Identification of the island-arc magmatic zone in the Lianghe-Raofeng-Wuliba area, south Qinling and its tectonic significance

LAI Shaocong (赖绍聪)[1], ZHANG Guowei (张国伟)[1] & YANG Ruiying (杨瑞瑛)[2]

1. Department of Geology, Northwest University, Xi'an 710069, China;
2. Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100080, China

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Abstract Detailed studies indicate that a typical island-arc magmatic zone exists in the Lianghe-Raofeng-Wuliba area of south Qinling. This is characterized by continental marginal andesite and bimodal volcanic rock association which was formed in a rift environment within an oceanic island-arc. The island-arc magmatic zone is the product of Devonian-Carboniferous oceanic crust subduction and rifting of Mianlue ancient oceanic basin. The presence of the island-arc magmatic zone suggests that the Mianxian-Lueyang suture zone had extended to the Bashan arcuate area. The Sunjiahe volcanic rock association of the Xixiang Group formed in a volcanic-arc setting which should have a close relationship with Mianlue suture zone.

Keywords: island-arc volcanic rock association, geochemistry, tectonic setting, south Qinling.

Tectonic evolution of the Mianlue suture zone is one of the most important but most controversial geological subjects in the studies of the Qinling orogenic belt because it has a great bearing on the overall evolution and the fundamental structural framework of the Qinling belt during the Phanerzoic time. Data available suggest that the Mianxian-Lueyang suture zone is a complicated ophiolitic tectonic mélange including many tectonic slabs of different origins[1—5]. Up to now, there is no firm evidence from volcanic rock assemblage and geochemistry that supports the extension of the Mianlue suture zone through the Bashan arcuate area to the South Dabie Mountains[6]. Previous studies have involved the Mianxian and Anzishan areas only. However, it is still unclear whether the Mianlue suture zone had extended eastwards to the Bashan arcuate area and then to the South Dabie Mountains. This paper presents petrological and geochemical evidence for the extension of the Mianxian-Lueyang suture zone to the Bashan arcuate area.

1 Regional geology and petrography

On the basis of the synthetic regional geology studies, a tectonic mélange zone was recognized in the Lianghe-Raofeng-Wuliba region of the Bashan arcuate area, which constitutes the eastern extension of the Mianxian-Lueyang ophiolitic tectonic mélange[1, 7]. This tectonic mélange zone goes from Lianghe, through Raofeng and Shiquan, then to the Gaochuan and Wuliba, with a length of about 60 km and a width of 5—10 km. It marks the boundary between the Qinling orogenic belt and the Yangtze microplate. The Yangtze-type sedimentary formation is confined south

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of the Lianghe-Raofeng-Wuliba tectonic mélange zone. Its Cambrian-Triassic strata belong to the stable platform type sediments and the Yangtze microplate lacking Devonian- Carboniferous deposition. In contrast, the Qinling-type sedimentary formation is distributed to the north of the Lianghe-Raofeng-Wuliba tectonic mélange zone. The complicated tectonic system of the Qinling orogenic belt makes some subjects still in controversy. Sinian to Triassssic sedimentation is basically continuous with only local hiatus and unconformabilities. The sedimentary formation-type and rock assemblage of the Qinling belt are distinctly different from the northern part of the Yangtze microplate. In the Lianghe-Raofeng-Wuliba tectonic mélange zone, the Devonian-Carboniferous rocks are obviously different from both sides of the southwestern part of Qinling and northeastern part of Yangtze, which were composed of alluvial fan sedimentary system of continental margin and then transit to turbidite, calcareous detritus turbidite and silicalite. The volcanic slabs distributed in Lianghe, Raofeng and Wuliba are involved in the tectonic mélange zone as tectonic blocks (fig.1).

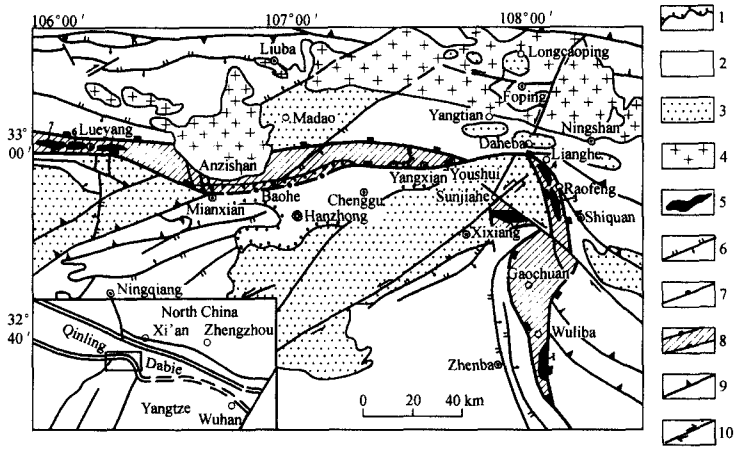

Fig. 1. Structure and geological sketch map of the Bashan arcuate area, South Qinling. 1, Cenozoic-Mesozoic sedimentary basin; 2, Phanerozoic eon; 3, Precambrian basement; 4, granite; 5, island-arc volcanic rock; 6, fault; 7, boundary of suture zone; 8, Mianlue suture zone; 9, thrust fault; 10, strike slip fault. The volcanic rock slab: 1, Wuliba island-arc rock slab; 2, Sunjiahe island-arc rock slab; 3, Raofeng island-arc rock slab; 4, Lianghe island-arc rock slab; 5, Dianchangba island-arc rock slab; 6, Qiaozigou island-arc rock slab; 7, Sanchazi island-arc rock slab.

To the west of the Lianghe-Raofeng-Wuliba tectonic mélange zone occurs the Sunjiahe volcanic rock association of the Xixiang Group. The Xixiang Group composed of metamorphic rocks and magmatic rocks was called the Hannan complex and is considered as the Precambrian basement of the Yangtze microplate traditionally[8—14]. Wang et al.[15] identified radiolarian fossils in the mudstone and silicalite of the Sunjiahe association that belong to upper Devonian-lower Carboniferous. This discovery has raised doubts and questions about the geology nd tectonic setting of South Qinling. Therefore, it is important to reconfirm geochemical characteristics and tectonic settings of the Sunjiahe volcanic rock association. Based on the intensive field investigations and

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geochemical analyses, this paper will discuss and reconsider the rock type and tectonic setting of the Sunjiahe volcanic rock association.

Most volcanic rocks in the studied region have been alternated slightly or affected by low-grade greenschist facies metamorphism. The Lianghe volcanic rock slab is distributed along the Wenshui River of Bashan arcuate area. It is about 3—5 km long and 100—300 m wide and consists of a series of bimodal volcanic rocks that have been deformed and exhibit cataclastic and mylonitic textures. The Raofeng volcanic rock slab is distributed to the west of Raofeng town and consists of metamorphic andesite.The Wuliba volcanic rock slab is distributed to the southeast of Wuliba village. It is about 6—8 km long and 50—600 m wide and tectonically emplaced between the Devonian,Carboniferous and Permian strata. The volcanic rocks are similar to the Lianghe slab, belonging to meta-basalt and dacitic-rhyolite. In addition, the Sunjiahe volcanic rock association mainly belongs to basaltic-andesitic lava, intermediate-acid and intermediate-basic pyroclastic rocks. Our samples were collected from Lianghe, Raofeng, Wuliba and Sunjiahe. Geochemistry of the volcanic rocks indicates that Lianghe and Wuliba were formed in a rift setting of oceanic island-arc, but Raofeng and Sunjiahe in a continental margin-arc.

2 Geochemistry

2.1 Discrimination of the volcanic rock association

The chemical composition, trace element and rare earth element analyses for the volcanic rocks are listed in table 1. It has been demonstrated that Nb and Y are immobile during metamorphism. The SiO_2-Nb/Y diagram can be effectively used to discriminate the series of volcanic rock that had withstood alteration/metamorphism[16]. According to fig.2(a), all of the samples studied belong to non-alkaline series. Moreover, the SiO_2-Zr/TiO_2 diagram (fig. 2(b)) indicates that these rocks mainly belong to subalkaline basalt, andesite and dacitic rhyolite.

2.2 Rare earth element geochemistry

Basalts from Lianghe are low in ΣREE (90—150 μg/g) (table 1). Their $(La/Yb)_N$ (2.62—4.60), $(Ce/Yb)_N$ (2.30—4.09), δEu (about 1.00) show features of slight enrichment in LREE without Eu anomaly. The dacitic-rhyolite in this area is high in ΣREE (108.77—303.60 μg/g, the average is 186.14 μg/g). Their $(La/Yb)_N$ (the average is 6.75) and $(Ce/Yb)_N$ (the average is 5.30) show a moderate enrichment in LREE. However, their δEu is variable. Sample QL10 exhibits significant Eu depletion (δEu=0.50). Sample QL13 has no remarkable Eu anomaly. And sample QL15 exhibits obvious Eu enrichment (δEu=1.56) (fig. 3(a), (b)).

REE features of the Wuliba bimodal volcanic rock association are very similar to those from Lianghe. They exhibit ΣREE=140—155 μg/g (the average is 151.02 μg/g), $(La/Yb)_N$ = 3.74—4.15, $(Ce/Yb)_N$=3.45—3.92 and the average δEu is 1.01. The dacitic-rhyolite has average ΣREE,

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Table 1 Average result of the major (%) and trace element (μg/g) analyses of the volcanic rocks

Area	Lianghe	Lianghe	Lianghe	Wuliba	Wuliba	Raofeng	Sunjiahe	Sunjiahe
Rock	basalt	dacite	rhyolite	basalt	dacitic-rhyolite	andesite	andesite	basalt
Sample No.	9	1	2	3	6	9	4	6
SiO_2	51.89	68.25	79.06	47.64	66.33	58.56	56.14	51.20
TiO_2	1.19	0.68	0.37	1.93	0.75	1.72	0.99	1.27
Al_2O_3	15.17	13.54	8.62	13.45	13.67	13.98	16.74	17.28
Fe_2O_3	5.17	2.86	1.66	6.59	2.80	4.43	3.73	4.26
FeO	5.88	1.87	0.84	8.14	3.07	6.60	4.31	5.39
MnO	0.26	0.19	0.07	0.31	0.15	0.19	0.16	0.20
MgO	5.77	1.53	0.46	6.24	2.37	2.91	2.94	5.01
CaO	7.35	2.93	1.86	9.05	1.88	2.01	5.03	6.16
Na_2O	3.17	4.71	3.99	2.75	3.07	3.99	4.94	3.56
K_2O	0.64	1.38	1.65	0.78	2.92	1.65	1.42	1.49
P_2O_5	0.18	0.19	0.15	0.15	0.19	0.18	0.18	0.18
H_2O^+	2.90	1.22	0.88	2.62	2.25	0.74	2.50	3.42
H_2O^-	0.31	0.21	0.15	0.52	0.41	3.11	0.51	0.56
Total	99.88	99.56	99.72	100.17	99.85	100.05	99.56	99.97
Sc	33.02	15.00	4.25	39.20	12.52	21.33	19.05	25.52
V	283.11	72.70	50.95	385.20	93.75	203.29	176.63	226.65
Cr	144.90	47.90	27.10	126.50	76.48	111.83	55.48	82.97
Co	40.47	8.30	3.05	48.00	17.35	31.84	23.98	34.70
Ni	53.61	15.40	7.55	59.13	35.20	53.30	20.65	42.58
Cu	49.32	11.10	10.10	115.50	31.00	51.47	58.30	70.62
Zn	133.23	125.80	25.00	162.17	96.07	147.51	97.25	139.63
Ga	19.42	18.10	13.45	20.29	19.27	23.16	20.53	20.33
Rb	17.52	29.40	21.90	14.97	85.87	43.01	26.65	44.10
Sr	439.77	254.00	99.10	387.43	169.28	215.41	551.53	462.83
Y	28.96	90.80	18.40	28.10	29.17	43.82	23.15	25.95
Zr	134.38	279.00	44.20	161.67	202.67	301.78	145.00	138.83
Nb	3.59	12.80	5.25	10.37	12.60	27.62	5.03	5.23
Sn	1.38	2.83	1.64	1.98	2.35	3.16	1.31	1.36
Cs	0.39	0.80	0.72	1.69	3.08	1.86	0.70	2.03
Ba	848.79	436.90	742.40	549.33	848.07	748.87	529.75	502.10
Hf	3.93	8.71	1.67	5.31	6.56	9.40	4.51	4.22
Ta	0.21	0.53	0.33	0.71	0.86	1.87	0.33	0.35
W	0.71	0.74	0.64	1.34	0.88	1.52	0.55	0.65
Pb	5.07	4.30	2.25	94.50	17.62	6.16	17.20	23.82
Th	0.96	1.39	7.82	1.80	7.04	6.08	3.26	3.10
U	0.23	0.45	0.94	0.42	1.18	1.15	0.74	0.80
La	13.23	26.60	23.05	16.70	31.00	37.84	19.60	22.95
Ce	30.09	65.60	46.25	40.13	65.62	79.36	42.03	48.05
Pr	4.18	9.83	5.48	5.55	7.40	10.08	5.73	6.36
Nd	17.48	43.90	17.55	21.30	26.90	37.50	22.18	25.48
Sm	4.34	11.63	3.46	5.65	5.42	8.35	4.92	5.51
Eu	1.53	2.01	1.35	2.00	1.23	2.21	1.56	1.77
Gd	4.71	12.69	3.38	6.54	5.08	8.48	4.65	5.28
Tb	0.76	2.13	0.49	1.06	0.80	1.30	0.67	0.74
Dy	4.86	14.65	2.95	6.36	4.82	7.92	3.99	4.45
Ho	0.96	2.94	0.62	1.27	0.95	1.49	0.77	0.86
Er	3.13	9.99	1.98	3.83	3.13	4.58	2.43	2.68
Tm	0.44	1.38	0.29	0.54	0.45	0.61	0.34	0.38
Yb	2.80	8.33	1.91	3.08	2.84	3.56	2.18	2.28
Lu	0.41	1.12	0.28	0.44	0.41	0.44	0.30	0.33

SiO_2—H_2O^- were analyzed by means of wet chemistry and Sc-Lu by ICP-MS at the Institute of Geochemistry, the Chinese Academy of Sciences (1999). The initial analysis data can be ordered from the first author.

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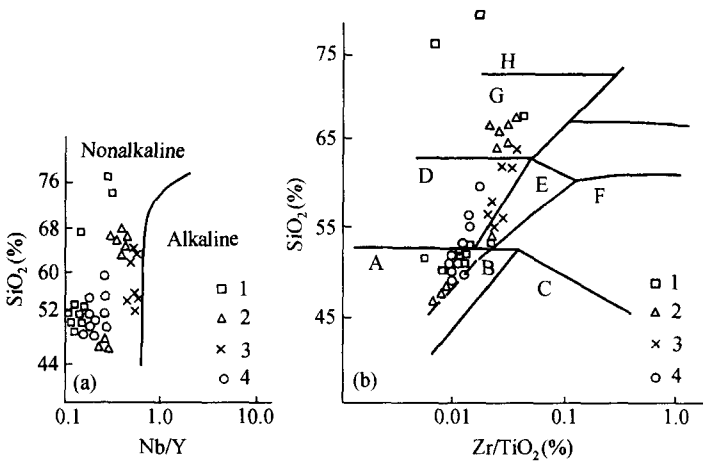

Fig. 2. Discrimination diagrams for volcanic rock series and rock type classification (after Winchester and Floyd[16]). (a) The SiO_2-Nb/Y diagram for rock series classification; (b) the SiO_2 -Zr/TiO_2 diagram for rock type classification. A, Subalkaline basalt; B, alkaline basalt; C, trachybasalt, basanite and nephelinite; D, andesite; E, trachyandesite; F, phonolite; G, dacitic-rhyolite, and dacite; H, rhyolite; 1, Lianghe volcanic rocks; 2, Wuliba volcanic rocks; 3, Raofeng volcanic rocks; 4, Sunjiahe volcanic rocks.

$(La/Yb)_N$, $(Ce/Yb)_N$, which are 185.20 μg/g, 7.92 and 6.49, respectively. Compared to the dacitic-rhyolites from Lianghe, those from Wuliba are lower in δEu (0.65—0.81, the average is 0.71) (fig. 3(d)).

The andesites from Raofeng are higher in ΣREE (190—300 μg/g, the average is 247.54 μg/g). Their $(La/Yb)_N$ (6.65—8.57, the average is 7.67), $(Ce/Yb)_N$ (5.67—6.88, the average is 6.22), and δEu (0.76—0.83, the average is 0.79) indicate that they are relatively enriched in LREE and slightly depleted in Eu (fig. 3(g)).

The Sunjiahe basalts have ΣREE=108.19—172.58 μg/g (the average is 153.07 μg/g), $(La/Yb)_N$ = 6.72—7.85 (the average is 7.21), $(Ce/Yb)_N$ = 5.43—6.16 (the average is 5.85) and δEu ≈1.0. The andesites show ΣREE=125.49—142.32 μg/g (the average is 134.48 μg/g), $(La/Yb)_N$ = 5.63—7.36, $(Ce/Yb)_N$ = 5.02—5.79 and δEu = 0.98 (fig. 3(e), (f)).

2.3 Trace element geochemistry and tectonic setting of volcanic rocks

According to the N-type MORB normalized trace element distributions (fig. 4), geochemical characteristics of the volcanic rock can be summarized.

The patterns for the bimodal volcanic rocks from Lianghe and Raofeng are very similar. The basalts (fig. 4(a), (c)) exhibit high Ba but Nb, Ta are relatively depleted, nearly the same as those within ocean island-arc basalt collected from South Sandwich[17]. Dacitic-rhyolite from Lianghe and Raofeng show strong enrichment in K, Rb, Ba and slight enrichment in Ce and Sm that characterize island-arc volcanics.

The basalts from Lianghe exhibit Th>Ta, Th/Ta=2.15—8.29 (the average is 4.78). In addition, they show Nb<La, Nb/La<0.31, Th/Yb=0.15—0.67 (the average is 0.35), and Ta/Yb=0.05

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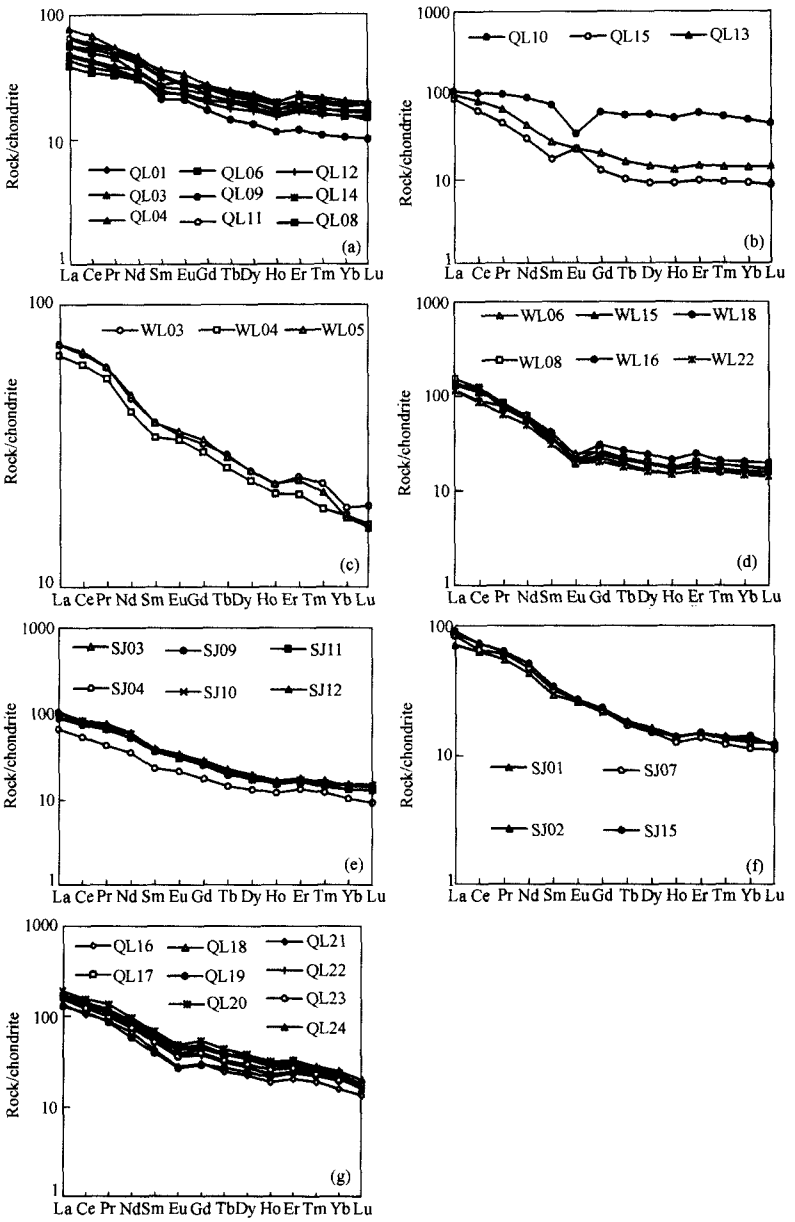

Fig. 3. Chondrite-normalized rare earth element distributions. (a) Basalt from Lianghe; (b) dacitic-rhyolite from Lianghe; (c)basalt from Wuliba; (d) dacitic-rhyolite from Wuliba; (e) basalt from Sunjiahe; (f) andesite from Sunjiahe; (g) andesite from Raofeng. Chondrite values are from Sun and McDonough[122].

—0.10 (the average is 0.076). The basalts from Wuliba exhibit Nb<La, Nb/La=0.32—0.34, Th/Yb=0.03, Ta/Yb=0.11, Zr/Y<4.5. These features indicate that the basalts are island-arc volcanic tholeiite[18]. In particular, all of the basalts from Lianghe and Wuliba show Ta/Yb<0.2, obviously different from the calc-alkaline basalt of active continental margin. In general, most of the basalts from island-arc ophiolite belong to tholeiitic series which often show typical features of

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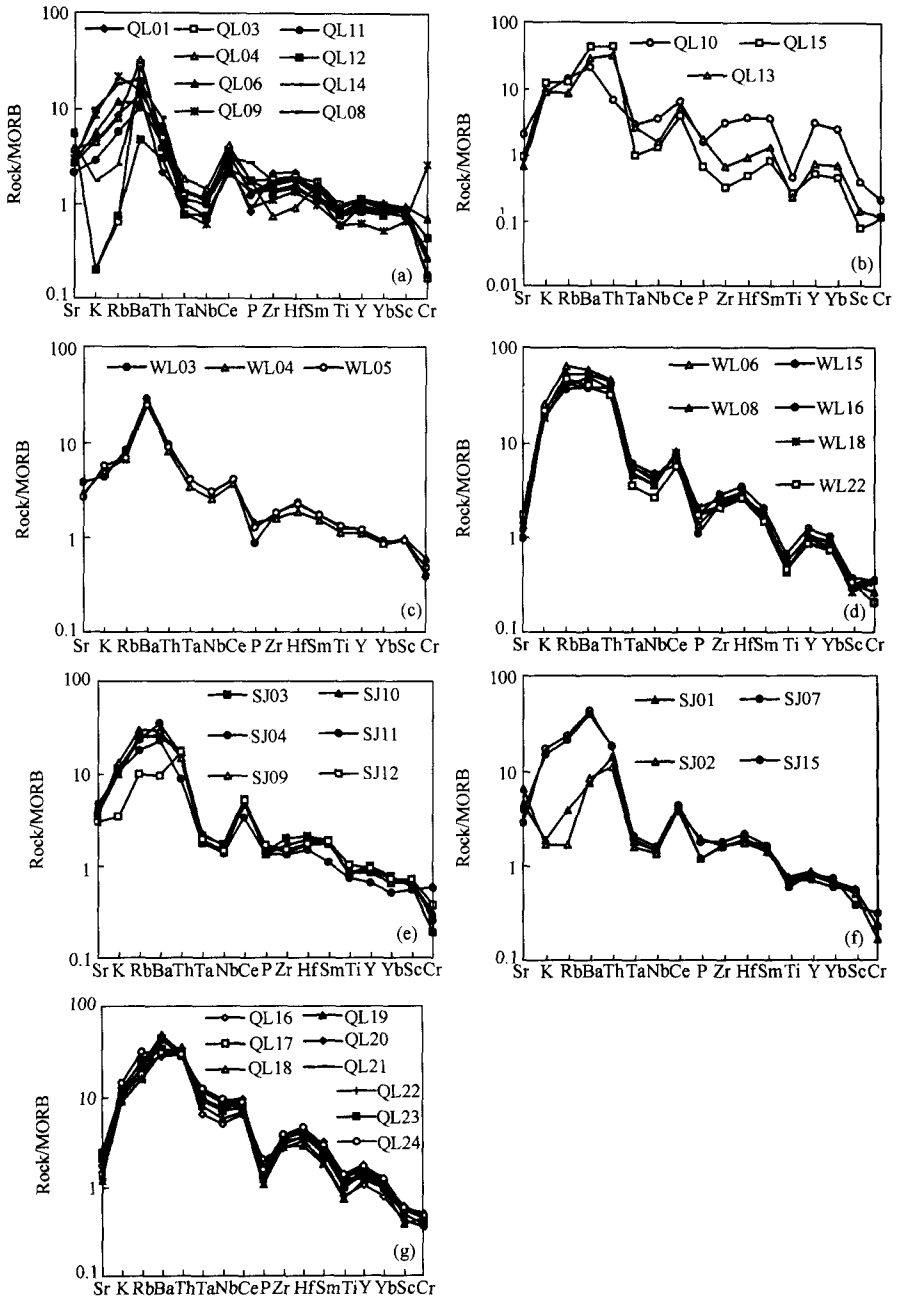

Fig. 4. N-type MORB normalized trace element distributions. (a) Basalts from Lianghe; (b) dacitic-rhyolites from Lianghe; (c) basalts from Wuliba; (d) dacitic-rhyolites from Wuliba; (e) basalts from Sunjiahe; (f) andesites from Sunjiahe; (g) andesites from Raofeng. N-type MORB values are from Pearce[17].

low Th/Yb ratio (for instance, the Oman ophiolite exhibits Th/Yb=0.05—0.1)[19], only a few basalt samples belong to calc-alkaline series. This is similar to the basalts from Lianghe and Wuliba. However, all of the basalts from Lianghe and Wuliba are enriched in LREE, that is exactly the

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geochemical feature of island-arc basalt. On the contrary, tholeiitic basalts from island- arc ophiolite are generally depleted in LREE (for example, Troodes, Oman, Vourinos and Betts Cove ophiolites)[19—21]. In summary, the basalts from Lianghe and Wuliba belong to oceanic island-arc volcanic rock[18].

The N-type MORB normalized trace element distributions of the andesites from Raofeng (fig. 4(g)) show volcanic-arc geochemical features.This group of andesite has Th>Ta, Th/Ta=2.63—5.03 (the average is 3.41); Nb<La, Nb/La<0.87; Th/Yb=1.39—2.22 (the average is 1.74); Ta/Yb=0.44—0.61 (the average is 0.52). However, the TiO_2 content (1.11%—2.11%) is higher than typical island-arc volcanic andesite[17]. Based on the Th, La, Yb and Ta features and the rock type, the andesites from Raofeng should belong to volcanic-arc association[18].

The N-type MORB normalized trace element distributions (fig. 4(e), (f)) for the Sunjiahe rocks show strong enrichment in K, Rb, Ba and Th as well as slight enrichment in Ce and Sm, indicating a volcanic-arc origin. In addition, the associated basalts exhibit Th>Ta, Th/Ta=8—10 (the average is 8.78); Nb<La and Nb/La<0.30; and Th/Yb=1.03—1.49 (the average is 1.35); Ta/Yb=0.14—0.18 (the average is 0.16). The andesites show Th/Ta=8.29—11.41 (the average is 9.85); Nb/La=0.24—0.27; Th/Yb=1.08—2.02 (the average is 1.51); Ta/Yb=0.13—0.18 (the average is 0.15). These features are similar to those of basalts in this area. Both the basalt and andesite from Sunjiahe are of volcanic-arc origin[18].

2.4 Trace elements and source of volcanics

Th, Nb and La are strong incompatible elements[22]. In addition, Nb, La, Th, Zr and Y are immobile during water/rock interaction and metamorphism. Therefore, the La/Nb-La and Nb/Th-Nb diagrams can be used to discriminate oceanic ridge, island-arc and oceanic island basalts[23]. According to fig. 5, all the samples from Lianghe, Wuliba and Sunjiahe belong to typical island-arc rocks. However, the Raofeng andesites are plotted between IAB and OIB fields and away from the island-arc region. As we know, the ionic radius of La and Th is larger than that of Nb. The migration capacity of La and Th is stronger than that of Nb. In fact, the alternation degree of the andesites from Raofeng is slightly higher than that of rocks from Lianghe, Wuliba and Sunjiahe, which might decrease the contents of La and Th compared to Nb. Therefore, the alternation might be responsible for shift of the Raofeng andesites from the IAB region in fig. 5. However, this needs further studies.

In fact, the ratio of Ta/Yb is mainly in a close relationship with partial melting and the geochemical features of the upper mantle. It is important to study the geochemical features of the source region of basalt[19]. In the Th/Yb-Ta/Yb diagram (fig. 6(a)), the rocks from the studied region fall in the CAB field and above the MORB-OIB trend, indicating that they belong to island-arc associations. The magma might be derived from a depleted upper mantle[24].

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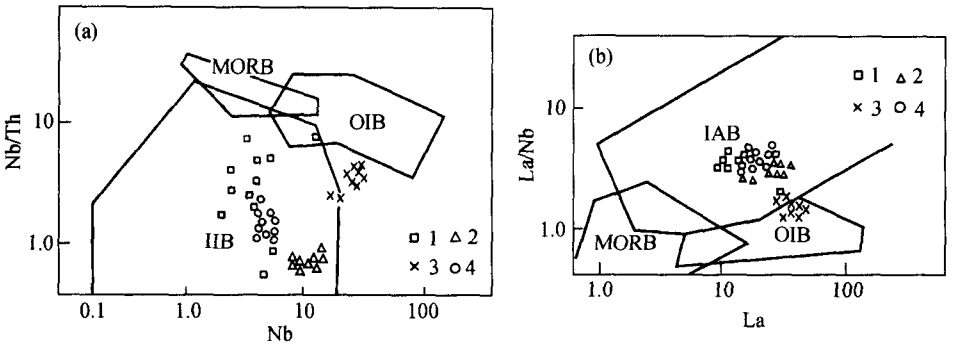

Fig. 5. The Nb/Th-Nb (a) and La/Nb-La (b) diagrams (after Li Shuguang[23]). 1, Volcanic rocks from Lianghe; 2, those from Wuliba; 3, those from Raofeng; 4, those from Sunjiahe.

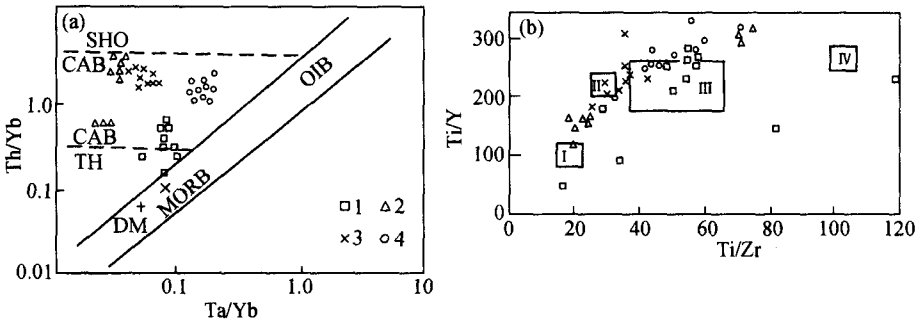

Fig. 6. The Th/Yb-Ta/Yb (a) and Ti/Zr-Ti/Y (b) diagrams (after Pearce[19], Hergt et al.[24]). For fig. 6(b): I, granite; II, Post-Archaean Terrestrial shale; III, low-Ti continental flood basalts; IV, MORB-type mantle. 1, Volcanic rocks from Lianghe; 2, those from Wuliba; 3, those from Raofeng; 4, those from Sunjiahe.

Ti in volcanic rocks is controlled by source composition and tectonic setting[19]. According to the Ti/Zr, Ti/Y ratios and the Ti/Zr-Ti/Y diagram (fig. 6(b)), most of the samples from the studied areas are located at the transition between crust and MORB-type mantle, indicating that the volcanic rocks belong to typical island-arc association and originate from the partial melting of mantle wedge of subduction zone.

In this paper, the study of the formation tectonic settings of the volcanic rock is based on the contents and ratios of immobile elements Ta, Nb, Th, La, Yb, Zr and Y. In order to check the completeness of acid sample digestion we used for ICP-MS analysis, the same set of samples were analyzed by the neutron activation analysis (NAA) method. The results obtained by the two different methods are nearly identical. Thus, the geochemical data used in this paper are of good quality.

3 Petrogenesis and tectonic significance

As discussed above, the volcanic rocks from Lianghe and Wuliba exhibit distinctive geochemical features of depletion in Nb and Ta, indicating that they belong to island arc origin[18]. Moreover, their Th/Yb, Ta/Yb, Ti/Zr and Ti/Y features imply that they formed in an oceanic is-

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land-arc tectonic setting. They are dominated by basalt and dacitic-rhyolite, which is different from the andesitic magmatism at the active continental margin, indicating that they should be a product of magmatism developed within a rift setting[25]. Of various tectonic settings, only rift within oceanic island-arc shows this kind of typical and complicated magmatism and rock association[26]. The rift within oceanic island-arc exhibits a transitional continental basement. The formation of this kind of tectonic setting can be due to the dome and extension of island-arc crust caused by uplift of deep-seated magma. On the other hand, it may be, in some degree, related to the partial subsidence caused by volcano-active and structure movement. This kind of tectonic setting can be considered as the initial result of the inter-arc basin development. It is obvious that the resulting tholeiites, in some degree,are similar to the MORB-type basalts that originated from a depleted mantle source. The difference is that the partial melting in the oceanic island-arc results from hydrated melting (fig. 7). Furthermore, the acid magma system, which exhibits typical island-arc geochemical features (such as Nb and Ta depletion), is generated by the partial melting of island-arc crust (fig. 7)[26].

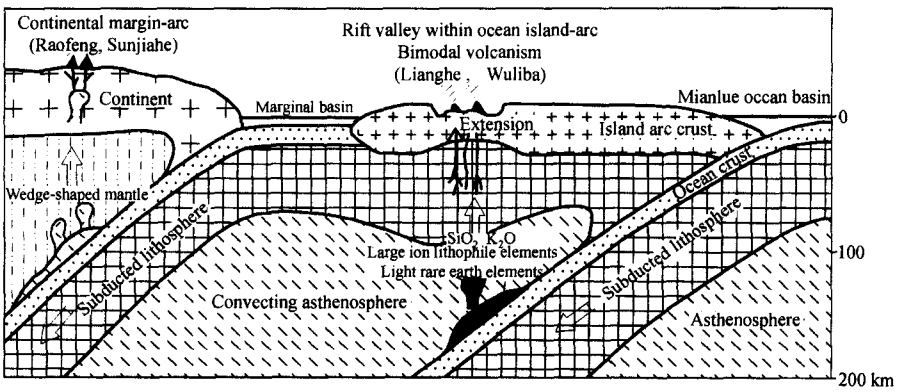

Fig. 7. Sketch map showing the formation model for the Lianghe-Raofeng-Wuliba volcanic-arc magmatic zone.

It is important that the andesites and basalts from Raofeng and Sunjiahe show Ba enrichment and Nb, Ta depletion. The Th/Yb, Ta/Yb, Th/Ta, Nb/La, Ti/Zr and Ti/Y of these rocks indicate that they formed in an active continental margin (fig. 7). The magma resulted from the partial melting of mantle wedge[26].

Comparatively, the basalts from Lianghe and Wuliba are similar to the island-arc basalts distributed in Qiaozigou, Mianxian-Lueyang area[3, 4]. The volcanic rocks from Raofeng and Sunjiahe are similar to the continental margin-arc volcanic rock association distributed in Sanchazi, Lueyang area[4]. This implies that the Lianghe-Raofeng-Wuliba volcanic-arc magmatic zone should be initially related with the Mianxian-Lueyang suture zone. The development of Devonian deep-water turbidites in the Mianxian-Lueyang suture zone suggests that the oceanic basin was open during the Devonian[1, 28]. Well-preserved Early Carboniferous radiolariae first discovered from siliceous rock interlayers of ophiolitic mélange near Sanchazi and Shijiazhuang villages, Lueyang County[27], indicate the Mianxian-Lueyang oceanic basin had lasted until Late Paleozoic.

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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 small oceanic 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 a Sm-Nd whole-rock isochron age of (242±21) Ma and a Rb-Sr whole-rock isochron age of (221±13) Ma[28], suggesting that the Mianxian-Lueyang paleo-oceanic basin closed in the Middle Triassic. In addition, the metamorphosed volcanic rocks distributed in Wenjiagou and Henxianhe region have the $^{40}Ar/^{39}Ar$ isochron age of (226.9±0.9) and (219.5±1.4) Ma[29], which is similar to the age of Heigouxia volcanic rocks.

The present study suggests that the Mianlue paleo-oceanic basin experienced a long geological history and complicated processes of development. The radiolariae recovered from siliceous rock near Sanchazi and Shijiazhuang suggests the typical oceanic crust ophiolite formed at Early Carboniferous[27] when Mianlue is a small oceanic basin seperating the Qinling-Dabie microplate from the Yangtze (South China) microplate. In general, as the extension of mid-oceanic ridge and the formation of new oceanic crust,the basin would become bigger and the intensity of compression force on the oceanic crust would increase step by step. Finally, the subduction zone developed[30, 31]. Based on the modern plate movement mechanism, the subduction and mid-oceanic ridge extension could be developed at the same stage. The scale of the oceanic basin could be determined by the relative intensity of subduction and mid-oceanic ridge extension[32]. The radiolariae discovered from siliceous rock interlayers of Sunjiahe volcanic-arc rock series indicates that the main part of the Lianghe-Raofeng (Sunjiahe)-Wuliba island-arc magmatic zone was formed in the Early to Late Carboniferous period. This implies that during the Carboniferous period the oceanic crust subduction and the mid-oceanic ridge extension of the Mianlue oceanic basin coexisted.

Discrimination of the oceanic island-arc bimodal volcanic rock association in the Lianghe and Wuliba areas as well as the continental margin-arc volcanic assemblage in the Raofeng and Sunjiahe areas indicates that there exists a typical island-arc magmatic zone in the Bashan arcuate area, which was a product of subduction of Mianlue oceanic basin. It is important that the Mianxian-Lueyang suture zone had extended to the Bashan arcuate area. On the other hand, it is suggested that the Mianlue oceanic basin experienced complicated processes of evolution during the Devonian-Carboniferous period. This has important tectonic significance in determining the timing of collision between the North China-Qingling and the Yangtze microplates and in deducing the evolutionary process of the Qinling orogenic belt.

4 Conclusions

A typical island-arc magmatic zone exists in the Lianghe-Raofeng-Shiquan-Gaochuan-Wuliba area of the Bashan arcuate region, south Qinling. The characteristic rocks in the zone are

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the bimodal volcanic rock association distributed in Lianghe and Wuliba areas which was formed in a rift setting within oceanic island-arc, as well as the continental margin-arc andesites distributed in Raofeng area. A Devonian-Carboniferous oceanic basin is suggested in south Qinling. This island-arc magmatic zone provides important evidence for the extension of the Mianxian-Lueyang suture zone to the Bashan arcuate area. The Mianlue ancient oceanic basin experienced complicated processes of evolution during the Devonian-Carboniferous period. The Sunjiahe continental margin-arc volcanic rock association of the Xixiang Group was formed in a typical volcanic-arc tectonic setting due to the subduction of Mianlue oceanic basin, which should be closely related to and initially connected with the Mianxian-Lueyang suture zone.

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