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RESEARCH ARTICLE

Geochemical characteristics and zircon U-Pb isotopic ages of island-arc basic igneous complexes from the Tianshui area in West Qinling

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Abstract The Liushuigou intermediate-basic meta-igneous complex at Guanzizhen, Tianshui area, is mainly composed of metagabbro, metagabbro diorite and metadiorite, while the Baihua basic meta-igneous complex consists mainly of pyroxenite, gabbro (gabbro diorite), diorite and quartz diorite. They form a relatively complete comagmatic evolutionary series. The geochemical characteristics of intermediate-basic igneous rocks indicate that they belong to a tholeiite suite. Their chondrite-normalized REE patterns are nearly flat and are LREE-slightly enriched type, and their primitive mantle-normalized and MORB-normalized trace element spidergrams are generally similar; the LILEs Cs, Ba, Sr, Th and U are enriched, while Rb and K and the HFSEs Nb, P, Zr, Sm, Ti and Y are depleted. All these show comagmatic evolutionary and genetic characteristics. The tectonic environment discrimination by trace element reveals that these igneous complexes formed in an island-arc setting. The Thermal Ionization Mass Spectrometry (TIMS) single-grain zircon U-Pb age for the Liushuigou intermediate-basic meta-igneous rocks in the Guanzizhen area is (507.5 ± 3.0) Ma, representing the age of these igneous complexes, which indicates that island-arc-type magmatite rocks in the northern zone of West Qinling are Late Cambrian and also reveals that the timing of subduction of the paleo-ocean basin represented by the Guanzizhen ophiolite and resulting island-arc-type magmatic activity are probably Late Cambrian to Early Ordovician.

Keywords basic igneous complex, geochemistry, island-arc setting, zircons U-Pb isotopic ages, Early Paleozoic, Tianshui area, West Qinling

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1 Introduction

The Tianshui area of West Qinling is located in the northeastern margin of the Qinghai–Tibet Plateau. Geotectonically, it lies at the junction of the Qilian orogenic belt and the North Qinling orogenic belt in the middle section of the Central Orogenic System of China, and also stretches over the S-N (Helanshan–Sichuan–Yunnan) tectonic belts in the central area of China. It occupies a superposed tectonic position, which is overlapped by the paleo-Asiatic tectonic domain, the Tethyan tectonic domain and the Pacific tectonic domain. Because it lies at the junction, the transition, transformation and connection sections of the Qilian orogenic belt and the Qinling orogenic belt, this region not only presents similarities with the two orogenic belts, but also many differences from them. It is of vital scientific significance for us to study the multi-phase orogenic processes between the convergence and divergence of the North China plate and the Yangtze plate, the composition, configuration, structure, evolution and transformation of orogenic mechanism at the junction of orogenic belt position, also orogenic process and the dynamics, etc. All these involve a significant foundation for the geological issues of the China continental geotectonic framework and evolution, the continental orogenic belt and continental dynamics.

Previous researches on regional stratum and geotectonics in the Tianshui area have laid a good foundation for this research (Bureau of Geology and Mineral Resources of Gansu Province, 1989, 1997; Song et al., 1991a, b; Xia et al., 1991; Zhang E P et al., 1992, 1993; Zhang W J et al., 1994; Zhang G W et al., 2001; Feng et al., 2002). Intermediate-basic igneous complex rocks and granitoid from the Caledonian, and also Indosinian granitoid, Proterozoic–Early Paleozoic moderate-, high-grade metamorphic rock series are distributed in the Liushuigou–Shuangchangxia regions of Guanzizhen and the Baihua–Liqiao regions. In recent years, in the process of doing the Tianshui City 1:250 000 regional geological survey, a set of metamorphic pyroxenite-gabbro-gabbro diorite units were discovered and identified in the metamorphic strata of the Sinian–Early Paleozoic Liziyuan Group in the Guanzizhen–Shuangchangxia region, originally subdivided Paleoproterozoic Qinling Group/Niutouhe Group and in the Baihua Forestry Center region, originally subdivided Mesoproterozoic Kuanping Group metamorphic strata (Bureau of Geology and Mineral Resources of Gansu Province, 1989, 1997; Xia et al., 1991; Song et al., 1991a, b; Zhang E P et al., 1992, 1993; Zhang W J et al., 1994; Feng et al., 2002). The latter composes the "Baihua igneous complex rocks" together with diorite-quartz diorite etc. units, which are distributed in the Baihua–Liqiao region and originally titled "Baihua rock body". These meta-igneous complexes have generally experienced intense ductile deformation and metamorphism reconstruction, which have been classified into different structural lithostratigraphic units according to the metamorphosed strata for a long time, and has affected the current understanding of the composition, texture, structure and evolution of the northern orogenic belt of West Qinling. According to the regional geological mapping data, the meta-plutonic complex is separated from the original metamorphic stratigraphic unit; the former is called the "Liushuigou intermediate-basic igneous complex", and the latter the "Baihua basic igneous complex" (Fig. 1). This paper reports geochemical and chronological data of the recently discovered metamorphic basic igneous complexes, and discusses the structural setting and the tectonic significance.

2 Regional geology background

The intermediate-basic igneous complexes in Guanzizhen of the Tianshui area are mainly distributed in the Changgou–Liushuigou, Guanzizhen; Shuangchangxia, Gangu; and Wujiahe, Wushan in western Tianshui City. The rock is irregular in shape, which trends along WNW-ESE. Both the east and west ends and the middle part of it are covered by Cenozoic strata. The northeastern side shows tectonic contact with the gneiss and the marble unit of the Paleoproterozoic Qinling Group, and the complexes ductilly thrust to the north above the Paleoproterozoic Qinling Group. The southwestern side also shows tectonic contact with the Early Paleozoic Guanzizhen ophiolite unit (composed of the N-MORB characteristic metamorphic basic volcanic rock

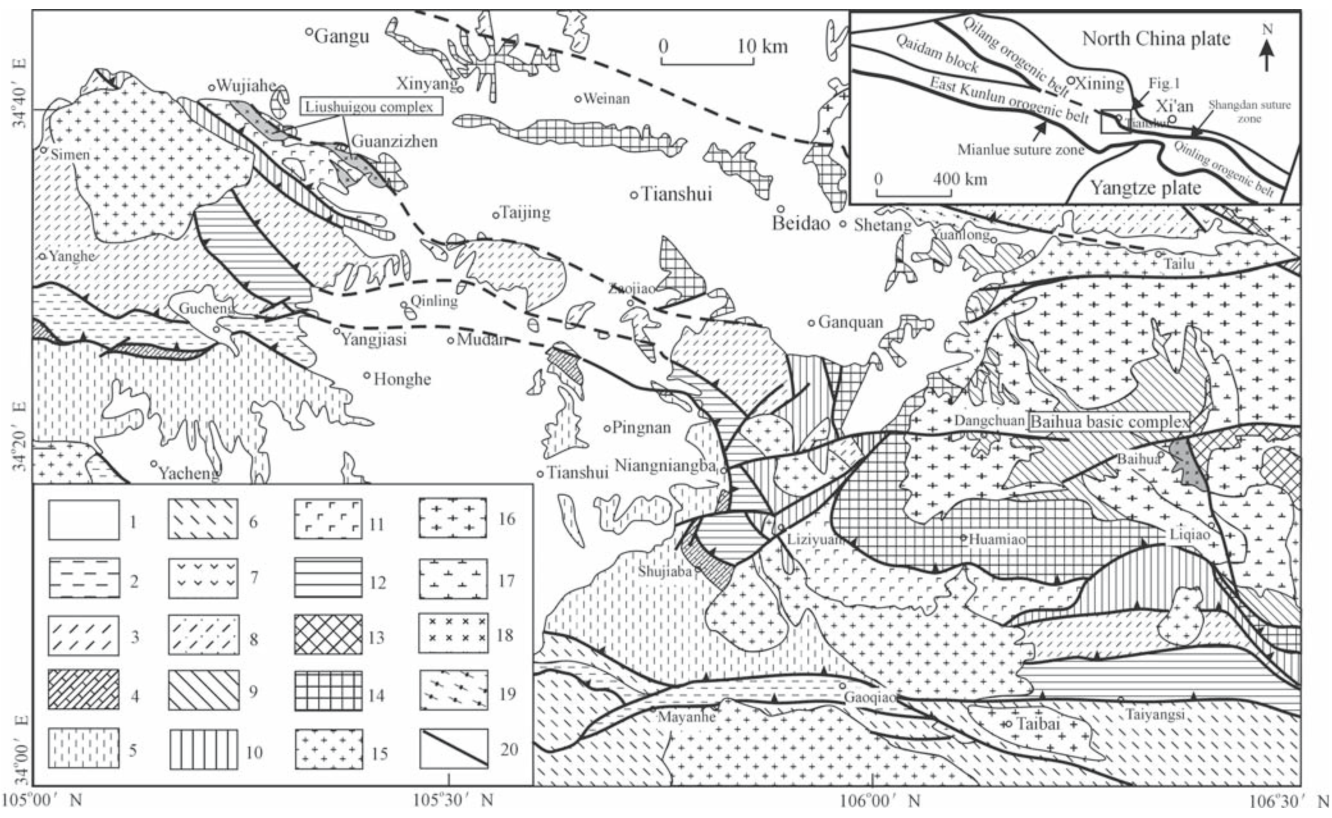

Fig. 1 Sketch geological map of the Tianshui area, West Qinling

1. Mesozoic–Cenozoic; 2. Carboniferous; 3. Upper Devonian Dacaotan Group; 4. Middle Devonian Shujiaba Group limestone unit; 5. Middle Devonian Shujiaba Group turbidite unit; 6. Middle–Upper Devonian Xihanshui Group; 7. Lower Paleozoic Hongtubao basic volcanic rocks; 8. Lower Paleozoic Huluhe Group meta-detrital rock; 9. Lower Paleozoic Caotangou Group; 10. Lower Paleozoic Liziyuan Group; 11. Lower Paleozoic Guanzizhen ophiolite; 12. Lower Paleozoic Taiyangsi Formation; 13. Mesoproterozoic Kuanping Group; 14. Paleoproterozoic Qinling Group; 15. Indosinian granitoid; 16. late Caledonian–early Hercynian granitoid; 17. Caledonian diorite-quartz diorite; 18. Early Paleozoic deformed gabbro-gabbro diorite; 19. deformed granite; 20. thrust and fault

and serpentinite, metapyroxenite, metagabbro tectonic massif) (Pei et al., 2004), where ductile shear deformation zone is also developed, which makes the tectonic foliation parallel and consistent, and dip steeply to the south or north at different sections. The mylonite light-red medium-, macro-grained porphyroid texture monzonitic granite bodies, which have lithological characteristics identical to the Indosinian Wenquan granite bodies, intruded in the intermediate-basic igneous complexes in the Shuangchangxia region.

The Baihua basic igneous complexes of the Baihua–Liqiao region in Tianshui are mainly distributed in the Baihua Forestry Centre–Sancha at northern Liqiao in the Beidao District of the Tianshui area. The rock is irregular, and more complicated because of emplacement and erosion of the new rock mass in later periods. The Baihua basic igneous complexes, which are adjacent to the biotite plagiogneiss and marble of the Mesoproterozoic Kuanping Group and the Devonian Xianping monzonitic granite body in the northeastern side, show intrusive contact with the Early Paleozoic Caotangou Group metamorphic island-arc-type volcanic-sedimentary rock series in the northwestern side, and also show fault contact with the Devonian Xiongshangou medium-, macro-grained porphyroid texture monzonitic granite body in the southwestern side, wholly trend NW strike in the region. At the southern side of the metamorphic igneous complexes, there distribute the Paleoproterozoic Qinling Group cluster felsic gneiss, marble, remnant of ophiolite at the Guanzizhen–Muqitan (serpentine schist, metamorphic basic volcanic rocks), and the Early Paleozoic Liziyuan Group mica-quartz schist interbedding the marble, greenschist, and the gravel-bearing detrital rock series of the Late Devonian Dacaotan Group from north to south, and they are tectonic contact. According to 1: 50 000 regional geological surveying data, the Baihua complexes intruded in the Kuanping Group and Ordovician Caotangou Group metamorphosed strata, and at a later time the complexes were invaded by the Xianping granite body (Rb-Sr entire isochronism age is 396 Ma) of the Devonian. Therefore, the time of the Baihua metamorphic igneous complexes may be constrained to the Early Paleozoic.

3 Petrologic characteristics of igneous complexes

3.1 The Liushuigou metamorphic intermediate-basic igneous complexes

Through geological mapping and comprehensive analysis, the Liushuigou metamorphic complex in Guanzizhen can be divided into three rock types: metagabbro, metagabbro diorite and metadiorite. Because the rock has experienced strong deformation and metamorphic transformation, and in general, developed intensively-oriented fabric, the original mineral assemblage has been generally substituted by the metamorphic assemblage, but the boundaries among each lithological unit are still clearly displayed. The rock with magma fabrics of blastogabbro texture etc. at the weak distortion zone can be seen, displaying a dark mineral amphibole aggregate with pyroxene-shaped characteristics. Besides, there are lenticular or lens-shape dark fine-grained pyroxenolite and gabbro inclusions (Fig. 2), their length is generally 10–20 cm, width is 4–12 cm; the macro-axis direction is consistent with the mineral directional arrangement. The complex is mainly composed of plagioclase, amphibole, epidote, quartz, a few chlorite and sericite under microscope. The main accessory

Fig. 2 Deformation enclaves and oriented fabrics of dark-colored gabbro in the Zhaojiamo metagabbro diorite at Guanzizhen, Tianshui

minerals are sphene, zircon, magnetite and apatite. The mineral particle diameter is generally 0.5–2.5 mm, and the complex has a medium-xenotopic columnar-grained granoblastic texture and gneissic structure. The essential minerals, intensely directionally arranged, are amphibole and plagioclase, and partly display mylonite fabric characteristics.

3.2 The Baihua metamorphic igneous complexes

Based on field surveys and comprehensive analysis, the Baihua metamorphic igneous complexes can be divided into five types. 1) Meta-pyroxenite: the majority of meta-pyroxenite is wrapped by the gabbro with different size masses. The deformation is weak. It is mainly composed of amphibole (90%–94%) and plagioclase, with medium–fine hedral–subhedral granular texture, massive-weak gneissic structure. The majority of amphibole remains the pyroxene short columnar crystal form. 2) Metagabbro-gabbro diorite: distributed in the east of the Baihua Forestry Center–Zao'erping. The rocks generally grow an oriental structure, and are mainly composed of amphibole (about 48%–74%), plagioclase (about 25%–48%) and a few biotites. They have medium–macro to medium–fine granular subhedral texture, blastogabbro texture, and on local weak-deformed area, amphibole still remains pyroxene pseudomorph. 3) Meta-diorite: distributed at the eastern Yingya–Baihua–Liqiao area. The major compositions are amphibole (20%–35%), plagioclase (55%–60%), biotite (2%–12%) and a few quartzes, with subhedral medium–macro granular texture. The interior usually includes gabbro inclusions, lenticle and lens-shape, and of different sizes and directional arrangement, and the macro-axis direction is consistent with the mineral directional arrangement. 4) The quartz diorite: mainly distributed in southern Liqiao–Yanghe–Xiaxianping, and mainly composed of amphibole (15%–25%), plagioclase (40%–67%), quartz (5%–15%) together with a few biotites and K-feldspar. It has subhedral-allotriomorphic medium–fine to medium–macro-grained granular texture. The interior usually includes gabbro etc. inclusions. 5) The biotite plagiogranite: mainly distributed from Longmen to Zhoujiagou in Liqiao, with porphyroid texture, massive structure–weak gneissic structure. The phenocryst, mainly composed of tabular plagioclase and a few perfectly round quartz, is less than 5%; the groundmass is mainly composed of plagioclase (45%–65%), quartz (20%–35%) and biotite (5%±). The series of magmatite combination takes on island-arc type magmatic activity characteristics. Because the rocks have already undergone strong ductile shear deformation and metamorphism transformation, and in general developed an intensely directional fabric, the original mineral assemblages have been almost substituted by the metamorphic assemblages, but the blastogabbro texture of magma fabrics in weakly distorted regions can still be observed, displaying a dark mineral amphibole aggregation with pyroxene-shaped characteristics, and there are dark medium-xenotopic granular pyroxenolite and gabbro enclosures in the diorite and quartz diorite. The boundary among each lithological unit is clear. The accessory minerals mainly are sphene, zircon, magnetite and apatite. This paper mainly studies part of basic igneous rock of the igneous complex (metapyroxenite and metagabbro).

4 Geochemical characteristics and tectonic environment of the igneous complex

The fresh rock samples of the Liushuigou igneous complex in Guanzizhen of the Tianshui area, including metagabbro-metagabbro diorite-metadiorite, and the Baihua igneous complex, including pyroxenite-gabbro(-diorite)-diorite, are tested for analysis (Table 1). The major elements are tested by wet analysis and volumetric analysis, and the trace elements and REE are tested by ICP-MS. The analytic precision of major elements is generally lower than 1%, and the analytic precision of trace elements and REE is higher than 5%.

4.1 The Liushuigou intermediate-basic meta-igneous complex

The content of SiO_2 is 52.47%–61.74%, and TiO_2 is 0.30%–0.88%, lower than MORB and OIB, but close to island-arc basalt. The $Mg^{\#}$ (100 MgO/(MgO + FeO) mol ratio) 52.01–56.65 is low, which reflects that the magma has undergone an evolution of crystallization differentiation. The content of FeOT is between 7.00% and 10.30%; ALK ($Na_2O + K_2O$) is between 1.69% and 2.12%; and $Na_2O > K_2O$, K_2O (0.10%–0.20%) is lower, showing rich Na and low K, and it belongs to low K suite. The rocks are within the area of gabbro-gabbro diorite-diorite in the TAS diagrams (Le Maitre, 1989; Middlemost, 1994), and they have the characteristics of the subalkaline series (Fig. 3a). In $TiO_2/Zr/P_2O_5/10\,000$ (Winchester and Floyd, 1977) and AFM diagrams, it is indicated that they all belong to the tholeiite series (Fig. 3b and c).

The REE distribution patterns are of nearly flat and slightly LREE-enriched type (Fig. 4a), LREE is relatively enriched to HREE, and the total REE is $\Sigma REE =$ 18.62–103.03 μg/g; the LREE/HREE ratio is 2.05–5.01; $(La/Yb)_n$ = 1.10–5.61; $(La/Sm)_n$ = 1.14–3.16; δEu = 0.85–1.01; and it has slightly Eu negative anomaly-no anomaly. The REE patterns are similar to those of island-arc volcanic rock (Henderson, 1984; Wilson, 1989).

In trace element spidergrams (Fig. 4b), the LILEs Cs, Ba, Sr, Th and U are enriched, while Rb and the HFSEs Nb, P, Sm, Ti and Y are relatively depleted. It is similar to low K island-arc tholeiite. In the MORB-normalized trace element spidergrams (Fig. 4c), Th and incompatible elements are enriched, while K, Nb, P, Ti, Cr are depleted. Ba and Sc have positive anomaly, and it has the characteristics of island-arc tholeiite and calcium-alkaline island-arc basalt (Pearce and Cann, 1973; Condie, 1989). The negative anomaly of Nb, in particular, is the marked indicator of island-arc volcanic rock, and it reflects the representative characteristics of magma rock in a plate subduction environment (Gill, 1981). The

Table 1 Major element (%), REE and trance element (μg/g) compositions of the Liushuigou intermediate-basic igneous zrocks and the Baihua basic igneous rocks from Tianshui, West Qinling

Sample No.	5022/1	5019/2	5325/1	5116/1	5116/2	5116/3	5116/4	5116/5
Rock body	Liushuigou complex			Baihua complex				
Rock type	Gabbro	Gabbro-diorite	Diorite	Pyroxenite	Pyroxenite	Gabbro	Gabbro	Gabbro
Location	Liushuigou	Shuangchangxia	Hanjiagou	Zao'erping				
SiO_2	52.47	55.94	61.74	45.18	43.08	48.32	52.48	46.10
TiO_2	0.88	0.37	0.30	0.30	0.24	0.25	0.76	0.84
Al_2O_3	17.73	15.86	14.42	11.71	13.83	15.45	17.29	17.24
Fe_2O_3	3.76	2.57	2.02	5.94	4.29	3.02	3.62	4.65
FeO	5.96	7.99	5.18	6.08	6.64	5.00	6.98	8.00
CaO	11.76	8.86	9.60	10.24	10.84	11.93	9.55	11.92
MgO	3.92	4.86	3.80	16.09	16.00	11.90	5.07	7.52
MnO	0.247	0.176	0.080	0.190	0.170	0.160	0.180	0.230
K_2O	0.20	0.19	0.10	0.29	0.14	0.12	0.19	0.15
Na_2O	1.52	1.96	1.59	1.02	0.84	0.83	1.75	1.46
P_2O_5	0.416	0.061	0.040	0.080	0.050	0.050	0.110	0.160
Lost	0.90	1.04	0.68	2.28	3.36	2.12	0.56	0.76
Total	99.763	99.877	99.550	99.400	99.480	99.150	98.540	99.030
FeOT	9.34	10.30	7.00	11.42	10.50	7.71	10.23	12.18
$Mg^{\#}$	53.96	52.01	56.65	82.50	81.11	80.92	56.41	62.61
Cr	9.10	72.1	50.6	478.0	427.0	362.0	32.0	26.2
Ni	10.0	18.1	16.2	234	222	124	9.25	10.5
Co	22.1	27.6	17.4	69.6	68.8	40.4	27.6	39.0
Rb	8.00	6.40	3.95	8.50	4.60	3.95	3.90	2.50
Cs	4.80	4.60	2.85	1.75	1.55	1.30	1.25	1.35
Sr	390	84	176	115	244	251	302	812
Ba	61.0	34.0	138.0	349.0	58.2	63.2	98.1	675.0
V	330	280	199	191	123	147	294	393
Sc	21.0	44.0		36.8	32.4	48.4	43.9	61.8
Nb	8.90	1.40	1.38	1.05	1.07	1.04	2.21	2.70
Ta	1.20	0.50	0.50	0.50	0.50	0.50	0.67	0.83
Zr	84.0	51.0	42.7	48.0	39.8	40.8	62.3	59.8
Hf	2.70	1.50	1.37	1.87	1.50	1.43	2.05	2.27
U	2.00	1.40	1.33	1.00	1.16	1.00	1.13	1.00
Th	5.00	1.70	3.34	1.74	0.12	0.96	0.56	0.68
Y	22.80	8.76	8.26	4.85	4.03	8.96	19.80	22.40
La	21.30	1.96	3.65	3.23	1.50	2.00	7.19	5.66
Ce	35.20	4.73	6.24	4.49	2.22	3.68	15.20	13.60
Pr	4.35	0.89	0.88	0.50	0.25	0.71	2.21	2.15
Nd	19.60	3.53	3.35	2.67	1.89	3.72	10.70	11.90
Sm	4.10	1.05	1.13	0.73	0.61	1.16	3.18	3.73
Eu	1.35	0.36	0.33	0.28	0.25	0.38	0.90	1.07
Gd	4.61	1.15	1.26	0.98	0.78	1.48	3.52	3.99
Tb	0.74	0.23	0.24	0.18	0.14	0.25	0.62	0.74
Dy	4.83	1.66	1.66	1.24	0.99	1.90	4.29	5.48
Ho	0.96	0.39	0.43	0.25	0.21	0.40	0.93	1.08
Er	2.74	1.17	1.26	0.64	0.65	1.25	2.82	3.42
Tm	0.420	0.180	0.180	0.092	0.090	0.190	0.440	0.480
Yb	2.50	1.17	1.17	0.61	0.47	1.11	2.57	3.08
Lu	0.330	0.150	0.200	0.096	0.086	0.160	0.360	0.430
LREE/HREE	5.01	2.05	2.43	2.91	1.97	1.73	2.53	2.04
REE	103.03	18.62	21.98	15.99	10.14	18.39	54.93	56.81
$(La/Yb)_n$	5.61	1.10	2.06	3.49	2.10	1.19	1.84	1.21
$(La/Sm)_n$	3.16	1.14	1.97	2.69	1.50	1.05	1.38	0.92
$(Ce/Yb)_n$	3.59	1.03	1.36	1.88	1.21	0.85	1.51	1.13
δEu	0.95	1.01	0.85	1.02	1.12	0.90	0.83	0.85

Notes: Major, trace and rare earth elements were analyzed at the Yichang Institute of Geology and Mineral Resources.

content of Zr in metagabbro and metagabbro diorite is 51–84 μg/g, similar to that in island-arc tholeiite, and the Zr/Y ratio is 0.16–0.39, closing to island-arc and ridge basalt; the Ti/Y ratio is 3.40–4.17, evidently >2, and it belongs to the area of island-arc basalt (Wilson, 1989). The content of Zr in metadiorite is 3.34 μg/g; La is 3.65 μg/g; La/Yb ratio is 3.12;

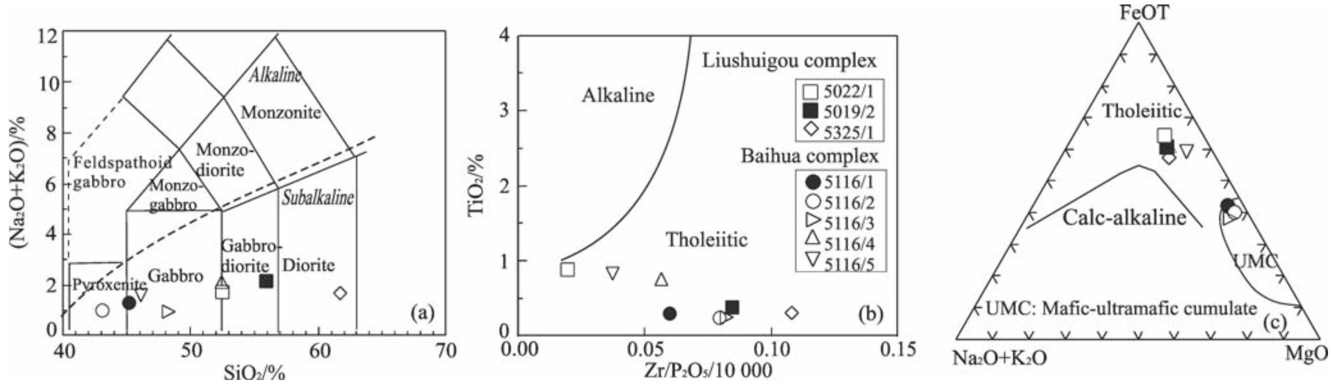

Fig. 3 Diagrams of basic and intermediate-basic igneous rocks in the Tianshui area
Note: TAS. after Le Maitre (1989); TiO_2-Zr/P_2O_5/10 000. after Winchester and Floyd (1977); AFM. after Middlemost (1994)

Zr/Y ratio is 5.17; Ti/V ratio is 9.05; Ti/Zr ratio is 42.15. These data are very similar to those of island-arc andesite (Condie, 1989; Wilson, 1989). In Ti-Zr-Y, Ti-Zr-Sr (Pearce and Cann, 1973) and La-Y-Nb (Cabanis and Lecolle, 1984) diagrams, samples are mostly in the area of island-arc basalt (Fig. 5). In Ba/Nb-Ba, La/Nb-La (Li, 1993) and Ti-V (Shervais, 1982) diagrams, samples are all in the area of island-arc basalt (VAB) (Fig. 6), and the La/Nb ratio is evidently more than 1 (1.40–3.08) and different from those of MORB and OIB.

The above geochemical characteristics show that the Liushuigou intermediate-basic igneous complex has the geochemical characteristics of island-arc volcanic rock, and reveals that it formed in an old island-arc tectonic environment, as the result of crystallization differentiation of island-arc magma and it does not belong to Guanzizhen ophiolite with the characteristics of N-MORB distributing in the south of the island-arc igneous complex.

4.2 The Baihua basic meta-igneous complex

The content of SiO_2 in pyroxenite is 43.08%–45.18% and the content of TiO_2 is 0.24%–0.30%, lower than those in MORB and OIB, but close to that of island-arc basalt. The content of MgO is 16.00%–16.09% and the $Mg^{\#}$ is 81.11–82.50, and both of them are high, which reflects that there is crystal accumulation of pyroxenite. The FeOT content is between 10.50% and 11.42%; ALK (Na_2O+K_2O) content is 0.98%–1.31%, and Na_2O content is more than K_2O content, showing enriched Na and low K. The SiO_2 content in gabbro(-diorite) is 46.10%–52.48%, and TiO_2 content is 0.25%–0.84%, lower than that in MORB and OIB, also close to that in island-arc basalt, which reflects that its sources may be related to the deeply subducted oceanic crust. MgO content is 5.07%–11.90%; $Mg^{\#}$ is 56.41–80.92, and both of them are high and changeable, which reflects that the primary magma has undergone an evolution of crystallization differentiation in its rising course. The FeOT content is between 7.71% and 12.18%, and ALK (Na_2O+K_2O) content is 0.95%–1.95%, and Na_2O is richer than K_2O, showing enriched Na and low K. Samples are in the area of pyroxenite and gabbro(-diorite) in the TAS diagrams (Le Maitre, 1989; Middlemost, 1994), and they have the characteristics of subalkaline series (Fig. 3a). In TiO_2-Zr/P_2O_5/10 000 (Winchester and Floyd, 1977) and AFM diagrams they display tholeiite series (Fig. 3b and c).

The REE patterns of pyroxenite are of nearly flat and slightly LREE-enriched type (Fig. 4d): the fractionation between LREE and HREE is inconspicuous; the total REE is $\Sigma REE = 10.14$–15.99 μg/g; LREE/HREE ratio is 1.97–2.91; $(La/Yb)_n = 2.10$–3.49; $(La/Sm)_n = 1.50$–2.69; δEu is 1.02–1.12, and has slightly Eu positive anomaly, which reflects crystal accumulation of plagioclase. The REE patterns of gabbro(-diorite) are also of nearly flat and slightly LREE-enriched type (Fig. 4d), which are very similar to those of pyroxenite. The fractionation between LREE and HREE is inconspicuous; the total REE is higher and more changeable than that of pyroxenite; ΣREE is 18.39–56.81 μg/g; LREE/HREE ratio is 1.73–2.53; $(La/Yb)_n = 1.19$–1.84, $(La/Sm)_n = 0.92$–1.38; δEu is 0.83–0.90, and has slightly Eu negative anomaly, which reflects crystal accumulation of plagioclase. The REE patterns are similar to those of island-arc volcanic rock (Henderson, 1984; Wilson, 1989).

In the primitive mantle-normalized trace element spidergrams (Fig. 4e), the distribution types of pyroxenite and gabbro(-diorite) are very similar. They show that LILEs Cs, Ba, Sr, Th, and U are enriched while Rb and HFSEs Nb, P, Sm, Ti, and Y are depleted. This reflects that they have the same forming characteristics of magma evolution. In the MORB-normalized trace element spidergrams (Fig. 4f), the distribution types of pyroxenite and gabbro (-diorite) are very similar. Incompatible elements are enriched; K, Nb, P, Zr, Ti and Y are depleted; Ba and Sc have a slight positive anomaly; Nb, Ti, Y and Yb are more depleted in pyroxenite than in gabbro(-diorite). This type is obviously different from those of MORB and OIB, showing the characteristics of island-arc tholeiite and calcium-alkaline island-arc basalt (Pearce, 1982, 1984). The negative anomaly of Nb in particular is the marked indicator of magma formed in an island-arc environment with plate subduction (Gill, 1981). The Zr content of gabbro

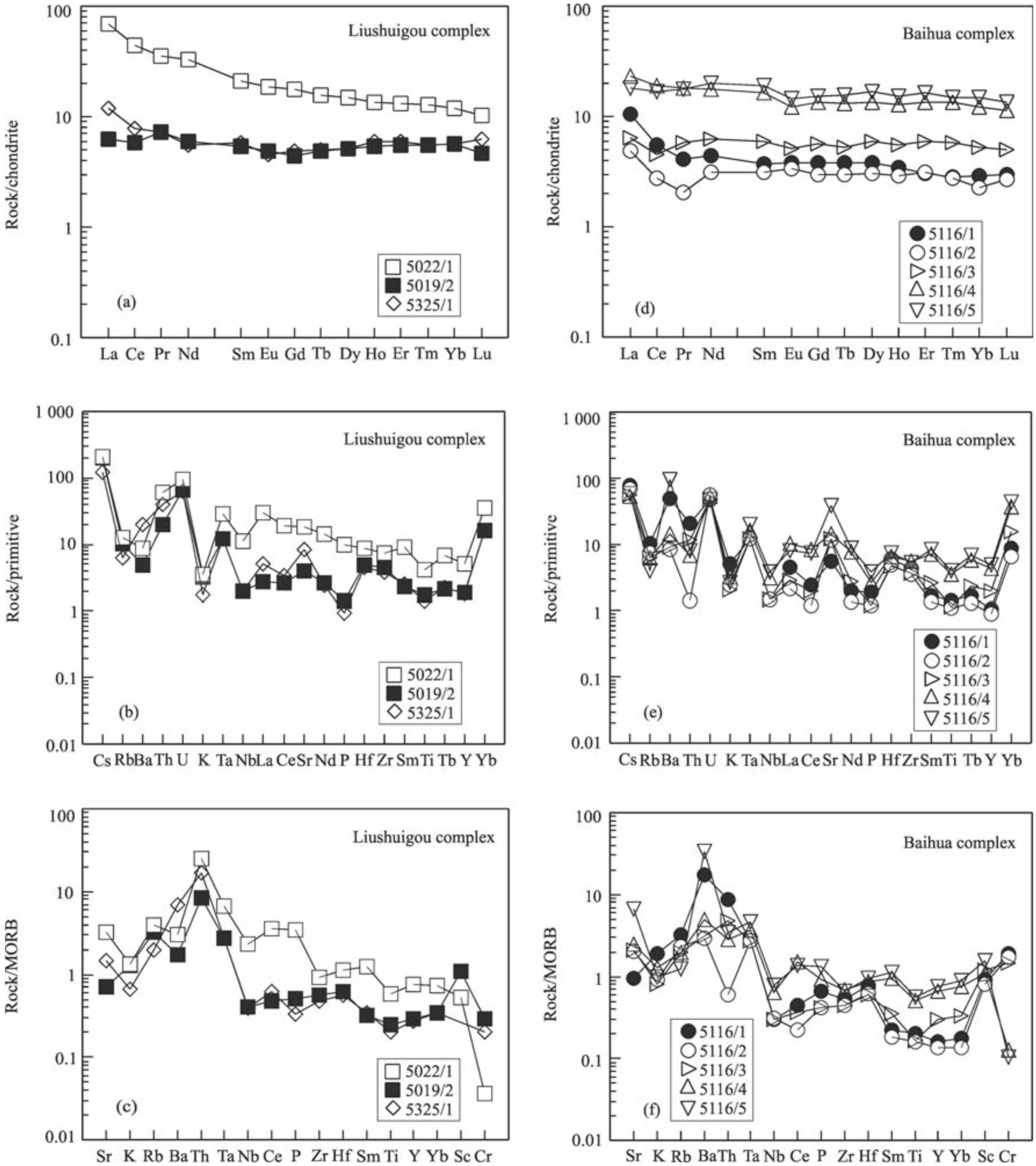

Fig. 4 Chondrite-normalized REE pattern (a, d), primitive mantle-normalized (b, e) and MORB-normalized (c, f) trace element spidergrams for basic and intermediate-basic igneous rocks in the Tianshui area
Note: chondrite-normalized data after Boynton (1984); mantle-normalized data after McDonough et al. (1992); MORB-normalized data after Pearce (1982) and Rollison (1993)

(-diorite) is 40.8–62.3 μg/g, close to the Zr content of island-arc tholeiite. The Zr/Y ratio is as low as 2.67–4.55, close to that of island-arc basalt; the Ti/Y ratio is 167–230; Ti/V ratio is 10.20–15.51; Nb/Y ratio is 0.11–0.12, all close to those of island-arc basalt. In the Ti-Zr-Y, Ti-Zr-Sr (Pearce and Cann, 1973), and La-Y-Nb (Cabanis and Lecolle, 1984) diagrams, samples are mostly in the area of island-arc basalt (Fig. 5). In the Ba/Nb-Ba, La/Nb-La (Li, 1993) and Ti-V (Shervais, 1982) diagrams, the samples are all in the area of VAB (Fig. 6), and they display La/Nb > 1 (1.40–2.64), obviously different from those of MORB and OIB.

The above geochemical characteristics indicate that the Baihua basic igneous complex in the Tianshui area was formed by the movement of island-arc magma in an active continental margin. It formed in an old island-arc tectonic environment as a result of crystallization differentiation.

Concerning the rock constituents, the Liushuigou intermediate-basic igneous complex is made up of metagabbro, metagabbro diorite and metadiorite. The Baihua igneous complex is mostly made up of pyroxenite-gabbro and gabbro (diorite)-diorite-quartz diorite. The latter has more rock types and better magma evolution, showing an intact

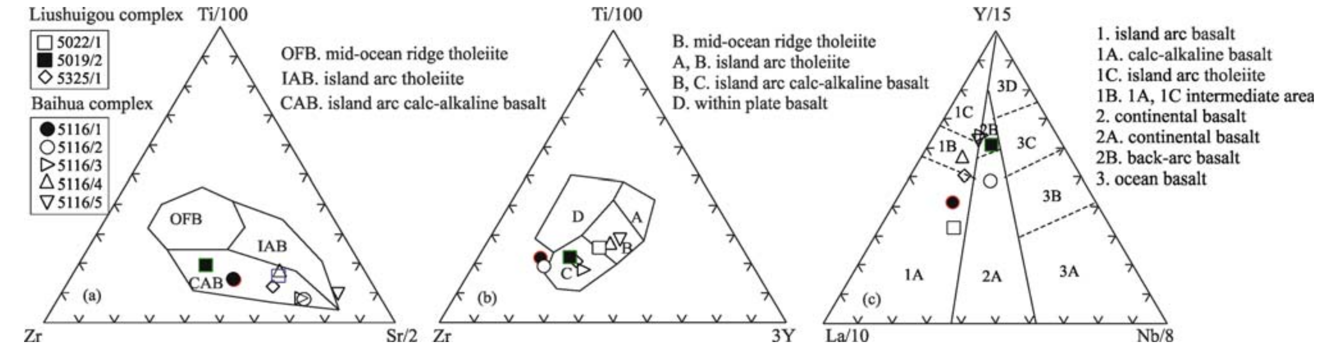

Fig. 5 Ti-Zr-Y and Ti-Zr-Sr diagrams of the basic and intermediate-basic igneous rocks in the Tianshui area (after Pearce and Cann (1973) and Cabanis and Lecolle (1984))

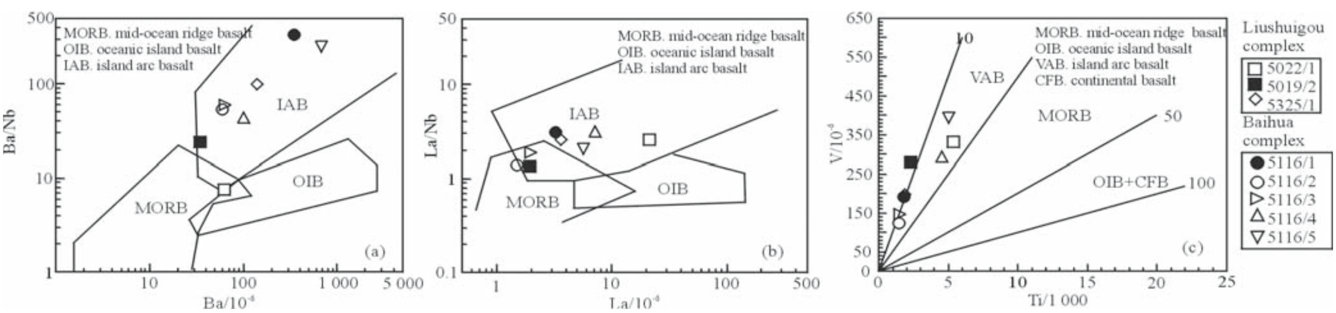

Fig. 6 Ba/Nb vs. Ba, La/Nb vs. La and Ti vs. V diagrams of basic and intermediate-basic igneous rocks from the Tianshui area (after Condie (1989) and Pearce and Cann (1973))

evolution series of comagma. The gabbro in the Liushuigou intermediate-basic igneous complex and the gabbro in the Baihua igneous complex have similar geochemical characteristics. Both of them belong to tholeiite series, and their REE patterns are of nearly flat and slightly LREE-enriched type. In the primitive mantle-normalized and the MORB-normalized trace element spidergrams, they have a similar distribution type. Their LILEs Cs, Ba, Sr, Th and U are enriched; Rb, K and HFSEs Nb, P, Zr, Sm, Ti and Y are depleted, which shows comagmatic evolutionary and genetic characteristics. The tectonic environment discrimination by trace elements reveals that these igneous complexes formed in an island-arc setting. From the magma evolution, the Baihua igneous complex has the better characteristics of magma crystallization differentiation evolution than the Liushuigou intermediate-basic igneous complex; the Baihua complex formed intermediate-intermediate-acid rock such as diorite and quartz diorite. Thus, the same type of rocks all formed in the Early Paleozoic and has the same geochemical characteristics and the same forming tectonic environment though they are different in rock constituents and space distribution.

5 The zircon U-Pb isotopic age of igneous complex

In order to obtain the forming time of the igneous complex body, the Thermal Ionization Mass Spectrometry (TIMS) method was adopted to determine the zircon U-Pb isotopic age of the rocks.

5.1 Methods

TIMS U-Pb ages determination were carried out in the Isotopic Geochronological Laboratory, of the Tianjin Institute of Geology and Mineral Resources. The collected samples were first carefully cleaned and then crushed until they could pass through the 100 meshes sift. Then the zircons were selected by using conventional methods. The zircons were manually selected under binocular stereomicroscope in order to obtain the zircons that are suitable for isotopic dating, only grains without inclusion, fracture, and highly transparent are selected. Isotopic dilution method is adopted to carry out the zircon U-Pb dating. Zircons dissolution and U, Pb separation were carried out under the Krogh procedure with some improvement. Zircons were dissolved by high concentration and pure hydrofluoric and nitric acid component solvents and diluted by ^{208}Pb-^{236}U component diluent in a 2.5-ml fluoroplastics container. The dissolved zircons sample liquor was distilled to dry, then U and Pb were added on the same single rhenium filament by using silastic-phosphoric acid solution. A high sensitivity Daly detector was used to carry out U-Pb isotopic measurement on the VG354 mass spectrograph. Pb isotopic data were collected as the filament temperature was 1 300°C –1 400°C, and then the U isotopic data were collected as the filament temperature increased to 1 450°C

–1 500°C. The mass discrimination were rectified by all the isotopic data of U-Pb. During the whole course of the experiment, Pb null is 0.030–0.050 ng, and U null is 0.002–0.004 ng.

5.2 Results

The samples were collected from the Liushuigou igneous complex body in Guanzizhen (N34°36.787′, E105°23.259′). The collected zircons from samples are pale yellow, transparent, short prismatic, hemi-pyramid, and mid-long prismatic crystals. The six zircon U-Pb isotopic data dots were tested by TIMS method, and acquired basic consistent isotopic age within error bands (Table 2; Fig. 7). From the results, all the dating zircons generally had higher common-Pb, represented by the lower $^{206}Pb/^{204}Pb$ value after deducting null test data and adjusting diluent. The highest reached 202, but the lowest was only 53. So the $^{206}Pb/^{238}U$ apparent age weighted average represented the zircons forming time. From the 6 dots of the sample, dots 3, 4, 5, 6 correspond with the better idiomorphism grade basaltiform zircons, and dots 3, 4, 5 have completely consistent $^{206}Pb/^{238}U$ apparent age, whereas dot 3 has three groups with completely concordant consistent apparent age, but the result of dots 4, 5 represented the single zircon dating results, so they are representative. Therefore, the $^{206}Pb/^{238}U$ (507.5 ± 3.0) Ma apparent age weighted average of dots 3, 4, 5 can represent the emplacement crystal age of the rocks. It is possible that the exanimation factor caused the lower age value of dot 6; however, dots 1, 2 are the massive half-coniform zircon crystal. The possibility of the remnant core of zircons cannot be eliminated, so the $^{206}Pb/^{238}U$ apparent age is slightly higher. Therefore, the dots 3–5 $^{206}Pb/^{238}U$ apparent age weighted average (507.5 ± 3.0) Ma is the rocks' form age of the Liushuigou igneous complex body.

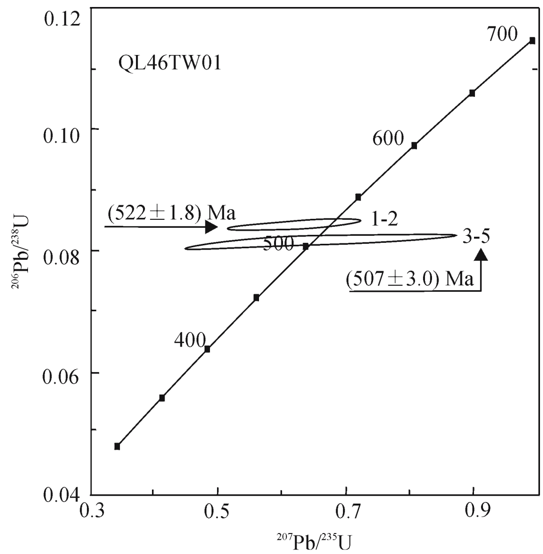

Fig. 7 Zircon U-Pb concordia diagram of the Liushuigou gneissic gabbro diorite (sample QL46TW01) from the Guanzizhen area, Tianshui

6 Tectonic significance

The geochemical characteristics of the Liushuigou intermediate-basic meta-igneous complex at Guanzizhen and the Baihua basic igneous complex in Tianshui indicate that

Table 2 TIMS single-grain zircon U-Pb age data for the Liushuigou gneissic gabbro-diorite (sample QL46TW01) from Guanzizhen

Sample feature		Mass number/(μg·g^{-1})			Common Pb/ng	Isotope ratio					Apparent age/Ma		
No.	Zircon feature	Weight/μg	U	Pb		$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1	Light yellow, transparent, hemi-pyramid	10	818	98	0.180	169	0.120 4	0.084 47 (32)	0.662 3 (358)	0.056 86 (289)	522.8	516.0	486.1
2	Yellow, transparent, hemi-pyramid	5	638	83	0.100	133	0.109 2	0.084 44 (84)	0.619 1 (848)	0.053 18 (691)	522.6	489.3	336.4
3	Light yellow, transparent, short pyramid	10	874	99	0.180	202	0.151 8	0.082 01 (78)	0.651 3 (245)	0.057 58 (199)	508.3	509.3	513.8
4	Yellow, transparent, dipyramid, short pyramid	5	520	120	0.240	53	0.137 5	0.081 92 (81)	0.738 4 (960)	0.065 38 (791)	507.6	561.5	786.4
5	Yellow, transparent, middle-long-prism	5	397	78	0.150	61	0.080 92	0.081 60 (108)	0.603 8 (1 286)	0.053 67 (1 084)	505.7	479.7	357.1
6	Light yellow, transparent, prism	10	550	71	0.190	118	0.081 90	0.080 23 (50)	0.580 0 (563)	0.052 43 (482)	497.5	464.5	304.2

Note: The zircon was analyzed for U-Pb isotopes and U, Th and Pb concentrations using TIMS at the Tianjin Institute of Geology and Mineral Resources. Analytical results: Nos. 1–2 dots yield $^{206}Pb/^{238}U$ weighted mean age of (522.8 ± 1.8) Ma; Nos. 3–5 dots yield $^{206}Pb/^{238}U$ weighted mean age of (507.5 ± 3.0) Ma; No. 6 spot yield $^{206}Pb/^{238}U$ weighted mean age of (504.5 ± 7.9) Ma they formed in an island-arc geological setting, and the gabbro-gabbro diorite-diorite and pyroxenite-gabbro diorite-diorite-quartz diorite igneous assemblages were formed in the island-arc setting. In the south of the island-arc igneous complex zone, the authors confirm the existence of Guanzizhen ophiolite, which is mainly distributed in the Guanzizhen–Wushan area of western Tianshui, and the Liziyuan–Muqitan–Xiajiaping region of southeastern Tianshui. The ophiolite is mainly composed of N-MORB characteristics meta-basalt and serpentinite, meta-pyroxenite, and meta-gabbro which occurred as a structure massif (Pei et al., 2004), and also attained the newly total rock Sm-Nd isochron age, which is (544 ± 47) Ma ($MSWD = 1.7$). This indicates that the forming time of ophiolite is mainly in the Early Cambrian. At the same time, the ophiolite zone extended westward to the north of the Wushan–Yuanyangzhen–Hualingou region, where meta-basalt and ophiolite (metaperidotite) and metapyroxenite, metagabbro also grew. The Liziyuan Group, to the south of the ophiolite zone, is the Early Paleozoic island-arc and fore-arc basin sedimentary-igneous assemblages, and the Caotangou Group of Ordovician is island-arc type calcalkalic intermediate-acidity assemblages of igneous-sediment in the Liqiao area in Tianshui. This implies that there was a paleo-ocean basin represented by the Guanzizhen ophiolite and the ancient volcano represented by island-arc type intermediate-basic igneous complexes of the Liushuigou in Guanzizhen, island-arc type basic-intermediate-acid igneous complex in Baihua and the Caotangou island-arc intermediate-acid igneous rocks–sedimentary rocks assemblages. All these represented paleovolcano-magma-island-arc zone of the active continental margin structure framework in the north of West Qinling, and supplied a significant geological basis to rebuild the north of West Qinling orogen frame during the Early Paleozoic period and the course of subduction-collision orogeny movement, also confirmed the conjoint relation of Qinling and Qilian orogens during the Early Paleozoic.

The zircon U-Pb isotopic TIMS age is (507.5 ± 3.0) Ma for the Liushuigou intermediate-basic meta-igneous complex in Guanzizhen of the Tianshui area reported by the authors, which indicates that the main forming time of island-arc type igneous complex in West Qinling is Late Cambrian, and the deadlines of paleo-ocean basin subduction which was represented by the ophiolite in Guanzizhen and that the forming time of volcano-magma island-arc were possibly during Late Cambrian–Early Ordovician.

Recently, Lu et al. (2003) reported that TIMS zircon U-Pb isotopic age was (514.3 ± 1.3) Ma for the Fushui island-arc type igneous complex rock body in Shangnan County, East Qinling area, and TIMS zircon U-Pb isotopic age is (523 ± 26) Ma for the Luohansi island-arc type in Fengxian County. Yang J S et al. (2002, 2003a, b) reported the SHRIMP zircon U-Pb age is (507 ± 38) Ma for ultra-high pressure eclogite and gneiss in the East Qinling. Xu et al. (2003) and Yang J S et al. (2003a) reported that the TIMS zircon U-Pb isotopic age is 515–486 Ma for Early Paleozoic volcano-magma island-arc zone in the northern margin of the Qaidam basin, and the TIMS and SHRIMP zircon U-Pb age is 495–440 Ma for ultrahigh pressure metamorphic (UHPM) belts in the northern margin of the Qaidam basin. These isotopic chronology evidences approach the subduction time of the early paleo-ocean basin that stands for ophiolite in Guanzizhen and island-arc type magmatism age. Thereby, it is believed that the Early Paleozoic Shangdan paleo-suture zone, East Qinling, which extends westward to the Tianshui area in the north of West Qinling (Liziyuan–Guanzizhen–Wushan ophiolite complex zone), could also further extend westward to join the subduction-collision zone of the northern margin of the Qaidam basin (Zhang E P et al., 1993; Pei, 1997; Yang J L et al., 2001; Zhang G W et al., 2001; Feng et al., 2002; Wang et al., 2002; Yang Z H et al., 2002; Yang J S et al., 2002, 2003a, b; Li et al., 2003; Xu et al., 2003; Pei et al., 2004). The subduction time that the paleo-ocean basin occurred and the forming deadline of the volcano-magma island-arc zone should be the Late Cambrian–Early Ordovician.

7 Conclusions

(1) The Liushuigou meta-intermediate-basic igneous complex rocks are mainly composed of metagabbro-gabbro diorite-diorite, in Guanzizhen of the Tianshui area on the northern zone of West Qinling, and the geochemical characteristics indicate that the meta-intermediate-basic igneous complex rocks formed in an island-arc structure setting. The Baihua meta-igneous complex is mainly composed of metapyroxenite-gabbro and gabbro diorite-diorite-quartz diorite-plagiogranite, and it composes a complete series of the homological magma crystal differentiation. The meta-basic-complex's geochemistry characteristics also indicate that they formed from a relatively paleo-island-arc setting.

(2) The TIMS zircon U-Pb isotopic age of the Liushuigou meta-intermediate basic igneous complex in Guanzizhen of the Tianshui area is (507.5 ± 3.0) Ma, which stands for the forming time of complex rocks, and also shows that the forming time is Late Cambrian for the island-arc type igneous on the northern zone of West Qinling. Meantime, it reveals that the deadline of the subduction of the paleo-ocean basin standing for the Guanzizhen ophiolite and occurrence of island-arc type magma activity is possibly Late Cambrian–Early Ordovician.

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