Geochemistry of the Ophiolite and Island-Arc Volcanic Rocks in the Mianxian-Lueyang Suture Zone, Southern Qinling and Their Tectonic Significance *

LAI SHAOCONG (赖绍聪), ZHANG GUOWEI (张国伟)
(Department of Geology, Northwest University, Xi'an, 710069)
YANG YONGCHENG (杨永成), AND CHEN JIAYI (陈家义)
(Regional Geological Surveying Team, Bureau of Geology and Mineral Resources of Shaanxi Province, Xianyang, 712000)

Abstract: Ultrabasic rocks in the Mianxian-Lueyang ophiolitic melange zone include harzburgite and dunite which exhibit LREE depletion with remarkable positive Eu anomaly. The diabase dike swarm shows LREE enrichment but slightly negative Eu anomaly. Metamorphosed volcanic rocks can be divided into two groups in terms of their REE geochemistry and trace element ratios of Ti/V, Th/Ta, Th/Yb and Ta/Yb. One is the MORB-type basalt with LREE depletion, representing the fragments of oceanic crust and implying an association of the MORB-type ophiolite and an ancient ocean basin between the Qinling and Yangtze plates during the Middle Paleozoic-Early Mesozoic era. The other comprises the island-arc volcanic rocks including tholeiitic basalt and a large amount of calc-alkaline intermediate-acid volcanic rock, which could not be the component of the ancient oceanic crust but the result of magmatism at the continental margin. This indicates that the Mianxian-Lueyang limited ocean basin had undergone a whole process of development, evolution and vanishing from Devonian-Cretaceous to Permian. And the Qinling area had become an independent lithospheric microplate, on the southern side of which there were exhibited the tectonic characteristics of active continental margins during the Late Paleozoic-Early Mesozoic. That is to say, the Qinling cannot be simply considered as a result of collision between the Yangtze and North China plates.

Key words: geochemistry; tectonics; ophiolite; southern Qinling

Introduction

Research on the ophiolite in the Mianxian-Lueyang suture zone of the Qinling orogenic belt is one of the most important but most controversial geological subjects because it has a great bearing on the orogenic process and the fundamental structural framework of the Qinling during its major orogenic period. And it is also a subject at issue recently. The Mianxian-Lueyang suture zone as one of the components of the Qinling orogenic belt and the final major suture zone between North and South China. Studies of its composition, formation, structure and evolution possess have important geological significance for scientists to understand the characteristics and final matching process of China's continent. The data available suggest that the Mianxian-Lueyang suture zone is a complicated ophiolitic tectonic melange zone including many tectonic

ISSN 1000-9426
* This project was jointly supported by the National Natural Science Foundation of China (No. 49290100) and the Special Science Foundation of Shaanxi Province.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

slabs of different origins (Zhang Guowei et al., 1995; Yang Zongrang et al., 1990; Zhong Jianhua et al., 1997; Zhang Guowei, 1993; Xu Jifeng et al., 1996). As viewed from petrology and geochemistry, what should be solved first and foremost is which tectonic slab belongs to the ophiolite (fragment of ancient oceanic crust) or the component of ophiolitic association. And on the contrary, which one does not belong to the ophiolite or the ophiolitic association. In addition, the forming age, tectonic setting, petrological and geochemical features of those tectonic slabs should be studied. And then the development and evolutionary history of the Mianxian-Lueyang suture zone could be deduced. In this paper, petrographical and petrochemical studies were carried out to attest our model of formation and evolution of the ophiolite and island-arc volcanic rocks and their tectonic significance.

Geology and Petrography of the Ophiolite and Island-Arc Volcanic Rocks

The Mianxian-Lueyang suture zone is located at the convergence part of the South Qinling and the Yangtze plate, forming an E-W trending zone which extends along the Bashan arcuate fault zone to the Wuliba area, Xixiang County in the east and to Kangxian and Wenxian counties in the west. The suture zone includes the Mianxian-Lueyang ophiolitic tectonic melange and its eastern extension —the Bashan arcuate thrust belt. In the Mianxian-Lueyang area it is constructed by a number of major faults and many tectonic slabs which are sandwiched in the intensely sheared matrix and manifest themselves as a typical southward imbricate thrust tectonic pattern. Clearly it is a tectonic melange zone (Zhang Guowei et al., 1995). The Mianxian-Lueyang ophiolitic tectonic melange zone, named the Sanhekou Group formerly, is separated by the Lueyang fault from the Precambrian Bikou Group to the south and by the Zhuangyuanbei fault from the Silurian Baishuijiang Group to the north. It consists mainly of several intensely sheared thrust slabs including the Sinian-Cambrian and Devonian-Carboniferous strata. The Sinian-Cambrian strata consist mainly of gravel-bearing argillite, argillic and pyroclastic rocks and carbonates; the Devonian strata consist of deep-water turbidite, argillic carbonate and argillite. And the Carboniferous rocks are mainly carbonates (Yang Zongrang et al., 1990; Zhong Jianhua et al., 1997). In contrast to the adjacent strata bearing the Silurian system, the Ordovician and Silurian strata are rare in the Mianxian-Lueyang tectonic zone (Zhang Guowei et al., 1993). Ophiolite complex and volcanic rocks as tectonic slabs are also recognized in this tectonic zone (Fig. 1).

The island-arc volcanic rocks in this region are chiefly distributed in the Sanchazi, Qiaozigou and Hengxianhe areas, Lueyang County. They constitute an association of metamorphic marine volcanic rocks including basic greenschist, basic-intermediate and intermediate albite-chlorite schist as well as intermediate-acid light-coloured chlorite-albite schist. All the rocks have been strongly sheared and deformed. The blastophenocrysts of plagioclase and amphibole have been identified under the microscope, indicating that the greenschist assemblage belongs to a volcanic rock series. The island-arc volcanic rocks developed in the Sanchazi area are closely coexistent with gabbros, diabasic dike swarms and ultrabasic rocks. They are mostly bounded with each other by nappe structures, thus forming a typical tectonic melange. Most of the ultrabasic rocks have altered intensely, and serpentinization is commonly observed. The content of serpentine in the rock often accounts for more than 90 % with serpophite and antigorite being dominant with a small amount of chrysotile. Bastite which is the result of pseudomorphism of orthopyroxene and the olivine pseudomorph have been identified in some thin sections of rock samples. The protoliths of the ultrabasic rocks in this region are mainly harzburgite and dunite.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Our four diabase samples were collected from Sanchazi Village (LQ36), Tianba (LQ45) east of the village, and Xiaosonggou (LQ46, LQ48) west of the village. The four samples are located in the Sanchazi complex which consists of island-arc volcanic rock, gabbro, diabase and ultrabasic rock. Our island-arc volcanic rock samples were collected from the Sanchazi and Qiaozigou areas. Moreover, two metamorphosed volcanic rock samples (dacite) were collected from the Wuliba area of the Bashan arcuate fault zone. The typical MORB-type basalts with LREE depletion in this region are distributed in the Wenjiagou-South Zhuangke area that ranges in width from 300 m to 700 m and trends more than 5 km in NWW-SEE. It is bounded in the south by the carbonaceous, carbonaceous-mud and carbonaceous-siliceous intense shear zone and in the north by the argillite, clastic rocks and argillic carbonatite of the Devonian system. At the boundary is a nappe structural plane that dips northward. This basalt slab is simple in rock assemblage, which is mainly a series of low greenschist facies metamorphosed tholeiites. Gabbros intergrowing with the tholeiites have not been found either in the field or under the microscope. Three samples of the MORB-type basalt were collected from South Zhuangke village (LQ49, LQ50 and LQ51) and another one was collected from Wenjiagou (M40) north to Sanchazi Village. Especially, the MORB-type basalt slab developed in the Wenjiagou-South Zhuangke area adjacent to the bimodal metamorphosed volcanic rock slab is distributed in Heigouxia Valley (Li Shuguang et al., 1996). These two slabs are separated by a shear schistosity zone. They belong to two different kinds of petrotectonic assemblage (Fig. 1).

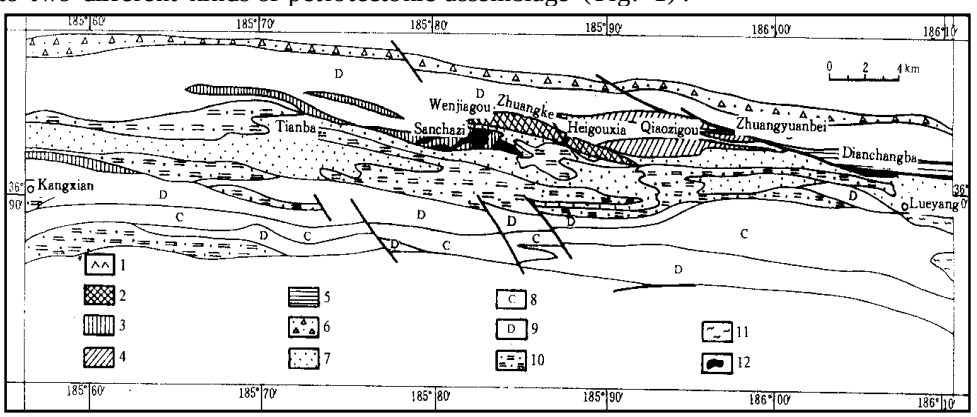

Fig. 1. Geological sketch map of the Mianlue suture zone in the Lueyang-Kangxian area (modified after 1:50000 Lueyang-Kangxian sheet). 1. Wenjiagou-South Zhuangke volcanic rock slab; 2. Heigouxia Valley volcanic rock slab; 3. Sanchazi island-arc volcanic rock complex; 4. Qiaozigou volcanic rock slab; 5. North Lueyang-Hengxianhe volcanic rock slab; 6. tectonic melange composed of cataclastic rock, breccia and mylonites; 7. carbonaceous, carbonaceous-muddy and carbonaceous-siliceous intense shear zone; 8. Carboniferous carbonate; 9. argillite, clastic rocks, minor argillic carbonate and conglomerate of the Devonian system; 10. gravel-bearing argillite, argillite, argillic and pyroclastic rocks of the Sinian-Cambrian system; 11. Archean Yudongzi complex; 12. ultrabasic rock.

Geochemistry

Major and trace element analyses of the samples (Table 1) indicate that the metamorphosed volcanic rocks and diabase in the region studied are high in H_2O and CO_2 (the content of H_2O is 1.42 % - 5.58 % with a mean value of 2.97 %; the mean value of CO_2 is 1.16 % and its

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

maximum value is 5.29 %). The H_2O content of serpentinite is so high as to be 11.60 %. It implies that these rocks experienced alteration/ metamorphism (greenschist facies). So this

Table 1. Major (mg/ g) and trace element (μg/ g) analyses for the studied area

Sample No.	LQ49	LQ50	LQ51	M40	LQ23	LQ25	M33	M46	LQ24	LQ35	LQ38
Area	Zhuangke	Zhuangke	Zhuangke	Wenjiagou	Qiaozigou	Qiaozigou	Sanchazi	Qiaozigou	Qiaozigou	Sanchazi	Sanchazi
Rock	Chlorite schist	Albite-chlorite schist	Albite-chlorite schist	Albite-chlorite schist	Albite-chlorite schist	Albite-chlorite schist	Albite-chlorite schist	Albite-chlorite schist	Light-coloured albite-chlorite schist	Light-coloured albite-chlorite schist	Light-coloured albite-chlorite schist
SiO_2	49.60	49.90	48.50	47.28	48.30	53.50	50.86	45.00	57.40	61.00	60.40
Al_2O_3	12.00	13.90	14.40	14.68	15.40	17.50	18.50	15.36	16.00	15.50	17.00
Fe_2O_3	3.50	4.81	6.15	3.89	6.89	2.08	4.59	2.15	3.65	3.46	2.30
FeO	10.10	7.19	6.90	11.25	4.10	6.68	5.10	6.36	4.10	4.10	4.74
CaO	3.63	5.55	7.53	8.84	10.30	7.40	5.28	8.64	8.27	3.30	2.95
MgO	7.00	6.91	8.36	4.69	7.81	4.38	6.02	7.72	3.51	3.16	2.63
K_2O	0.95	0.70	0.04	0.20	0.03	0.02	0.20	0.20	0.24	1.02	0.92
Na_2O	0.83	3.19	3.22	2.72	1.03	4.40	4.74	3.49	3.97	4.43	6.12
TiO_2	1.32	0.92	1.13	1.86	0.97	1.04	0.68	0.89	0.96	0.99	0.80
MnO	0.15	0.15	0.18	0.21	0.19	0.18	0.15	0.15	0.17	0.13	0.14
P_2O_5	0.15	0.14	0.15	0.12	0.17	0.23	0.21	0.13	0.25	0.27	0.25
H_2O	5.58	5.02	3.44	3.49	4.12	2.56	3.51	4.63	1.64	2.44	1.96
CO_2	3.39	1.45	0.05	1.23	0.38	0.38	0.47	5.29	0.05	0.19	0.05
Total	98.20	99.83	100.05	100.46	99.69	100.35	100.31	100.01	100.21	99.99	100.26
La	1.89	1.23	1.59	5.20	7.14	19.9	16.6	8.22	19.1	15.9	13.7
Ce	4.63	4.46	5.42	13.1	13.6	27.3	27.1	20.0	37.6	34.4	26.5
Nd	3.98	5.42	6.87	10.2	7.37	14.1	14.7	10.0	19.8	22.6	17.1
Sm	2.27	2.23	2.63	3.51	2.77	4.19	3.65	2.76	4.43	5.49	4.42
Eu	1.32	0.784	0.956	1.47	1.27	1.43	1.07	1.05	1.30	1.50	1.32
Gd	5.32	3.65	3.89	4.73	3.49	4.73	2.95	2.80	4.56	6.34	4.79
Tb	0.99	0.717	0.876	0.775	0.677	0.825	0.438	0.398	0.837	1.14	0.796
Ho	1.59	1.06	1.45	1.10	0.957	1.17	0.586	0.553	1.14	1.45	1.04
Tm	0.615	0.432	0.627	0.486	0.407	0.467	0.259	0.270	0.449	0.526	0.392
Yb	3.41	2.59	3.48	3.13	2.51	2.74	1.63	1.89	2.69	3.02	2.25
Lu	0.455	0.352	0.421	0.451	0.353	0.393	0.244	0.295	0.359	0.419	0.302
Cs	4.95	4.30	1.08	11.0	1.21	0.377	9.85	7.75	1.35	2.02	2.36
Rb	44	28	3.2	11	4.1	3.1	15	2	7.7	2	30
Ba	318	210	17	65	22	11	184	10	208	19	492
Hf	2.02	1.97	1.64	1.78	1.57	3.48	1.92	1.70	3.65	4.06	3.43
Ta	3.65	0.095	0.105	0.278	2.38	0.922	0.182	0.357	0.581	0.676	0.221
Th	0.151	0.146	0.153	0.517	0.652	2.53	2.73	1.04	2.47	2.22	2.27
U	0.235	0.249	0.259	0.251	0.322	0.643	0.789	0.0991	0.744	0.728	0.834
Nb	4.2	4.0	3.9	8.4	6.1	12	7.1	8.0	12	2.6	6.8
Sr	75	55	132	438	455	654	862	342	669	3.6	307
Zr	75	54	64	72	49	138	73	70	136	13	128
Y	29	25	28	29	21	24	17	19	23	1.3	22

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Table 1. (to be continued)

LQ43	M30	M49	M10	M13	LQ14	LQ33	M34	LQ36	LQ45	LQ46	LQ48
Sanchazi	Sanchazi	Qiaozigou	Wuliba	Wuliba	Dujiayuan	Dianchangba	Sanchazi	Sanchazi	Tianba	Xiaosonggou	Xiaosonggou
Light-coloured albite-chlorite schist	Light-coloured albite-chlorite schist	Albite-chlorite schist	Light-coloured albite-chlorite schist	Light-coloured albite-chlorite schist	Serpentinite	Serpentinite	Serpentinite	Diabase	Diabase	Diabase	Diabase
58.50	61.48	52.04	68.33	67.22	39.60	41.00	41.10	54.30	51.20	50.60	55.00
14.40	17.35	15.51	14.02	14.94	1.20	2.74	1.27	14.00	15.60	15.70	14.60
2.39	1.19	1.96	2.67	2.67	8.56	3.57	4.07	2.87	2.22	1.27	2.17
5.60	4.10	5.93	2.44	2.55	3.81	3.81	3.45	5.03	6.11	9.63	5.46
4.59	2.01	4.33	1.50	1.12	0.12	0.11	0.07	6.94	7.89	5.35	6.65
3.86	3.17	6.86	2.06	2.32	35.10	36.20	37.30	6.73	8.29	4.84	7.20
0.44	0.20	0.20	2.39	1.76	0.19	0.24	0.29	2.35	3.51	1.22	2.36
4.70	6.83	4.80	3.43	4.01	0.02	0.37	0.02	3.78	1.67	4.72	3.52
1.03	0.48	0.66	0.63	0.67	0.03	0.07	0.01	0.88	0.76	1.28	0.85
0.14	0.11	0.13	0.12	0.14	0.19	0.11	0.11	0.14	0.15	0.16	0.13
0.28	0.14	0.30	0.09	0.08	0.09	0.09	0.09	0.40	0.22	0.21	0.41
2.60	2.25	4.22	2.11	1.56	10.9	11.60	11.60	1.58	2.18	3.16	1.42
1.64	0.28	3.59	0.94	0.66	0.19	0.19	0.05	0.39	0.39	1.74	0.58
100.18	100.31	100.12	100.43	99.70	100.00	100.10	99.43	99.39	100.19	99.88	100.35
11.2	22.5	21.1	40.5	42.6	0.427	0.356	0.16	17.3	11.3	18.2	15.7
19.7	30.3	26.7	63.5	62.0	1.13	0.983	0.863	33.8	21.2	28.0	29.8
12.5	14.9	14.2	30.6	30.6	1.07	0.88	0.843	19.7	11.4	16.2	17.0
4.01	3.17	3.44	6.61	6.21	0.346	0.286	0.333	4.96	2.99	4.39	4.73
1.43	0.746	0.981	1.39	1.50	0.482	0.476	0.373	1.45	1.07	1.19	1.61
4.86	2.03	3.19	6.34	5.74	0.571	0.558	0.532	4.86	3.90	5.32	4.55
0.81	0.313	0.542	0.948	0.975	0.105	0.100	0.097	0.789	0.745	0.930	0.762
1.12	0.42	0.757	1.19	1.39	0.138	0.154	0.145	0.885	1.04	1.31	0.864
0.449	0.179	0.322	0.467	0.558	0.0432	0.075	0.052	0.303	0.432	0.506	0.335
2.61	1.10	2.01	2.79	3.23	0.223	0.500	0.258	1.72	2.37	2.94	1.98
0.383	0.191	0.289	0.444	0.447	0.03	0.079	0.032	0.257	0.328	0.416	0.242
1.00	6.04	7.30	31.2	12.7	1.93	1.38	1.07	3.12	1.70	1.24	2.08
12	6.7	7.2	89	80	2.6	2	29	46	102	48	55
166	110	68	977	834	11	10	530	1110	936	408	907
3.55	2.13	3.27	6.41	6.58	0.16	0.169	0.153	3.45	1.93	3.08	3.40
2.20	0.237	0.482	0.907	0.898	2.45	1.56	1.37	0.403	2.45	0.361	2.63
1.78	3.01	5.61	7.95	8.42	0.245	0.210	0.210	3.65	1.60	2.68	3.48
0.717	1.29	1.65	1.37	1.54	0.246	0.405	0.388	1.00	0.388	0.527	1.18
6.3	8.5	11	15	17	2.8	3.1	6.7	7.2	5.9	9.0	7.1
584	378	254	158	126	2.9	7.8	274	652	239	164	452
129	117	122	237	244	11	13	140	133	72	115	131
23	14	19	31	32	3.3	3.5	28	21	25	32	21

Note: SiO_2-CO_2 analyzed by means of wet chemistry at CAGS (1995); La-U analyzed by NNA at Chinese Academy of Sciences (1995); Nb-Y analyzed by X-ray fluorescence at Beijing Metallurgical Institute of Nonferrous Metals (1995).

paper will focus attention on those immobile elements (e.g. Nb, Ta, Zr, Hf, Th, REE? Ti and so on) to understand their geochemical behaviour.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Geochemical characters of the ultrabasic rocks

Most of the ultrabasic rocks are low in CaO (< 0.12 %) and Al_2O_3 (averaging 1.61 %, Table 1). Zavarichki's parameters: a = 0.27 - 0.96, m' = 81.8 - 87.33, f' = 9.29 - 15.05 and S = 38.10 - 39.05, show characteristic features of harzburgite and dunite. They are high in m/f (mean value is 7.90), belonging to magnesium ultrabasic rocks, and are chemically characteristic of metamorphic peridotites.

The ultrabasic rocks in this region are low in REE with $(La/Yb)_N$ = 0.4 - 1.24 (averaging 0.70), $(Ce/Yb)_N$ = 0.48 - 1.23 (averaging 0.84), and δEu = 2.72 - 3.61 (averaging 3.22), showing LREE depletion but HREE enrichment (Fig. 2a). They are similar to those of serpentinites from the Puerto Rico Sea trench (Henderson, 1984). In addition, the rare-earth elements may be influenced to some degree by alteration/metamorphism.

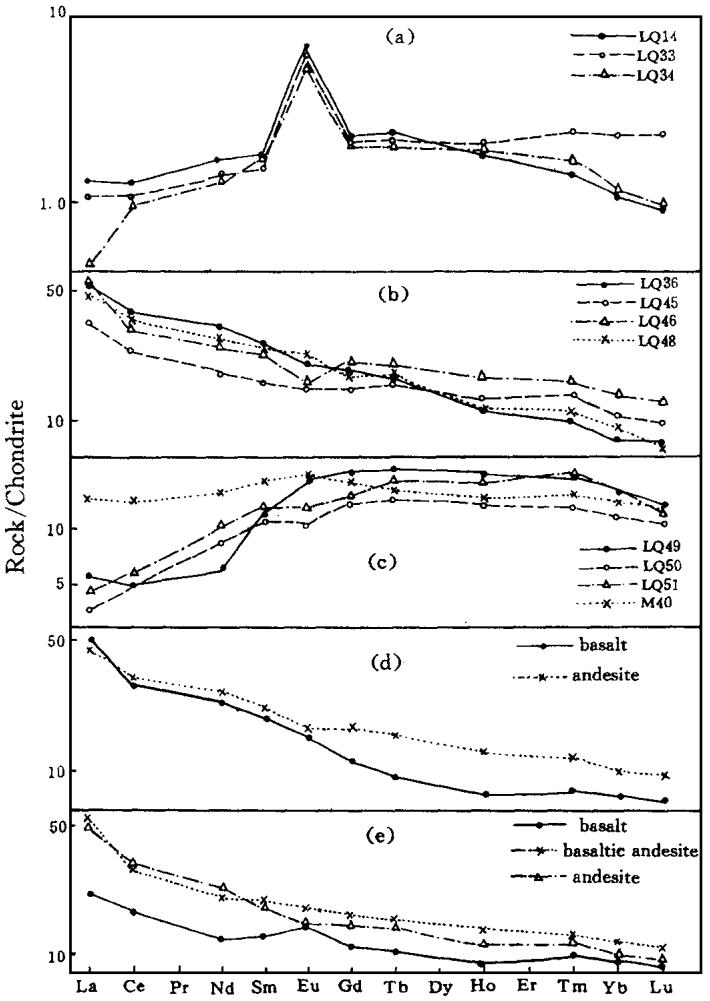

Fig. 2. Chondrite-normalized REE distribution patterns. (a) Serpentinite; (b) diabase; (c) MORB-type basalt collected from the Wenjiagou-South Zhuangke area; (d) island-arc volcanic rocks collected from the Sanchazi area; (e) volcanic rocks collected from the Qiaozigou area.

Compared with the primitive mantle (Wood et al., 1979) (Fig. 3a), the serpentinites in this region show the enrichment of Ta but the depletion of La, Ce, Nd, Hf, Ti and Y.

Geochemical characters of the volcanic rocks

(1) Geochemical characters of the MORB-type basalts developed in the Wenjiagou-South Zhuangke area Many studies have demonstrated that the elements Nb and Y belong to immobile elements. And the SiO_2-Nb/Y diagram can be used effectively to discriminate the series of volcanic rocks that had experienced alteration/metamorphism (Winchester et al., 1977). As can be seen in Fig. 4, all the four MORB-type basalt samples collected from the Wenjiagou-South Zhuangke area belong to non-alkaline tholeiitic volcanic rock series. This group of basalts is high in TiO_2 (0.92 % - 1.86 %, averaging 1.31 %), similar to the basalts collected from the modern mid-ocean ridge (Dmitrive

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

et al., 1989). And they are high in FeO + Fe_2O_3 and MgO. Especially, this group of rocks shows a typical MORB evolution trend (Condie, 1989). That is to say, their contents of Fe_2O_3 + FeO increase rapidly with decreasing MgO content.

Moreover, this group of basalts shows LREE depletion but HREE enrichment without remarkable Eu anomaly (Fig. 2c). Their $(La/Yb)_N$ = 0.30 - 1.07 (averaging 0.51), $(Ce/Yb)_N$ = 0.33 - 1.01 (averaging 0.54), and δEu = 0.84 - 1.13 (averaging 1.00). They are very similar to the typical MORB in the world.

Compared with the primitive mantle (Fig. 3c), this group of basalts shows a low-degree depletion pattern. From La to Y, the curve exhibits flattening and positive slope, indicating the geochemical features of basalts originated from depleted upper mantle. Especially, there is a "peak" of Nb on the curves, which is obviously different from the distinctive geochemical features of island-arc volcanic rocks. The rocks have Ti/V≈22, Th/Ta≈1, Th/Y = 0.04 - 0.17, Ta/Yb = 0.03 - 0.09, very similar to the typical MORB originated from depleted mantle of the asthenosphere (Pearce, 1983).

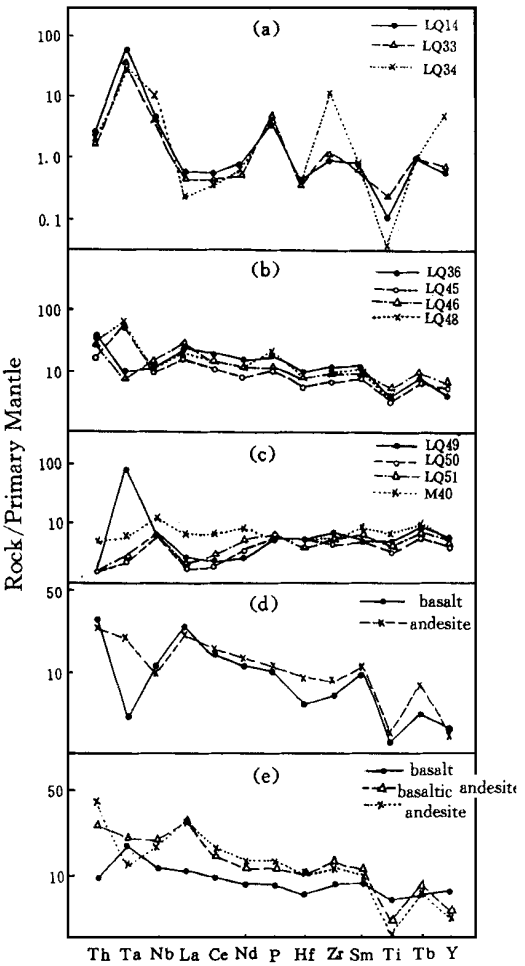

Fig. 3. Primary mantle-normalized trace element patterns. (a) Serpentinite; (b) diabase; (c) MORB-type basalt collected from the Wenjiagou-South Zhuangke area; (d) island-arc volcanic rocks collected from the Sanchazi area; (e) volcanic rocks collected from the Qiaozigou area.

(2) Geochemical characters of the island-arc volcanic rocks collected from the Sanchazi area The island-arc volcanic rocks in this region are chiefly distributed in the Sanchazi, Qiaozigou and Hengxianhe areas. Except one, the other samples belong to non-alkaline volcanic rocks series (Fig. 4). Among the five island-arc volcanic rock samples collected from the Sanchazi area, the basalt (M33) is low in TiO_2 (0.68 %) and its Fe_2O_3 and FeO contents are also lower than those of the MORB-type basalts collected from the Wenjiagou-South Zhuangke area. SiO_2 in andesites accounts for more than 57 % (averaging 60.25 %), belonging to high-silicon andesite (Gill, 1981). On the $lg\tau$-$lg\sigma$ diagram their data points fall in the B field, showing the chemical features of low-moderate potassium and high-silicon island-arc volcanic rocks.

The island-arc tholeiite collected from the Sanchazi area has $(La/Yb)_N$ = 6.59, $(Ce/Yb)_N$ = 4.02 and δEu = 0.98. It exhibits slight enrichment of LREE without remarkable Eu anomaly (Fig. 2d). The andesites have $(La/Yb)_N$ = 2.78 - 13.24 (averaging 5.84), $(Ce/Yb)_N$ = 1.82 - 6.66 (averaging 3.52), and δEu = 0.85 - 1.02 (averaging 0.93). They exhibit a moderate degree of enrichment of LREE with no remarkable Eu anomaly. Compared with the

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

primitive mantle (Fig. 3d), the trace element patterns in the island-arc volcanic rocks collected from the Sanchazi area mainly show a negative slope. From basalt to andesite, enrichment degree of the elements tends to increase but the TiO_2 content tends to decrease. Especially there appear "valleys" of the elements Ta and Nb for basalt and Nb for andesite. These rocks exhibit Th > Ta, Nb/La < 0.6, Th/Ta = 3 - 15, Th/Yb = 0.68 - 2.74 and Ta/Yb = 0.10 - 0.84, showing the geochemical characters of typical island-arc volcanic rocks (Francalanci et al., 1993).

Four diabase samples that are coexistent with the island-arc volcanic rock series in the Sanchazi area are high in SiO_2 content (50 % - 55 %) and low in the contents of Al_2O_3, CaO, ΣFe as well as variable MgO (4.04 % - 8.29 %). Their Zavarichki's parameters are: a = 9.17 - 12.96, S = 61.57 - 64.75, m' = 60.76 - 64.16, and m/f = 0.79 - 1.79, showing the chemical characters of high-Al ferruginous basic rocks. The diabases have $(La/Yb)_N$ = 3.09 - 6.51 (averaging 4.69), $(Ce/Yb)_N$ = 2.16 - 4.75 (averaging 3.21), and δEu = 0.76 - 1.06 (averaging 0.92). As viewed from their chondrite-normalized REE distribution patterns, the diabases exhibit LREE enrichment but HREE depletion (Fig. 2b) with no remarkable Eu anomaly. But one sample (LQ46) shows weak Eu depletion. For the diabases, their primary mantle-normalized trace element patterns show a slightly negative slope and there are no obvious "peak" or "valley" on the curves (Fig. 3b). The enrichment degree of the elements decreases with decreasing incompatibility.

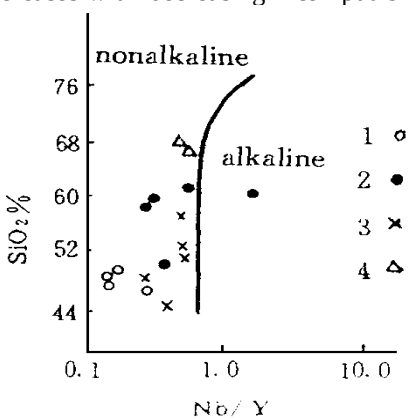

Fig. 4. SiO_2-Nb/Y diagram (after Winchester et al., 1977). 1. MORB-type basalts collected from the Wenjiagou-South Zhuangke area; 2. island-arc volcanic rocks collected from the Sanchazi area; 3. volcanic rocks collected from the Qiaozigou area; 4. volcanic rocks collected from the Wuliba area.

(3) Geochemical characters of the volcanic rocks collected from the Qiaozigou area All the five samples collected from the Qiaozigou area belong to non-alkaline volcanic rock series (Fig. 4). Among them, the TiO_2 contents of basalt and basaltic andesite range from 0.89 % to 1.04 % (averaging 0.89 %), slightly higher than those of island-arc tholeiites collected from the Sanchazi area, but obviously lower than those of the MORB-type basalts collected from the Wenjiagou-South Zhuangke area. And the andesite is high in SiO_2 (57.40 %), belonging to high-silicon andesites (Gill, 1981). The REE features of the volcanic rocks in the Qiaozigou area can be summarized below (Fig. 2e): the basalts have $(La/Yb)_N$ = 1.84 - 2.81 (averaging 2.35), $(Ce/Yb)_N$ = 1.31 - 2.56 (averaging 1.94), and δEu = 1.26 - 1.15 (averaging 1.21). They exhibit slight enrichment of LREE with weak Eu anomaly; the basaltic andesite possesses $(La/Yb)_N$ = 4.70, $(Ce/Yb)_N$ = 2.41, and δEu = 0.99. It exhibits a low degree of enrichment of LREE with no remarkable Eu anomaly; the andesite has $(La/Yb)_N$ = 4.59, $(Ce/Yb)_N$ = 3.38, and δEu = 0.88. It exhibits a low-moderate degree of enrichment of LREE with weak Eu depletion. Compared with the primitive mantle, the curves of the andesite and basaltic andesite have a negative slope (Fig. 3e), being similar to those of the island-arc andesites collected from the Sanchazi area. And their "valleys" of Ti, Nb and Ta are also obvious. These rocks are characterized by Nb/La < 0.63, Th/Ta = 2.74 - 4.25, Th/Yb = 0.92, and Ta/Yb = 0.22 - 0.34, still showing the geochemical characters of typical island-arc volcanic rocks (Francalanci et al., 1993).

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

More importantly, two basalt samples (LQ23 and M46) collected from the Qiaozigou area show obvious "peaks" of Ta but no "valleys" of Nb and Ti (Fig. 3e). These characteristics are obviously different from those of the typical island-arc volcanic rocks. It implies that the petrogenesis of the volcanic rocks distributed in the Qiaozigou area is very complicated. They generally possess the features of the island-arc volcanic rock association (for instance, the andesite and basaltic andesite). But there may exist another volcanic rock assemblage that was formed by other petrogenetic mechanism. This problem needs to be studied continuously in the future.

(4) Trace element evidence for tectonic setting discrimination On the Nb×2-Zr/4-Y and Ti/100-Zr-Y×3 diagrams the MORB-type tholeiites collected from the Wenjiagou-South Zhuangke area and the island-arc volcanic rocks in the region studied can be discriminated (Fig. 5). It is indicated again that there exist the MORB- and island-arc-type tholeiite assemblages in this region.

Formation Age and Geotectonic Significance of the Ophiolite and Island-Arc Volcanic Rocks

The Mianxian-Lueyang suture zone is a complicated tectonic melange zone which includes many tectonic slabs of different origins. The data available and the research results of this paper as well as geological mapping (1∶50000) indicate that this melange zone includes ophiolite slab (fragments of the ancient oceanic crust), island-arc volcanic rock slab, volcanic rock slab of the transitional stage from rift to ocean basin and slabs of different time-stratigraphic units (Zhang Guowei et al., 1995; Feng et al., 1996; Li Shuguang et al., 1996). So in this paper, the volcanic rock slabs which are distributed in different areas and are different in petrogenesis have been discriminated. Then their geochemical characteristics and petrogeneses will be discussed.

As a tectonic slab, the tholeiitic volcanic rocks distributed in the Wenjiagou-South Zhuangke area emerge to the north of the Sanchazi island-arc volcanic rock slab. Our extensive field investigations indicate that this group of tholeiites is not interlayered with island-arc volcanic rocks, and their rare-earth element characteristics and immobile trace element features indicate that they belong to the typical oceanic tholeiites (MORB-type basalts). Therefore, this tholeiitic volcanic rock slab represents the vanished ancient oceanic crust in this region, which is the result of magmatism induced by ancient oceanic ridge spreading, belonging to the genuine component of the oceanic crustal ophiolite. However, the volcanic rock slab distributed in the Sanchazi area consists mainly of the arc-type volcanic rocks that include a large amount of intermediate-acid rocks. Their geochemical features and rock assemblages indicate that they are neither the component of oceanic crust nor the component of primary oceanic island-arc. But they are similar to those of active continental margin-arc. It is clear that this group of the arc-type volcanic rocks has no direct relation to oceanic ridge spreading. They should be the result of magmatism induced by ancient oceanic crust subduction. In addition, the intermediate-acid volcanic rocks distributed in the Qiaozigou area are similar to the arc-type volcanic rocks distributed in the Sanchazi area. The rare-earth element features, and Nb/Zr/Y, Ti/Zr/Y, Cr-Y and Ti-Y association characteristics of the two tholeiitic basalts collected from the Qiaozigou area exhibit the geochemical characters of island-arc volcanic rocks. And they are interlayered with intermediate-acid volcanic rocks of the arc-type. However, their contents of Nb and Ta exhibit no remarkable depletion, different from the typical geochemical characters of island-arc volcanic rocks. Therefore, this group of basalts may be assigned to another petrogenetic association.

The development of deep-water turbidites of the Devonian system in the Mianxian-Lueyang suture zone suggests that the ocean basin was open during the Devonian (Zhang

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

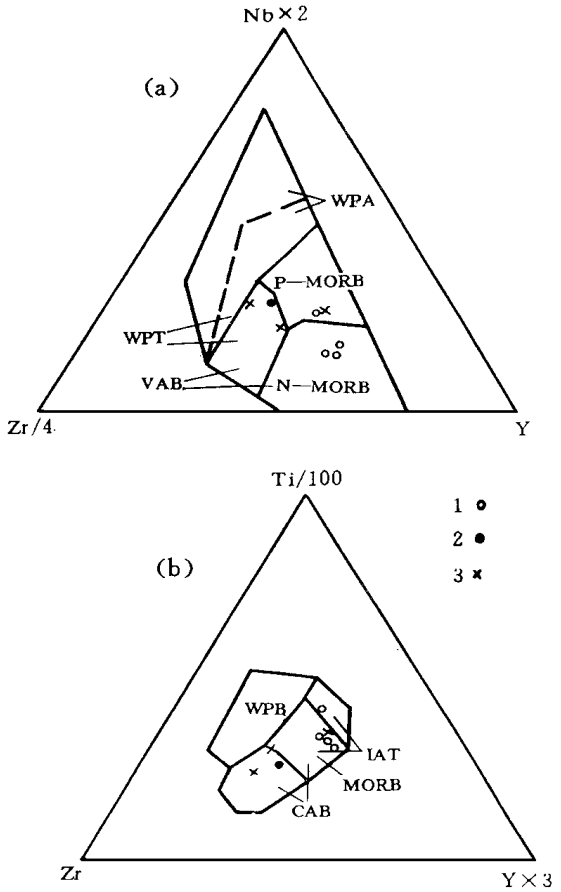

Fig. 5. Nb ×2-Zr/4-Y (a) and Ti/100-Zr-Y ×3 (b) diagrams (after Meschede, 1986; Pearce and Cann, 1973). 1. MORB-type basalt collected from the Wenjiagou-South Zhuangke area; 2. island-arc basalt collected from the Sanchazi area; 3. basalt collected from the Qiaozigou area; WPA. alkali basalt within the plate; WPT. tholeiite within the plate; WPB. basalt within the plate; P-MORB. P-type mid-ocean ridge basalt; N-MORB. N-type mid-ocean ridge basalt; MORB. mid-ocean ridge basalt; VAB. arc-type basalt; CAB. calc-alkaline basalt; IAT. island-arc tholeiite.

Guowei et al., 1995). Well-preserved Early Carboniferous radiolariae firstly discovered from siliceous rock interlayers of ophiolitic melange near Sanchazi and Shijiazhuang villages, Lueyang County, indicate the Mianxian-Lueyang oceanic basin had lasted till Late Paleozoic (Feng et al., 1996). In a word, during the Middle Paleozoic from Devonian to Carboniferous eastern paleo-Tethys had begun to open since the Devonian and apparently influenced the development of the Qinling. The Mianxian-Lueyang limited ocean basin was initiated as the northern branch of eastern paleo-Tethys. The metamorphosed volcanic rocks developed at Heigouxia Valley in the Mianxian-Lueyang suture zone have an Sm-Nd whole-rock isochron age of (242 ±21) Ma and a Rb-Sr whole-rock isochron age of (221 ±13) Ma, suggesting that the Mianxian-Lueyang paleo-oceanic basin closed in the Middle Triassic. Heigouxia Valley is adjacent to Zhuangke Village on its eastern side and Qiaozigou on its western side. Metamorphosed volcanic rocks developed at Heigouxia Valley belong to a bimodal volcanic series produced at the time when the continental rift was transformed into an ocean basin. And the volcanic rocks discussed in this paper should be assigned to the products of the mature stage of the Mianxian-Lueyang ocean basin (for instance, the oceanic crustal ophiolite developed in the Zhuangke area) as well as the products of middle-late stages of the ocean basin (for instance, the arc-type volcanic rocks developed in the Sanchazi area). It is implied that the Mianxian-Lueyang ocean basin had become a limited ocean basin during the Middle Paleozoic-Early Mesozoic.

Identification of the continental margin-arc volcanic rock assemblages distributed in the Sanchazi and Qiaozigou areas indicates that the Qinling had become an isolated lithospheric microplate whose southern marginal part should be of tectonic setting of an active continental margin during the Middle Paleozoic-Early Mesozoic. At that time, the oceanic crust of the Mianxian-Lueyang ocean basin subducted from south to north (Zhang Guowei et al., 1995; Yang Zongrang et al., 1990; Meng Qingren et al., 1996) and then resulted in a series of continental margin-arc volcanic rocks that were in relation to the oceanic crust subduction. Since the development of the Mianxian-Lueyang ocean basin, the Qinling microplate was separated from the

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Yangtze plate at the Devonian. It had its own evolutionary history since then. Clearly, the Qinling microplate is not at all a simple product of collision between the Yangtze and North China plates (Xu Jifeng et al., 1996).

Discrimination of the oceanic crustal ophiolite and continental margin-arc volcanic rock petrotectonic assemblages indicates that the Mianxian-Lueyang ocean basin experienced a whole process of development, evolution and then vanishing from D-C to P_2. This fact is of important tectonic significance in determining the collision time between the North China-Qinling and Yangtze plates and in deducing the evolutionary process of the Qinling orogenic belt.

Conclusions

The ultrabasic rocks in the Mianxian-Lueyang ophiolitic melange zone include harzburgite and dunite which exhibit LREE depletion with remarkably positive Eu anomaly. The diabase dike swarm shows LREE enrichment but slightly negative Eu anomaly. The metamorphosed volcanic rocks can be divided into two petrogenetic assemblages. The slabs of metamorphosed tholeiitic basalt developed in the Wenjiagou-South Zhuangke area exhibit typical features of oceanic tholeiites which are the fragments of vanished paleo-oceanic crust, representing the genuine component of the oceanic crustal ophiolite in the region studied. However, the metamorphosed volcanic rock slabs developed in the Sanchazi and Qiaozigou areas (including a large amount of intermediate-acid arc-type volcanic rocks) exhibit typical geochemical characters of arc-type magmatism. They are not the component of the paleo-oceanic crust but the products of magmatism in the active continental margin-arc due to the subduction of the paleo-oceanic crust.

References

Condie, K. C., 1989, Plate tectonics and crustal evolution (3rd ed.): New York, Pergamon Press, p. 310 - 350.

Dmitriev, L. V., A. V. Sobolev, and M. G. Reisner, 1989, Quenched glasses of TOR: petrochemical classification and distribution in Atlantic and Pacific oceans: Abstracts of 28th International Geological Congress: v. 1, p. 399.

Feng Qinglai, Du Yuansheng, Yin Hongfu et al., 1996, Carboniferous radiolaria fauna firstly discovered in Mian-Lue ophiolitic melange belt of South Qinling Mountains: Science in China (Series D), v. 39 (supp.), p. 87 - 92.

Francalanci, L., S. R. Taylor, M. T. McCulloch et al., 1993, Geochemical and isotopic variations in the calc-alkaline rocks of Aeolian arc, southern Tyrrhenian Sea, Italy: constraints on magma genesis: Contrib. Mineral. Petrol., v. 113, p. 300 - 313.

Gill, J. B., 1981, Orogenic andesites and plate tectonics: Heidelberg, Springer-Verlag, p. 358 - 368.

Henderson, P., 1984, Rare-Earth element geochemistry: Amsterdam, Elserier Science Publishers B. V., p. 103 - 106.

Li Shuguang, Sun Weidong, Zhang Guowei et al., 1996, Chronology and geochemistry of metavolcanic rocks from Heigouxia Valley in the Mian-Lue tectonic zone, South Qinling —evidence for a Paleozoic oceanic basin and its close time: Science in China (Series D), v. 39, p. 301 - 310.

Meng Qingren, Zhang Guowei, Yu Zaiping et al., 1996, Late Paleozoic sedimentation and tectonics of rift and limited ocean basin at southern margin of the Qinling: Science in China (Series D), v. 39 (supp.), p. 24 - 32.

Meschede, M., 1986, A method of discriminating between different types of mid-ocean basalts and continental tholeiites with the Nb-Zr-Y diagram: Chem. Geol., v. 56, p. 207 - 218.

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.

Pearce, J. A. and J. R. Cann, 1973, Tectonic settings of basic volcanic rocks determined using trace element analysis: Earth Planet Sci. Lett., v. 19, p. 290 - 300.

Pearce, J. A., 1983, The role of sub-continental lithosphere in magma genesis at destructive plate margins, in Hawkesworth et al., eds., Continental basalts and mantle xenoliths: Nantwich, Shiva Press, p. 230 - 249.

Winchester, J. A. and P. A. Floyd, 1977, Geochemical discrimination of different magmas series and their differentiation products using immobile elements: Chem. Geol., v. 20, p. 325 - 243.

Wood, D. A., 1979, A variably veined suboceanic upper mantle genetic significance for mid-ocean ridge basalts from geochemical evidence: Geology, v. 7, p. 499 - 503.

Xu Jifeng and Han Yinwen, , 1996, High radiogenic Pb-isotope composition of ancient MORB-type rocks from Qinling area —evidence for the presence of Tethyan-type oceanic mantle: Science in China (Series D), v. 39 (supp.), p. 33 - 42.

Xu Jifeng, Sheng Jifu, Han Yinwen et al., 1996, Priliminary study on ophiolites in the Mian-Lue area, in Zhang Qi, ed., Study on ophiolites and geodynamics: Beijing, Geological Publishing House, p. 163 - 166 (in Chinese).

Yang Zongrang and Hu Yongxiang, 1990, Indication of the paleoplate suture in Mian-Lue, Shaanxi Province and the relation to southern Qinling plate: Geology of Northwest China, n. 2, p. 13 - 20 (in Chinese).

Zhang Guowei, Meng Qingren, and Lai Shaocong, 1995, Structure and tectonics of the Qinling orogenic belt: Science in China (Series B), v. 25, p. 994 - 1003.

Zhang Guowei, 1993, Review of the main tectonic setting of the Qinling orogenic belt, in IGCP China Team of 321 Project, eds., Accretion of the Asiatic plate: Beijing, Seismic Publishing House, p. 95 - 98 (in Chinese).

Zhong Jianhua and Zhang Guowei, 1997, Study on tectonic sedimentation dynamics of the sedimentary basins in Qinling, Shaanxi Province: Journal of Petroleum University, v. 21, p. 1 - 5 (in Chinese).

© 1995-2005 Tsinghua Tongfang Optical Disc Co., Ltd. All rights reserved.