic slice emplaced onto the continental crust (Qinling Complex). Formation of

Fig. 1. (A) Showing tectonic location of the Qinling Mountains and the North Qinling belt (black area within the square) in China. NC=North China platform; SC=South China platform; KLS, QLS and DBS denote the Kunlun, the Qilian and the Dabie Mountains, respectively. (B) Generalized geologic map of the North Qinling belt. (C) Generalized geologic map of the Luonan komatiite area.

these complexes and their emplacement in the Qinling Complex took place during Jinningian period¹ (Zhou and Zhang G.-W., 1991; Zhang Z.-Q. *et al.*, 1994; Zhang Z.-J. *et al.*, 1995). The Qinling Complex (early Proterozoic; Zhang G.-W. *et al.*, 1989; Zhang Z.-Q. *et al.*, 1994), an assemblage of granulite-amphibolite facies metamorphic rocks and plutonic rocks showing deep-level structural styles, crops out northward. The Kuanping Group (see below in details) is exposed in the north of the Qinling Complex. A current tectonic model, mainly based on regional geologic relationships, suggests that the Kuanping Group may be formed in a marginal basin and the Qinling Complex could be a micro-continent rifted from the North-China platform with the opening of marginal basin of the Kuanping Group (Zhang G.-W. *et al.*, 1989; Zhang S.-G. *et al.*, 1991; Wang *et al.*, 1992), which had developed simultaneously with intra-oceanic backarc basin and volcanic arc system in a Proterozoic major ocean basin between the North-China and the South-China platform indicated by Songshugou ophiolite and Danfeng Group (Zhang Z.-J. *et al.*, 1995). The above Proterozoic lithotectonic units were generally overprinted by the Caledonian tectonothermal event, preceding and accompanying many early Paleozoic granitoidic plutons.

The early Paleozoic lithotectonic units in the belt, including Erlangping Group and some blocks tectonically juxtaposed within the Danfeng Group, are dominated by ophiolitic, volcanic-sedimentary sequences associated with island-arc, and melange, representing another important period, the Caledonian period, of plate movement and collision in the belt (Zhang

G.-W. *et al.*, 1989).

III. Field relationship and petrography

The length of exposure of the Kuanping Group is approximately 500 km with NWW trending in the north Qinling belt (Fig. 1B). The contact with the country rocks is a fault. Metamorphic grade of the Kuanping Group varies from the amphibolite to the greenschist facies (Zhang S.-G. *et al.*, 1991; Wang *et al.*, 1992). It is composed of a succession of massive to foliated amphibolites and greenschists in the lower formation, two-mica quartz schists in the middle formation, and marbles in the upper formation. Premetamorphic lithologies of these three formations apparently included basaltic (to komatiitic) volcanics, which locally present compositional layering, relict magma-flow and vesicular-amygdaloidal structures, and sedimentary rocks, which consist of felsic clastic rocks, limestone, pelites and minor cherty layers. However, this sequence is not always best exposed. Generally, the middle to the upper formation dominate the exposed section of the Kuanping Group. Primary compositional layering and distinct foliation in various rocks coincide in attitude, being in strike NWW, and steeply dipping.

Local geological relationships of the mapped komatiite-basalt area are shown in Figure 1C. Similar to regional observations, meta-basalts in the area chiefly present massive to foliated amphibolite and greenschist with varying amounts of plagioclase, hornblende, actinolite, biotite, epidote, chlorite, quartz and Fe-Ti oxides; they occur in two colors, the lighter and darker rock in the field, mainly differed by mineral model proportion. Relative to the darker rocks, the lighter rocks contain less volume of Fe-Ti oxides and biotite. The lighter colored meta-basalts are the dominant volcanic part of the Kuanping Group, whereas the darker colored meta-basalts most-

¹ Jinningian period is aged from 0.8 to 1.2 Ga. The tectonic movement took place at around 800-850 Ma in China, indicated by an unconformity, after which detrital deposits were formed at many places as the first platform cover sequence (after Yang *et al.*, 1986, p 44-50).

ly distribute in the Luonan area and appear to be closely associated to the komatiites. However, the contact relationship between the basalts and the komatiites was not observed well in the field, because of intensive weathering. Furthermore, several small segments mainly composed of diopside quartzite and diopsidite occur in the mapped area; the Caledonian granitoids intrude into the komatiitic and basic volcanic rocks.

The komatiites comprise massive to foliated, concordant tabular bodies or layers with exposed size varying from 200 to 30 meters in length and from 40 to several meters in thickness, and with strike NWW, dip to the SW. An intense weathering crust of several meters thickness usually obscures original structures of komatiites in the outcrop. However, we observed olivine-phyric and spinifex textures (Fig. 2A) with microscope, that may attest to the presence of ultrabasic flows. The principal mineral assemblage of the meta-komatiites is amphibole + talc + brucite + chlorite + serpentine + magnetite + leucoxene. Olivine, pyroxene and spinel are locally preserved with varying model proportion. Most commonly, olivine exhibits either a mosaic equigranular matrix with 0.01–0.05 mm grain size and polygonized anhedral, or an extremely irregular phenocryst with 0.5–1.5 mm grain size. Only in two samples, some olivine grains have spinifex skeletal crystal shapes with 2–15 mm in length and 0.3–0.5 mm in width, orientationally occurring in the metamorphic mineral matrix, and having approximately uniform extinction position under the crossed polar (Fig. 2A). The olivine in all investigated samples is characterized by an unusually low forsterite content, $Fo=73\text{--}83\%$. Pyroxene is locally identified as 0.05–0.1 mm size grain in the matrix of olivine-phyric rocks, which includes augitic clinopyroxene and bronzitic orthopyroxene. Spinel occurs mostly as a matrix component, occasionally as zoned

Fig. 2. (A) Microscopic sketch showing that randomly oriented elongate skeletal olivines (ol) set in fine-grained matrix (m) composed of metamorphic minerals, olivine and spinel and they present uniform extinctional position under the crossed polar in Luonan komatiites. (B) Microscopic sketch of zoned spinel (sp)-olivine (ol) aggregate, where ol zone consists of olivine and its alteration minerals (serpentine, talc, etc.).

spinel-olivine aggregate (Fig. 2B). Spinel composition is almost magnesioferrospinel: $(Mg, Fe) Al_2O_4$.

IV. Geochemistry

Major elements and Cr, Ni, Rb, Sr and Ba of 10 komatiites and 10 basaltic rocks (Table 1), Zr, Sc, Ti and V of 4 komatiites (Table 2), and rare-earth elements of 4 komatiites and 7 basaltic rocks (Table 3), were determined. In this study, we used to collect samples from test trenches and drillings provided by previous

Table 1. Abundances and inter-element ratios of major and some trace elements and CIPW normative components of basaltic and komatiitic metavolcanics from the Kuanping Group

Sample number	basalts										komatiites									
	low-Ti type					high-Ti type														
	8612	8613	8615	8617	8655	8651	8656	8606	86128	86529	8601	8603	8604	8605	86151	8639	86135	86124	8617	8607
major elements (Wt %)																				
SiO ₂	51.59	51.25	49.85	49.53	49.47	48.23	49.71	48.49	49.16	55.52	48.32	46.87	47.07	46.47	47.53	52.02	43.09	45.77	45.14	39.76
TiO ₂	0.92	1.17	1.67	0.97	1.64	3.19	3.11	3.00	1.83	2.44	0.51	0.92	0.61	0.61	0.91	1.07	1.02	1.12	0.67	1.58
Al ₂ O ₃	14.36	13.44	12.32	14.13	13.10	15.25	15.18	15.27	14.52	14.86	4.70	7.32	4.36	4.04	3.94	4.83	8.35	7.54	5.38	15.86
Fe ₂ O ₃	2.55	2.67	3.70	2.73	2.94	4.58	3.99	8.95	2.06	2.50	3.31	4.10	6.60	6.38	6.45	3.73	5.64	2.65	5.36	8.57
FeO	8.04	9.75	12.76	8.64	11.72	9.25	8.43	3.70	7.41	8.25	6.00	6.64	6.28	7.76	7.12	6.20	6.86	7.58	5.92	6.43
MgO	7.79	7.59	6.51	9.06	6.50	6.40	6.73	7.20	9.48	4.97	24.91	25.68	23.97	26.95	25.99	26.10	30.58	25.62	29.11	21.20
CaO	12.25	11.43	10.80	13.12	11.16	7.07	7.22	7.92	10.31	6.94	11.41	7.41	10.74	7.25	7.58	5.53	4.07	9.15	7.91	5.82
MnO	0.18	0.22	0.26	0.18	0.23	0.12	0.11	0.32	0.18	0.24	0.23	0.22	0.17	0.20	0.21	0.21	0.21	0.17	0.17	0.15
Na ₂ O	2.12	2.26	1.79	1.36	2.95	4.14	3.36	2.58	2.48	3.37	0.42	0.54	0.01	0.16	0.16	0.18	0.09	0.18	0.23	0.37
K ₂ O	0.13	0.12	0.22	0.17	0.17	1.38	1.80	2.15	2.34	0.57	0.07	0.09	0.07	0.07	0.06	0.04	0.07	0.06	0.06	0.11
P ₂ O ₅	0.07	0.08	0.12	0.07	0.11	0.40	0.36	0.41	0.21	0.33	0.10	0.21	0.10	0.10	0.04	0.09	0.02	0.15	0.03	0.14
LOI	1.22	1.75	1.39	1.67	2.34	1.81	2.50	2.37	1.32	1.14	1.14	2.68	0.73	0.32	0.71	2.31	3.56	0.96	1.15	7.19
Total	100.40	99.36	99.26	99.30	100.78	99.62	99.69	99.64	99.51	99.80	99.84	99.68	100.07	99.54	99.72	99.25	99.46	99.98	99.08	99.23
Mg#	0.43	0.38	0.29	0.45	0.31	0.32	0.36	0.38	0.51	0.32	0.74	0.71	0.66	0.67	0.67	0.73	0.72	0.72	0.73	0.60
FeO*/MgO	1.33	1.60	2.47	1.22	2.21	2.09	1.79	1.63	0.98	2.11	0.36	0.40	0.51	0.50	0.50	0.37	0.39	0.39	0.37	0.67
CaO/Al ₂ O ₃	0.85	0.85	0.88	0.93	0.85	0.46	0.48	0.52	0.71	0.47	2.42	1.01	2.46	1.79	1.92	1.15	0.49	1.21	1.47	0.37
P ₂ O ₅ /TiO ₂	0.08	0.07	0.07	0.07	0.07	0.12	0.12	0.14	0.12	0.14	0.20	0.23	0.17	0.17	0.17	0.09	0.02	0.14	0.05	0.09
Al ₂ O ₃ /TiO ₂	15.68	11.51	7.40	14.53	8.01	4.78	4.88	5.09	7.92	6.10	9.14	7.97	7.12	6.60	4.33	4.50	8.16	6.75	7.98	10.03
CaO/TiO ₂	13.38	9.79	6.48	13.48	6.83	2.22	2.32	2.64	5.62	2.85	22.16	8.07	17.52	11.83	8.33	5.15	3.98	8.18	11.73	3.68
K ₂ O/Na ₂ O	2.25	2.39	2.01	1.54	3.12	5.51	5.17	4.73	4.82	3.94	0.49	0.64	0.08	0.23	0.22	0.22	0.17	0.24	0.30	0.48
trace elements (ppm)																				
Cr	26.42	18.86	8.27	143.9	12.3	31.13	67.17	17	120	26	582	718	770	872	932	513	937	393	633	693
Ni	63.31	54.59	36.44	85.37	31.9	42.58	71.14	98	118	39	920	880	1100	940	850	550	940	630	960	650
Rb	1.18	0.96	4.47	2.26	2.08	23.96	37.21	29.76	43.8	25.34	12	12	12	6	10	7	12	6	10	12
Sr	149.18	100.21	94.78	71.57	206.91	394.1	408.5	350	380	230	180	130	250	200	180	130	150	130	200	150
Ba	73.13	22.24	50.71	25.69	1.8	306.2	555	960	810	876	580	620	690	660	700	840	770	860	610	750
Rb/Sr	0.01	0.01	0.05	0.03	0.01	0.06	0.09	0.09	0.12	0.11	0.07	0.09	0.05	0.03	0.06	0.05	0.08	0.05	0.05	0.08
Ba/Sr	0.49	0.22	0.54	0.36	0.09	0.78	1.36	2.74	2.13	3.81	3.22	4.77	2.76	3.30	3.89	6.46	5.13	6.62	3.05	5.00
CIPW norms																				
Q	2.57	2.09	3.86	3.86						9.90										
Or	0.77	0.71	1.30	1.30	1.00	8.16	10.64	12.76	13.83	3.37	0.41	0.53	0.42	0.42	0.36	0.24	0.41	0.35	0.36	0.65
Ab	17.94	19.12	15.15	15.15	24.96	34.39	28.43	21.93	16.97	28.52	3.56	4.58	0.09	1.36	1.36	1.52	0.76	1.52	1.95	3.15
An	29.28	26.17	24.93	24.93	22.00	19.04	21.02	23.84	21.58	23.74	10.75	17.31	11.70	10.14	9.90	12.27	20.12	19.59	13.52	28.12
Ne						0.26				2.18										
C																0.78				4.91
Wo	12.96	12.53	11.63	11.63	13.63	5.60	5.20	5.40	11.78	3.57	18.91	7.57	17.19	10.58	11.53	6.10		10.37	10.72	
Di	12.29	12.07	11.51	11.51	13.41	5.27	4.84	4.97	10.91	3.44	16.96	6.80	15.67	9.65	10.47	5.44		9.27	9.62	
Hy	18.59	21.01	22.81	22.81	11.06	12.59	14.57		18.44		18.16	28.55	24.11	29.55	35.44	66.01	26.39	22.65	16.32	20.15
Ol					6.29	13.65	4.76	3.29	15.80		27.13	28.90	26.36	33.84	25.62	2.44	45.88	29.97	43.02	35.18
Mt	3.70	3.87	5.36	5.36	4.26	6.64	5.79	6.55	2.99	3.63	2.92	3.51	3.07	3.07	3.51	3.73	3.66	3.80	3.16	4.49
il	1.75	2.22	3.17	3.17	3.11	6.06	5.91	5.72	3.48	4.63	0.97	1.75	1.16	1.16	1.74	2.03	1.94	2.13	1.28	3.02
Ap	0.17	0.19	0.28	0.28	0.26	0.95	0.85	0.97	0.50	0.78	0.24	0.50	0.24	0.24	0.10	0.21	0.05	0.36	0.07	0.33

Notes: Major elements are normalized to 100% on volatile-free basis. Major- and trace-elements were determined by XRF at Guiyang Institute of Geochemistry, Academia Sinica of China. LOI and Total are loss-on-ignition and total wt%, respectively. Mg# = MgO/(MgO+FeO*). FeO* = FeO+0.89Fe₂O₃. Analyzed specimens usually weighed 1 to 2 kilograms.

Table 2. Abundances and inter-element ratios of Ti, Zr, V and Sc for Luonan komatiites compared to those for Barberton-type, Munro-type komatiites and chondrite

	Luonan				Barberton type	Munro type	Chondrite
	8601	8603	8604	8605			
MgO (%)	24.91	25.68	23.97	26.95	25	27	
Ti (ppm)	3088	5510	3679	3675			
Zr	57	73	62	49			
V	270	320	250	260			
Sc	11.90	13.40	8.30	15.20			
Ti/Sc	259.52	411.18	443.22	241.77	106	88	83
Sc/Zr	0.21	0.18	0.13	0.31	0.78	1.25	1.23
V/Zr	4.74	4.38	4.03	5.31	4	8	12
Ti/Zr	54.18	75.48	59.33	75.00	82	110	102
Al ₂ O ₃ /TiO ₂	9.14	7.97	7.12	6.60	10	17	18
CaO/TiO ₂	22.16	8.07	17.52	11.83	22	27	20

* Barberton-type and Munro-type are average values after Smith and Erlank (1982). Ti, Zr, V and Sc for Luonan komatiites were determined by XRF at Guiyang Institute of Geochemistry, Academia Sinica of China.

works in order to sample specific and fresh rocks. For a comparison, we have also used relevant data in the recent literatures for 22 meta-basaltic samples from other areas of the

Kuanping Group (Zhang S.-G. *et al.*, 1991; Wang *et al.*, 1992; Zhang Z.-Q. *et al.*, 1994).

1. Evaluation of element mobilization

Since komatiites and basalts from the Kuanping Group have undergone low to medium grade metamorphism, it is necessary to evaluate if the rock compositions have been significantly affected by metamorphism.

A useful approach to this problem is to examine compositional relationships for these rocks with molecular ratio plot. In Figure 3, the molecular ratios of SiO₂/Al₂O₃ and SiO₂/TiO₂ of metavolcanics from the Kuanping Group are plotted against FM/Al₂O₃ and FM/TiO₂, respectively. Distinct linear trends are seen in this figure. However, such trends are

Table 3. Compositions (ppm) and inter-element ratios of rare-earth elements (REE) of basaltic and komatiitic metavolcanics from the Kuanping Group

Sample no.	basalts					komatiites			
	low-Ti type					high-Ti type			
	8612	8613	8615	8617	8655	8651	8656	8601	8603
La	1.94	3.16	4.70	2.22	4.03	39.44	39.01	7.40	19.20
Ce	6.07	8.58	13.15	7.01	10.70	80.15	76.80	10.90	43.10
Nd	5.24	6.63	10.53	5.72	8.12	40.66	38.86	7.90	20.00
Sm	1.74	2.19	3.38	1.88	2.67	8.30	7.92	2.50	4.00
Eu	0.76	0.92	1.37	0.81	1.14	3.02	3.04	0.50	1.20
Gd	2.53	3.06	4.19	2.60	3.76	7.86	7.37	2.70	3.90
Dy	3.08	3.80	5.25	3.24	4.64	6.96	6.53	2.60	3.40
Er	2.00	2.52	3.32	2.23	3.10	3.63	2.44	1.20	1.50
Yb	1.83	2.46	3.35	1.92	2.88	2.85	2.66	0.80	1.30
Lu	0.28	0.38	0.50	0.28	0.42	1.32	1.21	0.12	0.20
Sm/Nd	0.33	0.33	0.32	0.33	0.33	0.20	0.20	0.32	0.20
La/Nd	0.37	0.48	0.45	0.39	0.50	0.97	1.00	0.94	0.96
La/Sm	1.11	1.44	1.39	1.18	1.51	4.75	4.93	2.96	4.80
La/Ce	0.32	0.37	0.36	0.32	0.38	0.49	0.51	0.68	0.45
Ce/Nd	1.16	1.29	1.25	1.23	1.32	1.97	1.98	1.38	2.16
(La/Yb) _{ch}	0.70	0.85	0.92	0.76	0.92	9.12	9.66	6.09	9.73
(Gd/Yb) _{ch}	1.11	1.00	1.00	1.08	1.05	2.21	2.22	2.70	2.40
(La/Sm) _{ch}	0.68	0.88	0.85	0.72	0.92	2.89	3.00	1.80	2.92

Note: Determined by INAA at Beijing Institute of Uranium Deposit and Geology.

not seen in the plots of K_2O and Na_2O against Al_2O_3 and TiO_2 . Another approach is to examine the consistency of trace-element ratios, where the trace-element ratios would be relatively constant when metamorphism. The inter-REE ratios listed in Table 3 present such consistency for the komatiites and high-Ti basalts and for the low-Ti basalts, respectively, whereas the Ba/Sr ratio of komatiites and basalts has great variations (Table 1).

We cannot prove that alteration and weathering were unimportant, but treating the observations of petrochemical linear trends (Fig. 3) and constant trace-element ratios as generally representing of igneous features seems to be a reasonable working hypothesis, which is consistent with other observations such as the low to medium metamorphic grade and geochemical patterns quite similar to those of igneous rocks (see below). Therefore, I assume that most of the observed major- and trace-element abundance represent the primary, igneous features except for those elements such as Na, K and Ba.

Fig. 3. Molecular proportion ratio plots of SiO_2/TiO_2 vs. FM/TiO_2 and SiO_2/Al_2O_3 vs. FM/Al_2O_3 for komatiites and associated basalts from the Kuanping Group. $FM=FeO^*+MgO$. The k is a slope of each line.

2. chemical classification of metavolcanic rocks

The characteristics of less mobile elements have permitted a division into three categories for the metavolcanics: low-Ti basalts, high-Ti basalts, and komatiites (Table 1). The CIPW norm calculations (Table 1) indicate the low-Ti basalts to be tholeiitic while the high-Ti basalts are alkaline olivine basalts and olivine tholeiites.

Komatiites in the world have been classified into two chemical categories: the Barberton- or Al-depleted type and the Munro- or Al-undepleted type (e.g., Nesbitt *et al.*, 1979; Smith and Erlank, 1982; Herzberg and Ohtani, 1988). By geochemical comparison (see below), the Luonan komatiites appear to belong to the Barberton-type or Al-depleted komatiites.

3. Komatiites

The Luonan komatiites are characterized by typical komatiitic compositions with high MgO (21.2–30.58%, mean 26.01%), Cr (393–937 ppm, mean 704 ppm) and Ni (550–1,100 ppm, mean 842 ppm) contents (Table 1), and by the Al-depletion, that is lower $\text{Al}_2\text{O}_3/\text{TiO}_2$ value (4.33–10.03, Table 1) than that (~ 18) of chondrite. The Al-depletion is an important feature to characterize the Barberton-type komatiites. This would be more clearly shown by Figure 4, in which the Barberton-type and the Munro-type komatiites and associated basalts as well as basalts from back-arc basin (BAB), mid-ocean ridge (MORB) and ocean island (OIB) have also been shown. It may be noted in the plot that the Luonan komatiites and high-Ti basalts form the Al-depleted trend with Barberton-type komatiite-basalts and OIBs, whereas low-Ti basalts from the Kuanping Group form the Al-undepleted trend with Munro-type komatiite-basalts, BABs and MORBs.

Fig. 4. CaO/TiO_2 vs. $\text{Al}_2\text{O}_3/\text{TiO}_2$ plot for Luonan komatiites and other associated volcanics, chondrite, Barberton-type and Munro-type komatiites and modern-MORBs, OIBs and BABs (back-arc basin basalts). The data of MORBs, OIBs and BABs are from Flower (1991) and Saunders and Tarney (1991). Note two different trends: the Al-depleted and the Al-undepleted.

Incompatible trace element ratios of the Luonan komatiites are also similar to those of the Barberton-type komatiites. For example, the Ti/Sc ratio is higher, whereas the Sc/Zr, V/Zr and Ti/Zr are lower than chondritic values (Table 2). Trace and rare-earth element concentration patterns (Fig. 5, Fig. 6) show relative depletion in HFSEs (Sc, Zr, Y), Cr and HREEs, but enrichment in LREEs and large-ion lithophile elements (LILEs; e.g., Rb and Ba), and $(\text{La}/\text{Yb})_{\text{chondrite}}$ value is 6–14. As more examples, the Barberton-type komatiites from Barberton and Boston Township have shown geochemical features (Gruau *et al.*, 1990; Xie and Kerrich, 1994) similar to the Luonan komatiites. Significantly, such trace element pattern of komatiites is very similar to that of kimberlites that was generated by a small degree of partial melting of a deep mantle (>50 kb) followed by eclogite accumulation in the mantle (Fig. 5;

Fig. 5. Trace-element concentration in komatiites from the Kuanping Group, normalized to primitive mantle (Anderson, 1989) and compared with kimberlite and MORB (after Anderson, 1989). The elements to the right are incompatible in all major mantle phases while those to the left are retained in the garnet.

Anderson, 1989), but very different from the MORB's pattern of Munro-type komatiites (e. g., in Fig. 4; Cattell and Arndt, 1987; Xie and Kerrich, 1994).

4. High-Ti basalts: OIB-like basalts

The geochemical characteristics of the Luonan high-Ti basalts are in many ways similar to ocean island basalt (OIB) (Floyd, 1991). Compared to MORB and low-Ti basalt from the Kuanping Group, the Luonan high-Ti basalts have higher TiO_2 , P_2O_5 , K_2O , Na_2O , Rb, Sr, Ba contents and P/Ti, La/Ce, La/Nd and La/Sm ratios (Table 1, Table 3). Similar to OIB (Floyd, 1991) and BABs from the Lau and Fiji Basin that were derived from a source of enrolling OIB-component (Saunders and Tarney, 1991), the Luonan high-Ti basalts belong to the Al-depleted group (Fig. 4), and show LREE enrichment, $(\text{La}/\text{Yb})_{\text{chondrite}} = 9.1\text{--}9.7$, and strongly HREE-fractionated profiles, $(\text{Gd}/\text{Yb})_{\text{chondrite}} = 2.2$, $(\text{Yb})_{\text{chondrite}} = 1.4\text{--}5.2$ (Fig. 6). In Figure 7, the high-Ti basalt samples plot in the OIB field on FeO^*/MgO vs. TiO_2 plot and

Fig. 6. Chondrite-normalized REE patterns of basaltic and komatiitic rocks from the Kuanping Group. Normalizing values are from Boynton (1984).

form a significantly different trend from that of the MORB on $\text{Al}_2\text{O}_3/\text{TiO}_2$ vs. TiO_2 plot. The high-Ti basalts have similar LREE-enriched patterns with the komatiites, but are relatively more enriched in REE than the komatiites (Fig. 6).

5. Low-Ti basalts: MORB-like tholeiites

The low-Ti basalts have major- and trace-element characteristics within the range of modern NMORBs and BABs. They are characterized by higher $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (Fig. 4), lower to medium TiO_2 (0.92–1.67%), lower incompatible element ratios (Table 1, Table 3), LREE-depleted pattern, $(\text{La}/\text{Yb})_{\text{chondrite}} = 0.7\text{--}0.92$, $(\text{LREE})_{\text{chondrite}} = 5\text{--}14$, and flat HREE pattern, $(\text{Gd}/\text{Yb})_{\text{chondrite}} = 0.99\text{--}1.1$, $(\text{Yb})_{\text{chondrite}} =$

Fig. 7. Plots of TiO_2 vs. FeO^*/MgO , $\text{Al}_2\text{O}_3/\text{TiO}_2$ for basaltic and komatiitic rocks from the Kuanping Group. Symbols are the same as in Fig. 3. The reference fields shown in the upper and the lower plot are respectively from Sun and Nesbitt (1978) and Glassley (1974).

7.4–13.5 (Fig. 6). The low-Ti basalts from Luonan and other areas plot in the MORB field on the FeO^*/MgO vs. TiO_2 diagram, and follow the MORB trend on the $\text{Al}_2\text{O}_3/\text{TiO}_2$ vs. TiO_2 plot (Fig. 7). On the plot of $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus CaO/TiO_2 (Fig. 4), the low-Ti basalts plot in the BAB-MORB field, but close to the BAB field.

V. Petrogenesis

1. Primary magma origin and mantle source of komatiites

Published experimental results have indicated that HFSEs and REEs may be significantly fractionated during the melting of mantle rocks or the fractional crystallization of magmas at high pressures because of the presence of majorite and/or silicate-perovskite (Kato *et al.*, 1988; Ohtani *et al.*, 1989), and that melting-degree should decrease with increasing pressure (Takahashi and Scarfe, 1985; Herzberg and Ohtani, 1988; Herzberg, 1992). The trace-element pattern as well as Al-depletion characteristic of Luonan komatiites allow the following two possibilities: (1) there was fractionation of majoritic garnet in the deep mantle; or (2) the komatiitic magma may be produced by small degrees of partial melting of mantle rocks. Moreover, because garnet phase is not expected to greatly fractionate Ba, Rb, Sr, P and Ti compared to LREE, unless the degree of partial melting is small, these two processes can thus be discriminated. Thereby, the enrichment in LREEs and in other LILEs (e.g. Ba, Rb, Sr) and the depletion in HFSEs are more readily accommodated by a comprehensive model, in which these two processes may be equally important in forming such komatiitic magmas.

We show the result of melting calculations in Figure 8, by the model of batch melting and fractional melting (Allegre and Minster, 1978) of a garnet peridotite source with abundance of selected trace elements likes that of primitive mantle (PM in Table 4; Anderson, 1989) which could be taken to represent a source in a plume. From Figure 8, an interesting feature is that the difference in concentration of the refractory and HFS elements between batch melting and fractional melting is small for 5–6% degrees of partial melting, that all are very similar to the

compatible element patterns of the Luonan komatiites; but the difference in concentration of the incompatible elements (especially Ba, Sm) between the two melting models obviously presents, and an intermediate pattern of incompatible elements between batch melting and fractional melting is more likely for the Luonan

Fig. 8. Primitive mantle-normalized trace-elemental patterns of the calculated liquids produced by batch melting and fractional melting of the primitive mantle source (PM in Table 4), compared with that of the Luonan komatiites (Fig. 5). The percentages represent partial melting degree of the batch melting (the right side) and fractional melting (the left side). The equations that apply for batch melting and fractional melting are derived from Allegre and Minster (1978), and the bulk distribution coefficient D^l in two models is assumed to be constant. The distribution coefficients (K^l) of selected trace-elements in the calculations are taken from Anderson (1989) (Table 4), and the weight proportions of principal minerals for a hypothetical garnet peridotite are 55% olivine, 25% orthopyroxene, 15% clinopyroxene and 5% garnet.

komatiites. This significantly indicates that the critical melting model (Maaloe, 1985) may be more convenient for the origin of the primary magma of the Luonan komatiites. Evidently unless the source was more enriched in selected trace elements than the expected source, the degree of melting may be 5–6%, and the residue still contains garnet phase. This model is also supported by high-pressure melting experiments of natural peridotites that a low-degree melting ($<15\%$) is correspondent to the presence of garnet as a residual phase (Mysen and Kushiro, 1977).

Under these conditions, the high MgO contents of the Luonan and Barberton-type komatiitic magma clearly place the site of melting at great depth of 300–600 km (relevant depth of the mantle transition zone) where majoritic garnet is the principal liquidus phase according to experimental studies (Kato *et al.*, 1988; Herzberg and Ohtani, 1988; Ohtani *et al.*, 1989; Herzberg, 1992). On the other hand, the generation of such high-Mg komatiitic liquid also requires higher mantle temperature. This implies that komatiitic liquid was generated in unusually hot part of the mantle, such as in plume originated from an unstable thermal boundary layer deep within the mantle; most possibly at the transition zone for the Barberton-type komatiites.

Being different from features of the Barberton-type komatiites, the Munro-type komatiites show MORB-like geochemical patterns. Combined with new experimental

Table 4. Primitive mantle composition (PM) and partition coefficients of selected trace-elements used in the partial melting calculations (see text)

	Ni	Cr	V	Sc	Yb	Zr	Sr	Nd	Sm	Rb	Ba	Ce	La
PM	1961	2342	77	15	0.32	13	16.2	1.02	0.32	0.39	5.22	1.4	0.57
K_{ol}	3.8	1.8	0.09	0.25	0.004	0.03	0.016	0.0013	0.0019	0.01	0.0001	0.0008	0.0005
K_{opx}	3	2.8	0.3	1.1	0.0286	0.07	0.016	0.0019	0.0028	0.02	0.001	0.0009	0.0005
K_{cpx}	2	15	1.5	3.1	0.2	0.28	0.165	0.09	0.14	0.05	0.001	0.04	0.02
K_{gr}	0.8	22	0.27	6.5	4.03	0.3	0.014	0.087	0.217	0.02	0.0015	0.021	0.004

Note: Data source is given in Anderson (1989).

trace-element partitioning data that indicate that Sc, Zr and REE have similar degrees of compatibility at low pressures (<300 km), where olivine is the main liquidus phase (Kennedy *et al.*, 1993), the MORB-like characteristics should suggest that the Munro-type komatiites may have formed by relatively high degree partial melting at shallow depths (<300 km).

2. Crystal fractionation of komatiitic magma

As noted above, the Luonan komatiites have suffered from metamorphism. Thus a problem arises whether or not the observed compositions of olivine, pyroxene and spinel are of primary igneous ones. For example, the olivine that would be in equilibrium with the Luonan komatiite compositions (21–30% MgO) would contain more than 93% forsterite content, assuming $K_d^{\text{Mg-Fe}}=0.3$, but observed olivines are Fo 73~83 and are much less

magnesian than the predicted. Similar Mg-poor olivines have been reported in komatiites from Western Australia (Oliver *et al.*, 1972) and Lac Guyer of Canada (Stamateloupoulou-Seymour and Francis, 1980). A possibility has been discussed that the Mg-poor olivines are of metamorphic origin under reduced condition; Mg-poor olivines are the recrystallization products from serpentine and brucite assemblage in the absence of magnetite (Zhang, Y., 1981). Another possibility is the effect of pressure upon the Fe-Mg partitioning between olivine and melt phases. Apparent K_d values for the observed olivine and the komatiite may be calculated to be 0.48 to 0.66, assuming chemical equilibrium. Such values may be obtained by substituting pressure values of 90 to 180 Kbar into the pressure dependence formula of K_d , $K_d=0.3+0.002 P$ (Kbar), which was experimentally determined by Takahashi and Kushiro (1983) under dry condition and at pressures up to 35 Kbar. But such a long extrapolation

Fig. 9. CMAS projections (after O'Hara, 1968) of Luonan komatiites. (A) projection from olivine into the plane CS-MS-A. (B) projection from diopside into the plane C₃A-M-S. The whole-rock compositional trend show obvious trends of high-pressure evolution. The only plausible low-pressure crystal fractionation trends would involve fractionation of olivine alone, or possibly accompanied by cpx. However, the trends observed here are incompatible with either of these, and are better described by ol+opx addition or removal. ol = olivine, sp = spinel, gar = garnet, cpx = clinopyroxene, opx = orthopyroxene, pl = plagioclase.

outside the experimental range is not warranted and thus this hypothesis needs to be substantiated by further experimental works.

The higher pressure origin and possible fractionation trend of the Luonan komatiitic magma are investigated by means of projections within the CMAS system (Fig. 9). The compound control of olivine and orthopyroxene at pressures greater than 30 Kbar (O'Hara, 1968) is clearly indicated by this diagram. In addition, Figure 3 shows a linear trend with the slope near 1 for the Luonan komatiites, possibly suggesting that magma fractionation may have been significantly controlled by such phases with $\text{SiO}_2/\text{FM}=1$ as orthopyroxene, if the linear trend is primary.

3. Origin of basalts

Using geochemical data, we are not able to demonstrate that the low-Ti basalts from the Kuanping Group are genetically related with the Luonan komatiites and high-Ti basalts by means of a simple fractional crystallization from a parental magma, or by various degrees of partial melting of a homogeneous source. It is inferred from present data that the low-Ti basaltic magma was derived from different source and by different degree of partial melting from both komatiitic and high-Ti basaltic magma.

Spatially associated OIB-like basalts share the similar geochemical patterns with the komatiites. This implies that komatiites and OIB-like basalts should be genetically related to each other. It is possible that the OIB-like basalts are the products of either high-pressure segregation of komatiitic magma, or of another event of low-degree partial melting of a plume-related source at the depths greater than 300 km. In either cases, the komatiites and OIB-like basalts could be cogenetic in the activity of a rising mantle plume.

Our data show that the low-Ti basalts

were derived from a MORB-like, depleted mantle source. This conclusion is confirmed by their initial ϵNd value (+4.2 to +5.1) determined for the regional low-Ti basalts by Zhang Z.-Q. *et al.* (1994). Similar to the N-MORBs, the LREE-depleted pattern and chondritic Al/Ti value of the low-Ti basalts should indicate higher degree of partial melting of a shallow (asthenospheric) mantle. I agree to the interpretation (e.g., Gast, 1968) that such basalts with N-MORB geochemical characteristics could be produced by 15% to 30% degrees of melting of spinel peridotite mantle based on our modeling examination. Moreover, the major and trace element similarity of the low-Ti basalts to modern MORBs also suggests a similar magma fractionation.

VI. Tectonic implications of the komatiite-basalt association

The marginal basin model early proposed for the tectonic setting of the Kuanping Group (Zhang S.-G. *et al.*, 1991; Wang *et al.*, 1992) may be supported by new data of both low-Ti and high-Ti basalts in this study. In part similar to the modern-day Lau and Fiji Basin (e.g., Saunders and Tarney, 1991), a wide range of magmatic rock types may erupt in such basins, including MORB, OIB and arc tholeiites, reflecting the complex interplay of MORB, OIB and arc source (Saunders and Tarney, 1991). As discussed above, the MORB-like basalts were derived from a depleted (MORB-type), spinel peridotite source, whereas the OIB-like basalts and spatially associated komatiites were derived from a majoritic garnet peridotite source of the transition zone. However, no typical arc basalts have been found and reported in the Kuanping Group.

This suggests that the expected marginal basin may not be significantly affected by subduction processes or materials. In this tectonic condition, the association of high-Ti

basalts and komatiites in Luonan area should be significantly noted that a plume-type magmatism related with continental margin rifting and with oceanic spreading in the development of the Kuanping marginal basin was responsible for the high-Ti basalt and komatiite magmatism. Such rising mantle plume may not be only to generate komatiitic and basaltic magma, but also to provide great thermal and mechanical energies for lithospheric extension and melting of shallow (asthenospheric) mantle to generate MORB-like tholeiitic magma. Moreover, the MORB-like tholeiitic magma compositions should be related to high degrees of lithospheric extension according to the model of McKenzie and Bickle (1988). Ellam (1992) showed that such MORB-like magmas, produced by large degrees of partial melting of spinel peridotite, like the low-Ti tholeiites in the Kuanping Group, could be generated only if the lithosphere was relatively thin. Accordingly, from the fact of the dominant presence of MORB-like tholeiites in the Kuanping Group, the Proterozoic Kuanping marginal basin could once had more oceanic nature in the period of its development.

Another model proposed in this paper is that the Kuanping Group and Songshugou ophiolite were remnants of the lithosphere of a Proterozoic major ocean basin that had developed between the North-China and South-China platform and had emplaced onto the Qinling Complex during Jinningian-period collision. The present regional field relationships between these terranes may have been produced by complicated thrusting during and after collision. This interpretation is mainly based on following observations: (1) similarities in MORB-like composition and mantle source of basalts which can be well constrained by geochemical comparison of basalts from the Songshugou ophiolite (Zhang Z.-J. *et al.*, 1995) and the Kuanping Group described above; and

(2) similar crystallization age of basalts defined by whole-rock Sm-Nd isochrons, 986–1142 Ma. and 1030–1166 Ma. for Kuanping Group and Songshugou ophiolite respectively. In this model, the komatiite-basalt association should be simply considered as product of an oceanic mantle plume.

It is impossible, however, to clearly discriminate these two tectonic models for the formation of the Kuanping Group and the implication of the komatiite-basalt association in this study. For further achievement on this problem, more detailed geologic studies, accompanied with petrologic and geochemical analyses, of all related terranes mentioned above are necessary.

VII. Conclusions

In this study the author described geochemical characteristics of certain ultrabasic and basic metavolcanics occurring in the Luonan area within the 986–1142 Ma. Kuanping Group, Qinling orogenic belt. The komatiites have geochemical characteristics of Barberton-type (Al-depleted) komatiites, lower $\text{Al}_2\text{O}_3/\text{TiO}_2$, Sc/Zr, V/Zr and Ti/Zr, higher Ti/Sc ratios than those of chondrite, and peculiar HREE-depleted patterns. Spatially associated basalts have close geochemical affinity with OIBs, and share the similar geochemical patterns with the komatiites. In addition, the regionally dominant basalts show geochemical similarities with modern-MORBs and BABs.

A complex genetic model, that involves lower-degree (5–6%) of critical partial melting of a deep, majoritic garnet peridotite mantle source with majoritic garnet as a residual phase, followed by high-pressure fractionation of orthopyroxene and olivine, can explain the compositional features of the komatiites. The OIB-like basaltic melt may have been produced by high-pressure segregation of primary komatiitic magma or a low-degree melting

event of rising mantle plume. An unusual pressure condition to generate the komatiitic initial melt has been considered at the depth of the mantle transition zone. It has been suggested that a hot rising plume would have controlled the generation of komatiitic and basaltic magmas. The tectonic environment has been reconstructed as either a marginal basin in the southern margin of the North-China platform, or a Proterozoic major ocean which had developed between the North-China and the South-China platform at about 1.2 to 1.0 Ga.

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中国秦嶺造山帯原生界寛坪層群中の塩基性、超塩基性変成火山岩類の
地球化学特徴：成因と構造の意味

張 沢軍

中国秦嶺造山帯寛坪層群(約 1.0 Ga)から産する塩基性、超塩基性変成火山岩類の主成分と微量元素について研究を行った。本調査地域の変成火山岩類は次の 3 タイプの岩石から構成されている；(1) コマチアイト：Barberton タイプとの類似を特徴とする；(2) OIB 様玄武岩：コマチアイトと伴って産出する；(3) MORB 様玄武岩：中央海嶺と背弧海盆に産する玄武岩に類似した特徴を持つ。観察された事実と最近の高圧融解実験の結果から、本研究のコマチアイトマグマの成因は、地下約 400 km 以深での majorite マントルの低度(5-6%)臨界融解によるものと考えられる。OIB 様玄武岩質マグマの成因としては、地球化学特徴がコマチアイトと類似していることから、コマチアイト質マグマを形成したマントルから別の低度融解がおこったか、約 300 km 以深の高圧下でのコマチアイト質マグマからの分離によるかのいずれかであると考えられる。一方、MORB 様玄武岩は、枯渇した浅部のスピネルかんらん岩の 15-30% 部分融解で形成されることが考えられる。上昇する高温マントルプリュームが、コマチアイト質マグマと玄武岩質マグマの発生と分化を支配した。このプリュームは背弧海盆か、華北卓状地と華南卓状地の間に発生した主海盆のどちらかで形成された可能性がある。