Research Article

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Detrital zircon trace elements from the Mesozoic Jiyuan Basin, central China and its implication on tectonic transition of the Qinling Orogenic Belt

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Abstract: The Qinling Orogen and the Jiyuan Basin constitute a basin-mountain system during the Early Mesozoic. Therefore, sediments from the Jiyuan Basin can be used to deduce the orogenic process of the Qinling Orogen. This paper attempts to use detrital zircon trace elements with ages ranging from the Late Carboniferous to the Middle Triassic that were obtained from the Jiyuan Basin to discuss the tectonic evolution of Qinling Orogen. On the tectonic setting discriminating diagrams, most grains are concentrated in convergent continental margins/orogenic settings, whereas the remaining samples (268 Ma, 265 Ma, 264 Ma and 254 Ma) are plotted in anorogenic field. Compared to the Early Paleozoic (400–500 Ma) zircons, 306 Ma and 281 Ma grains represent higher Th/Nb ratios, which might be related to the Mianlve oceanic crust subduction. The lower Th/Nb ratios containing 268 Ma, 265 Ma, 264 Ma and 254 Ma grains might indicate lithospheric extension subsequently. The final continent-continent collision between South China and North China blocks took place after the Middle Triassic (242 Ma).

Keywords: Zircon, Basin-mountain interaction, Subduction-collision transition, Mianlve Ocean

1 Introduction

Zircon has strong resistance to weathering and/or alteration during sedimentation, magmatism, and metamorphism. Therefore, zircon U–Pb ages, along with Hf and O isotopes, are widely used in earth science researches [1–4]. The trace element composition of magmatic zircon is strongly controlled by the composition of parental melts [5, 6]. Although some challenges exist like the complicated

trace element distribution in zircons, it can also be an indispensable tool that should be developed for application in discriminating the host rock types [5–9], magmatic evolution and metamorphism [10, 11], crustal evolution [12], reconstructing mountain-basin interaction [14, 15].

Many investigations, concerning detrital zircon chronology, have been successfully performed in the surrounding basins of the Qinling Orogen [4, 16–25]. The Qinling Orogen emerged as the closure of the Mianlve Ocean, which resulted in the final amalgamation of the South China Block and the North China Block [26, 27]. But the Mianlve suture is now largely buried by later long-distance overthrusting [28, 29]. Therefore, to investigate the tectonic evolution of the Mianlve Ocean seems difficult. However, the Late Paleozoic detrital zircons largely preserved in the surrounding basins of the Qinling Orogen are suggested to be related to the Mianlve suture zone [18]. These zircons can be a good object to collect some important information about the development of the Mianlve Ocean. In addition, provenance analysis of the Late Paleozoic sediments on the southern North China Block reveals that the tectonic uplift of the Qinling Orogen retreated during the Permian [20, 30–33]. However, there is a lack of data describing the Permian tectonic transition of the Qinling Orogen.

There are some important achievements regarding interactions between Jiyuan Basin and Qinling Orogen during Middle Triassic to Middle Jurassic. These works mainly focus on the filling feature of sediments [34, 35], geochemistry of mudstones [36, 37], detrital zircon geochronology and Hf isotopes [24, 33, 38], and suggest that the Late Triassic was the critical period to the formation of the Jiyuan Basin controlled by the Qinling orogenesis. This paper focuses on the detrital zircons from the Middle Triassic–Middle Jurassic Jiyuan Basin and integrated zircon geochronology with geochemistry, to unravel the evolutionary process of the Mianlve Ocean during the Late Paleozoic to the Middle Triassic.

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Figure 1: (a) the location of the Qinling Orogen and the Jiyuan Basin in China. (b) schematic tectonic map of the Qinling Orogen and the surrounding basins. (c) geological sketch map of the Jiyuan Basin defined by the Mesozoic strata, and showing the sampled location.

2 Geological setting

The Qinling Orogen is expressed as the South China, Qinling, and North China blocks converged along the Shangdan and Mianlve suture zones [26, 27]. These two sutures, integrated with the Luanchuan fault, separate the Qinling Orogen into the North Qinling and the South Qinling belts (Figure 1-a, b).

The Shangdan Ocean is considered to be formed at least before the Cambrian [26]. The northward subduction of the Shangdan Ocean plate didn't happen until the early time of Cambrian [39–41]. A large number of subduction-related intrusions, mainly concentrated at 514–420 Ma, are found in the North Qinling Belt [27, 42]. The closure of the Shangdan Ocean, constrained by the detrital zircons from the Liuling Group [43], is considered to have occurred in the Early Devonian. Thereafter the North Qinling Belt was exhumed and denudated [44], however the deposition continued on the South Qinling Belt. A continent-continent subduction model, expressed as the subduction of the South Qinling Belt underneath the North Qinling Belt, is proposed to visualize the tectonic evolution along the Shangdan suture during the Late Paleozoic [26, 27].

The Mianlve Ocean might be formed at the Devonian and constrained from expanding before the Carboniferous [27, 40]. The island-arc volcanics from the Permian

to Early Triassic indicate the subduction of the Mianlve Ocean along the southern margin of the South Qinling Belt [45, 46]. The Mianlve Ocean closed at the Late Triassic, which resulted in the Triassic orogeny between the South China Block and the North China Block [47]. The syn-collisional granites with the ages of 220–210 Ma are largely distributed in the South Qinling Belt [48], and the post-collision process occurred subsequently during ca. 210–200 Ma.

The Jiyuan Basin is located to the north of Qinling Orogen, and adjacent to the Taihang Mountains (Figure 1-b, c). During the Early to Middle Triassic, the Jiyuan Basin was an intracratonic terrestrial depression in the south margin of the North China Block and developed a suit of red beds with stable distribution [35, 49, 50]. The Liujiagou Formation in the low part of the Early Triassic strata mainly represents several layers of light red conglomerates intercalated in purple red thick-bed middle-fine grained sandstones and thin-bed mudstones. The Heshanggou Formation in the upper part of the Lower Triassic strata is composed of bright red siltstones and mudstones with incidental fine grain conglomerates. The Middle Triassic strata can be divided into two formations by the occurrence of green mudstones. The lower part named Ermaying Formation is characterized by grayish yellow sandstones interbedded with purple red siltstones and mudstones, whereas the up-

Figure 2: Measured section from the Middle Triassic to Middle Jurassic Youfangzhuang, Chunshuyao, Tanzhuang, Anyao, Yangshuzhuang and Mao formations.

per part named Youfangzhuang Formation contains yellow green fine grained sandstones interbedded with purple red and green siltstones, muddy sandstones and sandy mudstones. As the South China Block collided with the North China Block in the Late Triassic, the eastern part of North China Block was extensively uplifted, whereas the western part underwent tectonic subsidence [34, 35, 51]. Continuous deposition occurred in the Jiyuan Basin forming the Chunshuyao and Tanzhuang formations in ascending order. Both of the formations represent gray yellow fine-grained sandstones, siltstones, sandy mudstones and mudstones, but the Tanzhuang Formation contains 9-10 layers of black oil shales. Great changes took place in the depositional environment, sedimentary sequence

and petrographic features, which indicated the tectonic attribute of Jiyuan Basin alternated from a part of intracraton to a foreland basin [34, 35, 51]. The lithofacies evolved into thick conglomerates and coal beds in the southern part of the Basin and lacustrine turbidites in the northern part of the Basin were controlled by the intense thrusting of Qinling Orogen during the Early Jurassic [52, 53]. This unit named the Anyao Formation mainly consists of gray yellow thick layered fine-grained sandstones, gray green mudstones, muddy sandstones and siltstones. The Middle Jurassic Yangshuzhuang Formation records a sequence of a shore-shallow lacustrine sedimentary system, with gray yellow and gray green mudstones, intercalated with yellow muddy sandstones, siltstones and fine-

Figure 3: The relative probability density diagrams of detrital zircon U-Pb ages for the analyzed samples [24]. (a) detrital zircon U-Pb ages from the Middle Triassic Youfangzhuang Formation; (b) detrital zircon U-Pb ages from the Late Triassic Chunshuyao Formation; (c) detrital zircon U-Pb ages from the Late Triassic Tanzhuang Formation; (d) detrital zircon U-Pb ages from the Early Jurassic Anyao Formation; (e) detrital zircon U-Pb ages from the Middle Jurassic Yangshuzhuang Formation; (f) detrital zircon U-Pb ages from the Middle Jurassic Maa Formation.

grained sandstones. The Jiyuan foreland basin was closed in the late Middle Jurassic as the Taihang Mountains uplift. The Maa Formation, unconformable to the underlying Yangshuzhuang Formation, was formed during this period, and represented a series of coarse quartz sandstones in the lower part and green mudstones in the upper part.

3 Zircon geochronology

The sedimentary evolution history suggests that the Jiyuan foreland basin developed from the Late Triassic to the Early Jurassic [35, 37], which should theoretically preserve sediments derived from the Qinling Orogen. Therefore, detrital zircon samples mainly concentrated on this period,

but two samples are collected from the Middle Triassic Youfangzhuang Formation and Middle Jurassic Maa Formation respectively to have a comparison between each stage of the basin-mountain interaction (Figure 2). Samples from the Youfangzhuang and Chunshuyao formations are medium-grain sandstones, but fine-grain sandstones from the Tanzhuang, Anyao and Yangshuzhuang formations, whereas a sample from the Maa Formation represents coarse-grain sandstone.

Sample preparation and test procedure were given by Yang *et al.* [24]. Off-line conversion of signals into isotope ratios, ages, and geochemical data were conducted by software ICPMSDataCal [54, 55]. Concordia diagrams and weighted mean age calculations were generated by using the Isoplot 3.0 software [56]. Six detrital zircon sam-

Figure 4: Relative probability of detrital zircon U-Pb ages from the surrounding basins of Qinling Orogen. (a) Middle Triassic-Middle Jurassic sediments from Jiyuan Basin [24]; (b) Late Triassic sediments from Erdos Basin [4, 23]; (c) Jurassic sediments from Hefei Basin [66]; (d) Late Triassic sediments from Songpan-ganzi Basin [22]; (e) Middle-Late Triassic sediments from Sichuan Basin [19]; (g) Jurassic sediments from Huangshi basin [67]; (f), (h) referenced from Yang *et al.* [24].

ples yielded a total of 444 available ages (more than 90% concordance, discordance was defined as $100\% \times \text{abs} [1 - (^{206}\text{Pb}/^{238}\text{U} \text{ age}) / (^{207}\text{Pb}/^{235}\text{U} \text{ age})]$, Figure 3). They are plotted on a probability density diagram and can be characterized by the age peaks at: 2.5 Ga, 1.9 Ga, 840 Ma, 439 Ma, and 261 Ma, respectively (Figure 4-a). 2.5 Ga and 1.9 Ga represent the tectonic-magmatic events during the Late Neoproterozoic in North China Block [57, 58] and the development of Paleoproterozoic Trans-North China Orogen [59–62], respectively (Figure 4-f). 840 Ma and 439 Ma are associated with the Qinling Orogenic Belt (Figure 4-h). They represent the Neoproterozoic collisional event on the south margin of North China Block [48, 63] and the subduction-collision of Qinling Block with the North China Block along the Shangdan zone [64, 65], respectively.

Additionally, we suggest that the Late Paleozoic–Middle Triassic zircons with age peaks at 261 Ma are also related to the Qinling Orogen. The following arguments are considered: (1) although most opinions suggested that the Late Paleozoic detrital zircons delivered from the Inner Mongolia Palaeo-Uplift (the northern margin of North China Block) [30, 31, 38], the age peak of these zircons (290–300 Ma) is different with the samples from Jiyuan Basin. (2) 400–500 Ma detrital zircons not only exist largely in the Carboniferous Benxi Formation in the North China Block [32], but also in the overlying strata Taiyuan Formation with the extra 900–1000 Ma detrital zircons [38]. These dates suggest that the North Qinling was a highland during the Late Carboniferous and Early Permian. Although provenance analysis of Early-Middle Permian strata revealed

Figure 5: Magmatic genesis zircons discriminating diagrams. (a) zircon age and Th/U relationship diagram; (b) The overabundance of the LREE discriminating diagram. Igneous zircon fields data are from [5]; (c), (d) magmatic zircon and hydrothermal zircon discriminating diagrams. Color-shaded fields of "magmatic" and "hydrothermal" are from Hoskin [77].

that the source area was converted to the north margin of the North China Block [38], the detrital composition statistics from the Upper Permian sandstones represented high quartz and feldspar content, indicating arc orogen sources [34]. This fact confirmed that the Qinling was uplifted in the Late Permian (253 Ma), which was in accordance with the progradational delta deposit system developing on the south margin of North China Block [34]. As the Qinling Orogen continuously uplifted in the Triassic [35], a large amount of sediment sourced from the Qinling Orogen is preserved in the Early Triassic strata [33]. Therefore, the Qinling Orogen was certainly an important source to the

Jiyuan Basin as the mountain building after the Middle Triassic. (3) The Late Paleozoic materials were found in the surrounding basins of Qinling Orogen, such as the Ordos Basin [4, 23] (Figure 4-b), Hefei Basin [66] (Figure 4-c), Songpan-Ganzi Basin [22] (Figure 4-d), Sichuan Basin [18, 19] (Figure 4-e), Huangshi Basin [67] (Figure 4-g), and also the internal basin of the Qinling orogen [68]. Qian *et al.* [18] suggested that these zircons might derive from the Mi-anlve suture zone, which were now largely buried by later long-distance overthrusting [28, 29].

4 Zircon trace elements

62 Late Paleozoic-Middle Triassic detrital zircons were compared with 36 Early Paleozoic (500-400Ma) zircons to evaluate the tectonic significances, because the Early Paleozoic zircons might provide valuable information in subduction and collision [46]. However, many restrictive factors, such as apatite and monazite inclusions, metamorphism, secondary alteration, and metamictization, make the difficulties for zircon trace elements interpretation [10, 11, 69]. Therefore, it is important to distinguish magmatic zircons from LREE overabundance zircons, metamorphic zircons, and hydrothermal zircons.

Metamorphic zircon experiences a complex elementary process of solution and reprecipitation, substitution, and diffusion [5, 70, 71]. Therefore, magmatism signatures are hardly deciphered by metamorphic zircon trace elements. Metamorphic zircons usually show considerably lower Th/U, which can be a criterion to distinguish magmatic zircon from metamorphic zircon [11, 72, 73]. Figure 5-a shows the selected zircons with Th/U > 0.1.

REE pattern of zircons is distinctly influenced by the existence of garnet, monazite and feldspar under various metamorphic conditions [74–76]. Therefore, abnormal REE patterns of zircons, such as LREE-overabundance or HREE-depleted, should be removed. In addition, LREE-overabundance is not always displayed on the chondrite-normalized REE distribution diagram. La_N and $\Sigma LREE$ (La, Ce, and Pr) values are suggested to illustrate whether the LREE is over enriched (Figure 5-b).

Various trace element compositions of hydrothermal zircon can be formed in similar geological and geophysical conditions, which cause considerable difficulties for the trace elements interpretation [5]. $(Sm/La)_N$ -La and Pr_N -La_N diagrams can be used to distinguish hydrothermal zircon from magmatic zircon [77] (Figure 5-c, d).

On the basis of the foregoing works, the remaining zircons contain 27 grains with ages ranging from the Late Carboniferous to the Middle Triassic and 23 Early Paleozoic grains. LA-ICP-MS trace element data for these zircons are listed in Table 1. They possess steep chondrite-normalized REE patterns with positive Ce and negative Eu anomalies (Figure 6), and high Th/U (Th/U = 0.28-2.35), which are indicative of derivation from an igneous source [5, 78].

Figure 6: Rare earth element (REE) concentrations normalized to chondrite [98] for magmatic genesis zircons.

5 Discussion

5.1 Provenance signatures of zircons

Grimes *et al.* [13, 79] suggested Hf and Y versus U/Yb diagrams to discriminate zircons crystallized in oceanic crust from continental zircon. Further contribution had been done to introduce various tectonic settings to these diagrams [14], which was beneficial to detrital zircon provenance analysis. Figure 7-a and b show that most of the zircon samples are plotted in convergent continental margins. Little of them are present in the mixed field of convergent continental margins and post-collision extensional settings. Yang *et al.* [15] proposed two discriminating diagrams, Th/U versus Nb/Hf and Th/Nb versus Hf/Th, to understand the tectonic settings (Figure 7-c, d). The results show that most of zircon samples are plotted in an arc/orogenic-related field, while 264Ma sample indicates a within-plate/anorogenic setting. There are also several grains, including 268 Ma, 265 Ma and 254 Ma samples, falling in the mixed field.

Barth *et al.* [80] suggested that the Th/Nb ratio could be used to discriminate zircons crystallized from arc-related magmas, MORB (mid ocean ridge basalt), and OIB (oceanic island basalt) lavas. Compared to the Early Paleozoic (400-500Ma) zircons mainly formed under the subduction-collision setting [41, 46], 306Ma and 281Ma grains with higher Th/Nb ratios may reflect arc-related magmas with more differentiated materials. Grains of 268 Ma, 265 Ma, 264 Ma and 254 Ma with lower Th/Nb ratios indicate the enhanced involvement of mantle materials (Figure 8).

Table 1: LA-ICP-MS analytical results (ppm) of magmatic origin zircon trace elements with the ages ranging from the Late Carboniferous to the Middle Triassic from the Jiuyuan basin, China.

Sample No.	$^{206}\text{Pb}/^{238}\text{U}$ Age(Ma)	1σ	Pb	Th	U	P	Ti	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf
J-m-5-8	222	5	8.9	90	203	110	6.9	197	0.73	0.042	18.1	0.06	0.55	1.03	0.29	4.3	1.4	16	6	29	7	72	16	12408
T-c-5-8	242	2	28.1	440	565	87	3.1	635	1.10	0.227	31.6	0.28	2.44	3.67	1.62	13.9	4.4	49	19	90	21	230	56	11393
J-m-12-2	243	4	5.6	103	114	196	15.8	363	1.00	0.011	25.2	0.06	1.43	2.42	0.78	11.6	3.5	35	12	50	10	98	20	10150
T-y-6-7	249	3	19.1	405	348	225	4.8	1105	2.02	0.085	51.8	0.38	6.31	8.79	3.03	31.5	9.0	99	35	157	35	350	72	11459
J-m-11-2	254	4	6.3	100	124	234	2.3	1135	6.36	0.180	24.2	0.15	1.49	5.05	0.04	26.4	9.4	109	42	174	35	316	60	10292
J-m-1-7	255	3	16.1	204	317	134	4.7	781	0.56	0.048	12.6	0.15	2.30	4.66	1.26	18.9	6.2	69	25	115	26	255	55	10720
T-c-6-9	255	2	23.9	336	474	408	12.9	1860	3.93	0.064	30.0	0.24	4.27	7.16	2.36	38.8	12.9	163	64	288	62	580	111	8713
J-m-10-1	259	3	7.9	35	178	43	1.6	116	0.18	0.002	1.1	0.00	0.18	0.31	0.08	1.6	0.5	7	3	18	5	57	14	10953
J-m-10-6	259	3	14.2	268	264	374	8.3	1827	3.23	0.047	19.2	0.33	5.14	8.72	1.57	43.0	13.2	165	64	287	59	543	110	7991
J-m-7-6	263	4	8.8	136	172	258	13.0	803	0.99	0.016	13.6	0.06	1.40	3.01	0.59	17.5	5.7	70	26	119	25	235	48	11242
J-m-8-3	264	3	9.5	119	188	355	7.3	785	1.36	0.007	12.9	0.04	0.49	1.87	0.33	13.6	5.0	62	26	123	27	257	52	12331
J-m-6-4	264	3	18.1	225	360	313	2.6	2478	11.76	0.042	44.9	0.18	4.28	10.80	0.48	69.8	24.1	278	99	400	72	574	101	8146
J-m-2-6	264	3	25.1	188	513	89	1.9	389	0.63	0.070	8.7	0.04	0.78	0.65	0.23	4.4	1.7	24	11	61	16	192	46	13814
T-y-2-8	265	4	8.1	179	132	324	11.2	1162	1.69	0.036	28.4	0.19	2.35	5.96	1.51	28.6	9.4	108	39	179	38	362	72	10247
J-m-1-5	265	3	13.4	193	249	192	2.6	1530	6.36	0.014	24.1	0.12	1.97	5.80	0.03	35.2	12.7	152	57	242	48	415	78	9735
J-a-10-4	266	26	13.1	271	223	304	5.7	137	1.62	0.070	29.9	0.23	3.57	6.11	1.92	25.3	7.9	96	37	175	41	425	90	10778
T-t-7-8	268	2	24.6	226	498	591	1.0	1836	8.09	0.002	20.5	0.05	1.23	4.28	0.14	30.7	11.6	151	63	300	69	694	137	11864
T-y-3-3	272	4	10.9	169	193	233	6.6	750	2.89	0.009	55.6	0.12	1.87	3.65	1.22	18.4	5.5	67	25	117	26	250	52	10174
J-m-1-1	275	3	17.8	220	393	224	2.5	892	1.82	0.039	14.6	0.07	0.91	2.46	0.45	14.0	5.3	68	28	140	33	326	70	10738
J-m-4-8	277	3	17.3	204	325	353	6.4	1269	0.90	0.198	12.5	0.22	3.14	4.75	1.30	26.1	8.5	104	42	196	44	438	90	10861
T-t-3-3	280	4	17.6	182	335	273	5.2	810	1.10	0.020	9.8	0.07	1.30	2.67	0.49	13.2	4.6	63	26	126	29	283	59	11413
J-m-7-1	281	3	41.0	952	625	249	1.4	1375	0.12	0.109	10.1	0.34	5.66	7.59	4.36	32.1	10.3	117	43	200	45	461	96	4863
T-y-6-8	284	3	39.3	558	668	310	1.9	2346	3.30	0.071	33.8	0.45	8.32	13.13	2.87	60.9	19.1	216	79	358	78	740	147	10671
J-m-6-2	306	4	11.8	199	181	111	5.2	382	0.17	0.024	4.8	0.09	1.19	1.82	1.40	8.4	2.6	32	12	60	14	158	36	9160
T-c-6-8	307	3	27.3	171	495	226	4.1	1274	4.45	0.044	27.2	0.08	0.94	2.66	1.57	17.6	6.5	86	38	201	51	561	128	11463
T-t-11-7	312	4	17.7	483	205	478	4.2	2296	4.34	0.198	73.0	1.06	13.87	20.81	8.73	86.4	24.2	251	84	336	67	582	108	9544
T-c-6-6	334	3	39.4	561	539	257	6.9	1683	7.07	0.184	79.8	0.52	7.74	12.03	3.19	45.2	14.2	158	56	244	51	477	90	10129
T-t-1-6	359	4	12.8	101	186	202	5.2	1462	1.10	0.013	4.8	0.17	4.15	8.91	0.87	40.2	13.0	146	53	221	43	381	73	10130
T-t-3-5	361	4	16.8	241	214	326	13.1	1261	1.81	0.114	27.9	0.30	3.42	6.12	0.86	31.2	9.5	111	42	183	37	337	65	11948
J-y-3-2	374	3	39.1	298	532	212	3.5	859	4.61	0.008	44.4	0.03	0.60	1.94	0.47	12.1	4.8	64	27	137	32	338	73	11479
T-t-2-6	383	5	15.3	229	177	391	4.2	1505	2.07	0.014	30.3	0.38	6.07	9.61	3.70	43.3	12.3	139	50	222	48	464	99	10694
J-a-4-6	384	4	13.2	140	165	170	5.8	530	2.22	0.032	27.0	0.05	0.19	1.87	0.42	9.7	3.4	41	17	82	20	207	42	10688
J-y-7-4	388	3	30.5	264	386	467	4.8	1288	2.23	0.006	38.0	0.07	1.96	4.42	1.27	23.9	8.2	103	42	202	45	446	95	10441
J-m-5-4	393	5	50.4	325	674	289	4.8	1130	3.05	0.183	16.2	0.94	7.33	7.68	2.42	26.9	9.1	102	37	168	37	340	70	11293
J-y-9-6	406	3	61.8	476	758	312	6.6	984	7.59	0.052	54.5	0.23	2.75	3.13	0.65	16.4	6.3	77	32	153	36	355	72	11881
J-y-1-3	421	6	8.9	72	104	204	12.8	398	0.90	0.005	14.4	0.04	0.65	1.32	0.35	7.8	2.8	34	13	60	14	131	27	11111
J-y-9-2	421	5	30.9	257	369	271	10.0	778	1.48	0.010	21.2	0.10	1.63	3.14	0.92	15.7	5.3	61	24	118	28	275	59	10484
J-y-2-5	421	5	11.6	134	122	320	10.2	660	0.66	0.002	28.9	0.12	1.88	4.29	1.27	17.9	5.2	59	21	95	20	196	41	10352
J-y-11-2	421	5	21.9	317	216	221	14.0	880	0.90	0.049	29.7	0.67	10.76	13.55	5.17	40.1	10.0	94	30	114	23	207	40	8473
J-y-16-1	423	4	50.7	341	631	115	2.1	615	1.47	0.042	30.2	0.09	1.73	2.76	1.33	13.0	3.8	46	18	88	21	229	52	11101

Table 1: ... continued

Sample No.	$^{206}\text{Pb}/^{238}\text{U}$ Age(Ma)	1σ	Pb	Th	U	P	Ti	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf
J-y-3-4	429	4	21.2	188	234	210	10.8	1172	0.75	0.002	9.4	0.23	3.56	5.86	0.67	25.0	8.6	101	40	178	37	335	68	10809
J-y-8-3	432	6	10.6	121	111	262	18.8	1258	0.77	0.037	16.9	0.40	5.76	8.92	1.88	35.2	10.6	119	43	180	36	331	66	10000
J-y-12-1	436	5	11.1	107	119	169	6.1	792	0.85	0.044	19.1	0.27	3.96	5.34	2.25	23.5	6.6	69	25	114	25	252	55	10190
J-y-6-2	436	6	10.3	80	115	236	10.3	537	1.53	0.002	15.8	0.04	0.47	1.25	0.30	8.5	3.3	43	17	83	19	187	39	11572
J-y-5-4	438	6	9.7	74	107	343	10.0	579	0.37	0.010	16.9	0.05	0.96	1.96	0.63	11.3	3.9	46	18	86	19	194	42	10980
J-a-3-2	440	4	53.4	244	641	195	0.5	833	2.08	0.045	7.9	0.04	0.93	1.73	0.23	11.2	4.4	60	26	136	33	342	73	12360
J-y-7-1	446	5	46.4	284	538	255	6.0	687	1.99	0.226	15.1	0.48	3.69	3.41	1.10	11.7	3.9	49	20	108	27	297	71	10991
J-a-2-4	459	4	55.0	181	635	1989	10.6	3196	3.03	0.122	4.6	0.14	2.10	6.94	0.17	51.2	21.4	283	114	525	111	1002	182	13212
J-y-2-4	463	5	32.3	332	309	415	17.6	821	1.30	0.050	30.7	0.33	5.04	5.59	1.90	21.1	6.1	69	27	123	26	254	54	9801
J-y-17-2	474	6	8.1	49	88	170	6.7	362	0.95	0.006	7.0	0.01	0.38	0.93	0.43	5.2	1.8	25	11	59	15	175	43	9945
J-y-4-1	511	6	16.5	159	140	182	19.9	392	2.22	0.006	28.4	0.14	2.31	4.18	0.65	15.1	4.3	41	14	54	10	90	16	10667

Figure 7: The possible tectonic settings of magmatic genesis zircons. Zircon Hf and Y vs. U/Yb diagrams from Grimes *et al.* [13] and Gao *et al.* [14]; Zircon Th/U vs. Nb/Hf and Th/Nb vs. Hf/Th diagrams from Yang *et al.* [15].

Figure 8: Th/Nb against the detrital zircon ages diagram.

The Late Carboniferous - Middle Triassic zircons were largely persevered in the Late Paleozoic - Middle Triassic strata in the North China Basin [24, 30–33, 38]. Some authors argued that these zircons were sourced from the Inner Mongolia Palaeo-Uplift in the north margin of the North China Block. The Inner Mongolia Palaeo-Uplift experienced crustal contraction related to the collision of the North China Block and the Mongolia terrane during the Middle Permian, and crustal extension caused by upwelling of calc-alkali magma at the end of the Permian [81]. Another controversial source area is the Xingmeng Orogen (the south margin of the Central Asian Orogenic Belt) along the north margin of the North China Block. Two main arguments had been proposed to explain the tectonic evolution of the Xingmeng Orogen: (1) the north margin of North China Block was an Andean-style continental margin at the Late Carboniferous, which represented the subduction of the paleo-Asian oceanic plate beneath the North China Block. Postcollisional/postorogenic lithospheric extension occurred after the final collision between the Mongolian arc terranes with the North China Block during the Late Permian-Middle Triassic [82–84]. (2) The Xingmeng Orogen was generated at the Middle Devonian, and then stepped into the post-collision at the Late Devonian-Early Carboniferous [85–87]. These tectonic evolutionary models are not consistent with the result of the zircon trace element analyses in this paper, which indicates that the Late Carboniferous - Middle Triassic zircons mainly crystallized from the subduction-collision/orogenic setting, only a few of them (zircon ages of 268 Ma, 265 Ma, 264 Ma and 254 Ma) displayed an extensional/anorogenic environment. For these perspectives, the Late Carboniferous - Middle Triassic detrital zircons are most likely derived from the Qinling Orogen along the south margin of the North China Block, which is consistent with the detrital zircon age analyses as discussed above.

5.2 Development of the Mianlve Ocean

The Mianlve Ocean is interpreted as a remnant branch of the Palaeo-Tethys Ocean that rifted from the north margin of the South China Block. Most scholars believed that the Mianlve Ocean developed from the Late Paleozoic to Middle Triassic [26, 27]. Therefore, the most probably source of the Late Carboniferous - Middle Triassic detrital zircons are related to the Mianlve suture zone [18], which in turn can be used to decipher the tectonic evolution of the Mianlve Ocean.

According to the zircon trace element analyses, continent-continent subduction between the South Qin-

ling Belt and the North Qinling Belt could generate more differentiated materials before the Early Permian (281Ma). After that, the subduction of the Mianlve Ocean was formed, which could weaken the continent-continent subduction [26, 27]. Then afterwards, some mantle materials could intrude into the upper crust at the Middle Permian (268Ma), which could result in extension of the lithosphere restrictedly. This tectonic regime may be lasting to the Early Triassic (254Ma). The final continent-continent collision between South China and North China blocks took place after the Middle Triassic (242Ma) (the formation of mostly granites occurred in subduction zones and post-collision extensional settings, [46]), then the Qinling Orogen stepped into mountain building. This evolution process can be responded by the Late Paleozoic paleogeography of the southern North China Block. Provenance analyses indicated that the Qinling Orogen was a highland during the Late Carboniferous to Early Permian [31, 32]. This topographic feature constrained transgression had to take place from the northeast of the North China Block at the Late Carboniferous. However, topographic conversion occurred at the Middle Permian, which could be certified by the transgression originated from the southeast of the North China Block and the fluvial delta extended from north to south [88, 89]. We attributed the subsidence of southeastern edge of the North China Block (including the Qinling Orogen) to the extension occurred in the Qinling Orogen. Marine deposits ending at the Early Triassic might be related to the continuous subduction of the Mianlve Oceanic plate. In addition, Wang *et al.* [20] reported detrital zircon U-Pb ages from the Middle - Late Permian sediments in the southern North China Block. Their data suggests that the south margin of the North China Block and the Qinling Orogen subsided during the Middle Permian, and subsequently uplifted during the late Late Permian. This conclusion supports the viewpoint from the zircon trace elements in this paper.

Many other geologic records have also been listed to demonstrate the Late Paleozoic oceanic subduction in the Qinling Orogen, such as subduction-related deformation [90], zircon trace elements and types of mineral inclusions [91, 92], Permian-Triassic HP metamorphic terrane in the Tongbai Orogen [93], muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained from the Nanwan flysch (262 ± 2 Ma) and the Foziling Group (271 - 261 Ma) [62, 94], and the island-arc volcanics from the Permian to Early Triassic along the south margin of the South Qinling Belt [45, 95, 96]. In addition, the Late Paleozoic-Early Triassic trough in the Qinling Orogen might be the response to the extension [96, 97].

In summary, the Qinling Orogen was a highland during the Late Carboniferous, which should be related to the

Early Paleozoic tectonic framework or the initial subduction of the Mianlve Ocean (Figure 9-a). The lithospheric extension could be understood as back-arc spreading, which made the Qinling Orogen and the south margin of North China Block subsided (Figure 9-b). However, the continuous subduction of the Mianlve Ocean was existence and caused the strong uplift of the Mianlve suture zone (Figure 9-c). The lithospheric extension disappeared in the Middle Triassic, and then the continent-continent collision occurred in the Qinling Orogen (Figure 9-d).

Figure 9: Possible supplement of the sediments to the interior of the North China Block, and showing the tectonic uplift model of the Qinling Orogen. (Revised after Zhu *et al.* [31]). IMPU: Inner Mongolia Palaeo-Uplift; MO: Mianlve Ocean; NCB: North China Block; NQ: North Qinling Belt; SQ: South Qinling Belt; YZB: South China Block.

6 Conclusion

1. According to the analyses of magmatic zircon trace elements, most Late Carboniferous - Middle Triassic grains crystallized from convergent/orogenic tectonic settings. Only a small number of grains indicate extensional/anorogenic tectonic environments. The process of magmatism and tectonic evolution, proposed by the zircon trace elements, is different with that of the north margin of North China Block but similar to the Qinling Orogen. Integrated with detrital zircon age analyses, it is convincing that the Late Carboniferous - Middle Triassic detrital zircons are related to the Qinling Orogen rather than the north margin of the North China Block.
2. The subduction of Mianlve Ocean was already formed before the Early Permian (281Ma), which induced the limited lithospheric extension subsequently. The final continent-continent collision between South China and North China blocks took place after the Middle Triassic (242Ma).

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