Geochemical fingerprints and pebbles zircon geochronology: Implications for the provenance and tectonic setting of Lower Cretaceous sediments in the Zhucheng Basin (Jiaodong peninsula, North China)

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This paper conducts a petrogeochemical analysis of the Lower Cretaceous Laiyang Group's sandstones, compares the results with the Neoproterozoic and Mesozoic intrusive rocks in the southern Sulu Orogen (also called the Jiaonan Orogen), and performs an LA-ICP-MS zircon geochronology analysis of the granitic gneisses in the conglomerates of the Laiyang Group and the intrusive rocks in the Jiaonan Orogen. The results show that the major element proportions of the Longwangzhuang Formation (LWZ Fm) and Qugezhuang Formation (QGZ Fm) of the Laiyang Group in the Zhucheng Basin are similar. The values of various indices for the LWZ Fm are similar to the average sandstone content of active continental margins, whereas, the values for the QGZ Fm are similar to those of continental island arcs. The comparison shows that the REE characteristics of the LWZ Fm and QGZ Fm of Laiyang Group are similar to those of the Neoproterozoic granitic gneisses in the Jiaonan Orogen but obviously different from those of the Early Cretaceous intrusive rocks. A tectonic setting discrimination diagram reveals that the provenance of the Laiyang Group includes features of active continental margins and continental island arcs. A number of indicators, e.g., the sandstone type, the Chemical Index of Alteration, the Chemical Index of Weathering, the Plagioclase Index of Alteration and the Index of Chemical Constituent Variation, indicated that the sandstones did not undergo intense weathering and were deposited near the source area. The zircon ages of the granitic gneiss material in the conglomerates at the base of the Laiyang Group are 790 ± 8.4 Ma, close to the ages of the Neoproterozoic granitic gneiss in the Jiaonan Orogen (739–819 Ma), and very different from the ages of the Early Cretaceous intrusive rocks. Combining with paleocurrent directions, geochemical character, the Neoproterozoic granitic gneisses in the Jiaonan Orogen may represent the primary provenance of the Laiyang Group in the Zhucheng Basin. During the depositional period of the Laiyang Group, the source rocks did not experience intense weathering, which indicated the Jiaonan Orogen experienced rapid uplift during this time, and coincided with the high exhumed rate of 2.0 km Ma^{-1} from before *ca.* 128 to 123 Ma in Jiaonan Orogen. The rapid subsidence during the formation of the Laiyang Group in the Zhucheng Basin and the rapid uplift of the Jiaonan Orogen are the result of a single regional extensional event associated with the lithospheric thinning and destruction of North China and peripheral cratons.

Keywords. Jiaodong peninsula; Sulu Orogen; Zhucheng Basin; Early Cretaceous; sandstones; petrogeochemistry.

1. Introduction

The North China Craton experienced a series of plate collision–suture activities between the late Paleozoic and the early-middle Mesozoic (Xiao *et al.* 2003; Suo *et al.* 2012). As the South China Block (SCB) subducted underneath the North China Craton and collided with it, the Qinling–Dabie–Sulu Orogen was formed in southern North China (Xu *et al.* 2009; Wang *et al.* 2012) (figure 1). Following this collision–suture process along its southern boundary, the North China Craton experienced intra-continental compressional deformation in the late Jurassic followed by extension (Ren *et al.* 2002), forming extensive extensional structures, such as rifted basins (Billia *et al.* 2013) and metamorphic core complexes (Liu *et al.* 2005, 2013) (figure 1).

Basins and orogens have constituted two basic tectonic units at the surface of the North China Craton since the late Mesozoic (Erikson *et al.* 2012; Luo *et al.* 2012; Holt *et al.* 2015). Researchers have primarily studied the basins that developed in the front edge of the orogeny, such as the Hefei Basin and Dabie Orogen, to identify the provenance characteristics and evolutionary history (Grimmer *et al.* 2003; Wang *et al.* 2003; Meng *et al.* 2007).

The Sulu Orogen, usually viewed as the eastern extension of the Dabie Orogen (Li *et al.* 2002, 2009, 2012), is developed on the eastern side of the famous Tan-lu Fault (figure 1). The Cretaceous Jiaolai Basin developed along the Sulu Orogen's northern margin (Zhang *et al.* 2003) provided a comprehensive window to understand the uplift and evolution processes of the Sulu Orogen. The Cretaceous Zhucheng Basin is located on the southern margin of the Jiaolai Basin and is adjacent to the Jiaonan Orogen (also referred to as the southern Sulu Orogen) (figure 2a). The Jiaonan Orogen is famous for its abundant eclogites (Chen *et al.* 2010; Wang *et al.* 2014), but the uplift rate of this orogen since the late Mesozoic is unknown. Additionally, few researchers have studied the relationship between this orogen and the Zhucheng Basin.

Many discoveries have been made by utilizing petrogeochemical analyses of the sandstones that developed in the frontal basins of orogens to determine the tectonic settings of the sandstone's formation, the provenance of the basins and the provenance tectonic settings (Adeigbe and Jimoh 2013; Billia *et al.* 2013; Ejeh *et al.* 2013; Ikhane *et al.* 2014). These studies provide another way to understand the features and evolution of basins and provenances. This paper focuses on samples from the Lower Cretaceous Laiyang Group of Zhucheng Basin, Jiaodong peninsula for sandstone petrogeochemical research to probe the source region's properties and paleo-weathering characteristics. This research is

combined with a study of the zircon geochronology of the sandstones to uncover the coupled relationship between the uplift of the Jiaonan Orogen and the subsidence of the Zhucheng Basin.

2. Geological setting

The Jiaodong peninsula lies along the south-eastern margin of the North China Craton (Charles *et al.* 2011a), to the east of Tan-lu Fault. The area includes three tectonic units: the Jiaobei Uplift, the Sulu Orogen and an Early Cretaceous extensional basin (Charles *et al.* 2011b; Tang *et al.* 2014; Wu *et al.* 2014) (figure 2a).

The Jiaobei Uplift consists primarily of meta-sedimentary rocks from the Archean basement (Jiaodong Group and Jingshan Group), Paleoproterozoic Fenzishan Group and Neoproterozoic Penglai Group (Webb *et al.* 1999; Zhang 2012) and upper Mesozoic unmetamorphosed magmatic rocks (Goss *et al.* 2010; Charles *et al.* 2011a; Ma *et al.* 2014) associated with the Linglong Metamorphic Core Complex (MCC) (Charles *et al.* 2011b).

The Sulu Orogen is primarily composed of Neoproterozoic felsic gneiss and granitic gneisses (739–819 Ma) (Hacker *et al.* 2006; Huang *et al.* 2006), Paleoproterozoic meta-sedimentary rocks (1.9–2.1 Ga) (Xie *et al.* 2015) (e.g., the Jingshan Group and Fenzishan Group), which experienced ultrahigh-pressure metamorphism (Hacker *et al.* 2006), and unmetamorphosed Mesozoic plutons (Guo *et al.* 2005; Yang *et al.* 2005) associated with the Wulian MCC, which developed along the Sulu Orogen's southern segment (the Jiaonan Orogen) (Ni *et al.* 2013). The vast majority of the outcropping Mesozoic plutons are Lower Cretaceous intrusive rocks (Yang *et al.* 2005) (figure 2a).

The late Mesozoic extensional basin, called the Jiaolai Basin by previous researchers, is primarily filled with Lower Cretaceous Laiyang Group sedimentary rocks (135–120 Ma), Qingshan Group volcanic rocks (120–105 Ma) and the Upper Cretaceous Wangshi Group (85–65 Ma) (Zhang *et al.* 2003; Li *et al.* 2008) (figure 2b).

The Zhucheng Basin is located on the southern edge of the Jiaolai Basin, with a NE–SW-oriented depocenter parallel to the Sulu Orogen, and the exposed basin's basement consists primarily of Neoproterozoic granitic gneiss (figure 2c). The Laiyang Group is universally present in the Zhucheng Basin and has a sedimentary contact relationship with the Neoproterozoic granitic basement and a maximum thickness of 6000 m. The Qingshan Group is a set of volcanic sedimentary rocks with uneven thicknesses and a maximum thickness of 3000 m. The Wangshi Group is locally distributed and is relatively thin (figure 2c).

Figure 1. Late Mesozoic and Cenozoic extensional basin and tectonic framework of North China and its adjacent areas.

The Laiyang Group is a set of fluvial-lacustrine facies deposits with widespread parallel bedding, graded bedding (figure 3a, b), rhythmic bedding (figure 3c) and trough cross-bedding (figure 3d). The rock types primarily consist of grey sandstones, secondary shales, conglomerates and locally interbedded volcanic rocks. The Laiyang Group can be divided into the Linshansi Formation (kl), Longwangzhuang Formation (LWZ Fm; klw), Qugezhuang Formation (QGZ Fm; klq) and Fajiyang Formation (klf) from bottom to top (figure 2d). Based on geochronological data from the amphiboles and zircons in the basalts that intruded into the Laiyang Group and fossil data, the formation

age of the Laiyang Group is approximately 135–120 Ma (Zhang *et al.* 2003). The Qingshan Group, in which the Bamudi Formation (kqb) primarily developed, is a set of andesitic volcanic rocks, which lies on an angular unconformity over the Laiyang Group (figure 2d).

3. Sample collection and analytical methods

3.1 Sample collection and paleocurrent directions

Geological profiles with relatively good outcrops were chosen along field trip routes. Sandstones

Figure 2. (a) Tectonic location map, (b) stratigraphic framework of the Cretaceous system, (c) simplified geologic map, (d) profile map of the Zhucheng Basin, and (e) paleocurrent directions rose diagrams. 1: Bamodi Formation in the Qingshan Group (Kqb); 2–5: Laiyang Group (K1L); 2: Fajiyang Formation (K1f); 3: QGZ Fm (K1q); 4: LWZ Fm (K1lw); 5: Linshansi Formation (K1l); 6: dioriticporphyrite; 7: monzonite; 8: Fenzishan Group; 9: Neoproterozoic granitic gneiss; 10: angular unconformity; 11: normal fault; 12: compressive shear fault; 13: extensional crushed zone; 14: detachment fault zone; 15: locations of samples or photographs; 16: stretching lineation; 17: gneissosity attitude; and 18: sedimentary rock attitude.

Figure 3. Photographs of the Laiyang Group's sedimentary rocks. (a) Conglomerate layer and a single-graded bed; (b) conglomeratic sandstone; (c) fine-grained sandstones interbedded with siltstone; (d) medium-grained sandstone with trough cross-bedding. The sample locations are shown in figure 2.

from close to the basin's basement westward to the Qingshan Group's volcanic rocks were collected for petrogeochemical analysis. The sampling sites were equally distributed (figure 2c).

Based on the collective features of the Laiyang Group, the sandstone in the Laiyang Group accounts for approximately 81–90% of the total thickness. The sizes of the grains influence the geochemical features of the sedimentary rocks (Pettijohn *et al.* 1972; Bhatia 1983); thus, the selection of sandstone samples for geochemical analysis should be based on the observation of specimens and thin sections. We collected 12 evenly medium- and fine-grained sandstones as analytical and test subjects. For comparison, we chose a small number of Neoproterozoic plutons and Mesozoic intrusions for the petrogeochemical analysis.

Conglomerate samples for zircon analysis were collected at the junction of the basin and orogen (figures 2c and 3a). We selected gravel samples (clast diameters >4 cm) from conglomerates with clasts composed of granitic gneiss and then selected zircon grains from granitic gneiss. For comparison, we chose Neoproterozoic granitic gneiss and Mesozoic intrusive rocks for the zircon geochronology tests (figure 2a).

According to the occurrence of sandstone surface and oblique bedding or pebble dip, we drew the

rose diagram of paleocurrent direction (figure 2e). Generally, the paleocurrent direction in Laiyang Group is NW-trending, indicating that the provenance is in the SE direction of the basin.

3.2 Analytical methods

Fresh whole-rock samples (13WL-6, JDW-11, 10RZ-14, 10RZ-20) were crushed in a steel crusher and powdered to grain size <200-mesh using an agate mill for major and trace-elemental analyses. Zircon grains were separated from heavy minerals by hand-picking under a binocular microscope. After zircon grains were mounted in epoxy, the resin discs were polished until the exposure of the grain centre of most zircon grains. Internal structures of zircon grains were imaged using the cathodeluminescence (CL). The CL images were obtained using a microprobe JEOL JXA-8900RL at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), Beijing (figure 4). The specific procedures are described in Xie *et al.* (2003).

3.2.1 Major and trace element analysis

The major elements of the sandstones were measured with a Regaku 3080E1 XRF spectrometer at

Figure 4. CL images of some dated zircons (with analytical sites marked, together with site numbers as listed in tables 3 and 4).

the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Beijing. Analytical procedures are described in detail by Gao *et al.* (1995). The results are listed in table 1.

Trace element contents were analysed by double focusing inductively coupled plasma mass spectrometer (ICP-MS) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS), Beijing, using Finnigan MAT Element. Analytical procedures were described in detail by Xu *et al.* (2007). Analytical errors are generally better than 5% (2σ). The analytical results are shown in table 2.

When processing the major element data, the loss on ignition was removed to calculate the percentages of each major element. The samples with CaO contents greater than 5% required special treatment because of the obvious calcite cementation. Generally, the highest CaO content to Na₂O content ratio is 1:1 in silicates; the data were normalised according to this principle. After processing, the data approximate the real major element contents of the sandstones (table 1).

3.2.2 Zircon morphology

Four samples of the granitic gneiss conglomerate (13WL-6), granitic gneiss (10RZ-14 and JDW-11), and syenite (10RZ-20) were used in this study. Typical CL images of the zircons are presented in figure 4, together with U–Pb ages for relevant spots.

The zircons of samples 10RZ-14 ($\text{Th}/\text{U}=0.94\text{--}1.67$) and JDW-11 ($\text{Th}/\text{U}=0.30\text{--}1.21$) show magmatic oscillatory zones (figure 4b, c). The zircons of sample 13WL-6 ($\text{Th}/\text{U}=0.77\text{--}2.15$) have two kinds of oscillatory zones; one kind of magmatic oscillatory zone is obvious, i.e., 13WL-6-31, 13WL-6-41 (figure 4a), being similar to those of the former two samples, the other kind of oscillatory zones are weak, e.g., 13WL-6-48.1 (figure 4a). The zircons

of sample 10RZ-20 ($\text{Th}/\text{U}=1.29\text{--}2.02$) are different from the zircons of the former three samples, although they show the zones, they have unobvious oscillatory zones.

3.2.3 U–Pb dating

U–Pb dating of zircons (10RZ-14) was conducted synchronously by the LA-ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan. 13WL-6, JDW-11 and 10RZ-20 were conducted synchronously by the LA-ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing. Laser sampling was performed using a GeoLas 2005. An Agilent 7500a ICP-MS instrument was used to acquire ion-signal intensities. The specific methods are described in Wiedenbeck (1995), Andersen (2002) and Jackson *et al.* (2004). The ages of the granitic gneisses are shown as the weighted mean ages of $^{206}\text{Pb}/^{238}\text{U}$, with 1σ errors and a 95% confidence interval for the weighted mean age. The test and processing results are shown in tables 3 and 4 and figure 5.

4. Results

4.1 Zircon chronology

4.1.1 Granitic gneiss in the conglomerates

The gravels in the conglomerate have complex and various components, containing quartzites, marbles, granitic gneisses, etc. We choose the zircons from four granitic gneiss pebble samples, whose diameters are 7–10 cm.

Forty-eight points were analysed among the selected zircons from the granitic gneisses in the conglomerates (13WL-6), and eight points were rejected due to low precisions (table 3, figure 5a).

Table 1. Major oxide results for the sandstones in the Laiyang Group from the Zhucheng Basin and the Proterozoic and Mesozoic intrusive rocks in the Jiaonan Orogen.

Sample source	Rock no.	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^T	MnO	MgO	CaO	CaO*	Na ₂ O	K ₂ O	P ₂ O ₅	Total	K/N	FM	S/A
LWZ Fm	JDW71	73.67	0.44	12.48	2.52	0.04	1.03	3.1	3.21	4.55	1.91	0.13	100	0.42	3.56	5.88
	JDW74	71.99	0.56	11.83	3.43	0.05	2.12	4.78	2.88	2.88	1.94	0.16	100	0.67	5.55	6.25
	JDW82	72.93	0.37	12.01	1.87	0.04	0.23	6.2	3.24	3.24	2.63	0.11	100	0.81	2.11	6.25
	Average	72.86	0.46	12.11	2.61	0.04	1.13	4.69	3.11	3.56	2.16	0.13	100	0.63	3.74	6.13
QGZ Fm	JDW28	62.79	0.96	16.17	7.83	0.07	2.16	1.6	1.65	6.27	1.81	0.30	100	0.29	9.99	3.85
	JDW29	66.01	0.68	15.59	5.52	0.08	2.39	2.27	2.36	4.59	2.57	0.23	100	0.56	7.90	4.17
	JDW77	63.34	0.79	15.17	6.11	0.08	1.57	4.55	4.74	5.25	2.73	0.21	100	0.52	7.69	4.17
	JDW78	75.67	0.35	13.23	2.53	0.04	0.97	0.32	0.32	3.27	3.48	0.12	100	1.06	3.51	5.88
	JDW79	70.39	0.53	15.41	4.46	0.08	1.24	6.57	2.07	2.07	3.54	0.20	100	0.38	4.98	4.55
	JDW80	72.86	0.46	12.79	3.23	0.07	1.47	1.86	1.90	5.08	1.95	0.19	100	0.38	4.70	5.56
	JDW81	72.48	0.47	12.49	4.01	0.10	1.98	4.81	2.58	2.58	3.15	0.15	100	1.22	5.85	5.88
	JDW83	76.43	0.43	12.39	2.54	0.04	0.34	5.28	2.68	2.68	2.29	0.16	100	0.85	2.79	6.25
	JDW85	69.69	0.56	14.70	4.03	0.09	1.14	3.04	3.14	4.13	2.35	0.17	100	0.57	5.17	4.76
	Average	69.96	0.58	14.22	4.47	0.07	1.47	3.37	2.38	3.99	2.65	0.19	100	0.65	5.84	5.26
Fajiaying Fm	JDW32	68.88	0.63	15.20	4.74	0.03	1.29	1.85	1.85	5.07	2.14	0.18	100	0.42	5.87	4.53
Laiyang Group Average		70.55	0.56	13.80	4.06	0.06	1.38	3.56	2.51	3.97	2.50	0.18	100	0.63	5.36	5.23
Neoproterozoic granitic gneiss	10RZ12	75.30	0.21	12.89	1.77	0.03	0.36	0.67		3.56	4.59	0.07	100	1.29	2.13	5.84
	10RZ14	77.26	0.17	12.47	0.89	0.05	0.10	0.35		4.37	4.23	0.01	100	0.97	0.99	6.20
	JDW11	76.27	0.21	13.31	1.02	0.13	0.15	0.36		6.34	1.90	0.04	100	1.03	1.47	6.15
	Average	76.28	0.20	12.89	1.23	0.07	0.20	0.46		4.76	3.57	0.04	100	1.10	1.53	6.06
Early Cretaceous intrusive rocks	10RZ20	60.25	0.85	16.62	4.98	0.09	2.68	3.79		4.37	4.50	0.45	100	1.03	7.66	3.63
	JDW27	60.26	0.59	17.02	6.05	0.11	1.86	2.47		4.39	3.82	0.35	100	0.87	7.91	3.54
	JDW47	62.12	0.58	15.20	4.60	0.13	2.06	2.86		3.70	4.74	0.40	100	1.28	6.66	4.09
	Average	60.88	0.67	16.28	5.21	0.11	2.20	3.04		4.15	4.35	0.40	100	1.05	7.41	3.74
OIA		58.83	1.06	17.11	1.95	0.15	3.65	5.83		4.1	1.600	0.266		0.39	5.6	3.44
CIA		70.69	0.64	14.04	4.82	0.1	1.97	2.68		3.21	1.89	0.16		0.59	6.79	5.03
ACM		73.86	0.46	12.89	3.06	0.1	1.23	2.48		2.77	2.90	0.09		1.05	4.29	5.73
PCM		81.95	0.49	8.41	3.28	0.05	1.39	1.89		1.07	1.71	0.12		1.60	4.67	9.74
UCC		66.6	0.64	15.4		0.1	2.48	3.59		3.27	2.80	0.15		0.86		4.32

S/A = SiO₂/Al₂O₃; K/N = K₂O/Na₂O; FM = Fe₂O₃^T+MgO; OIA: ocean island average chemical composition; CIA: continental island arc sandstone average chemical composition; ACM: active continental margin sandstone average chemical composition; PCM: passive continental margin sandstone average chemical composition. The above data are derived from Bhatia (1983). UCC: upper continental crust average chemical composition, derived from Rudnick and Gao (2003).

The observed ²⁰⁶Pb/²³⁸U zircon ages fall between 744±15 and 882±26 Ma. Among these zircon ages, 744±15 Ma might be the latest zircon crystallisation age of the granitic gneiss, and the zircon of 882±26 Ma might be an older magmatic zircon, which represents the older crystallisation age (figure 4a-48.1). The weighted mean age is 790±8.4 Ma (MSWD=3.1), which represents these granitic gneisses belong to Neoproterozoic.

4.1.2 Felsic intrusions in the Jiaonan Orogen

Three samples from the intrusions in the Jiaonan Orogen were chosen to conduct zircon geochronology tests, and all the analysed points were on the oscillatory zoned margins of the zircon grains.

Sample 10RZ-14 is granitic gneiss with 15 analyses, among which eight points had reliable precision. The acquired ²⁰⁶Pb/²³⁸U zircon ages are relatively similar, between 764±11 and 777±10 Ma, and have

a ²⁰⁶Pb/²³⁸U weighted mean age of 771±6.4 Ma (MSWD=0.21) (table 4, figure 5b), indicating that this granitic gneiss was emplaced in the Neoproterozoic.

Sample JDW-11 is granitic gneiss that intruded into sample 10RZ-14 based on field observations. Nineteen points were analysed, of which all points met the required precision. The ²⁰⁶Pb/²³⁸U ages are between 728±10 and 786±10 Ma, with a weighted mean age of 751±6.3 Ma (MSWD=1.9) (table 4, figure 5c), indicating that this granitic gneiss was also emplaced in the Neoproterozoic.

Sample 10RZ-20 is syenite that was emplaced into Neoproterozoic granitic gneiss. Eighteen points were analysed, and 17 points met the required precision. The ages of the points are primarily between 120±3 and 141±5 Ma, and the ²⁰⁶Pb/²³⁸U weighted mean age is 126±3 Ma (MSWD=2.9) (table 4, figure 5d), indicating that the syenite intruded in the early Cretaceous.

Table 2. Results of rare earth element and trace element contents for sandstone of Laiyang Group in Zhucheng Basin, Proterozoic granitic gneiss and Mesozoic intrusive rocks in Jiaona Orogen ($\times 10^{-6}$).

	LWZ Fm.						QZ Fm.										Mesozoic intrusive rock						Proterozoic granitic gneiss			
	J-71	J-74	J-82	Avg.	J-77	J-78	J-79	J-80	J-81	J-83	J-85	J-29	Avg.	J-32	J-47	J-27	R-5	Avg.	R-27	R-14	R-12	Avg.	R-27	R-14	R-12	Avg.
La	27.86	30.64	36.26	31.59	54.00	34.2	46.1	39.68	47.32	36.09	43.23	42.56	42.90	46.3	93.98	78.28	86.28	86.18	41.5	23.66	22.72	29.29	41.5	23.66	22.72	29.29
Ce	51.06	49.68	63.58	54.77	96.72	63.3	67.4	74.26	75.66	66.41	78.52	77.14	74.93	82.96	162.60	136.28	157.30	152.06	77.88	55.76	49.82	61.15	77.88	55.76	49.82	61.15
Pr	5.75	6.21	7.08	6.35	10.33	6.55	9.4	8.26	8.57	7.44	8.7	8.84	8.51	9.54	16.76	14.32	16.39	15.82	8.9	6.44	4.52	6.62	8.9	6.44	4.52	6.62
Nd	21.18	23.36	26.6	23.71	37.22	23.34	36.34	31.5	32.98	28.56	31.8	33.1	31.86	35.5	57.22	49.84	62.64	56.57	32.16	24.32	15.48	23.99	32.16	24.32	15.48	23.99
Sm	3.72	4.26	4.87	4.28	6.23	3.78	6.65	5.61	5.82	5.25	5.53	5.88	5.59	6.17	8.44	7.01	10.03	8.49	6.58	5.63	2.66	4.96	6.58	5.63	2.66	4.96
Eu	0.85	0.91	1.18	0.98	1.65	0.89	1.67	1.21	1.37	1.16	1.41	1.53	1.36	1.6	2.04	1.88	2.91	2.28	0.58	0.61	0.4	0.53	0.58	0.61	0.4	0.53
Gd	3.04	3.77	3.84	3.55	5.11	2.94	5.37	4.5	4.85	4.33	4.6	5.02	4.59	4.95	6.31	4.97	7.57	6.28	6.21	5.15	2.3	4.55	6.21	5.15	2.3	4.55
Tb	0.41	0.53	0.51	0.48	0.68	0.38	0.75	0.63	0.66	0.61	0.63	0.69	0.63	0.65	0.76	0.57	0.88	0.74	1.05	0.87	0.38	0.77	1.05	0.87	0.38	0.77
Dy	2.28	3.07	2.91	2.75	3.74	2.05	4.27	3.83	3.85	3.73	3.56	3.88	3.61	3.49	3.86	2.93	4.47	3.75	6.84	5.41	2.57	4.94	6.84	5.41	2.57	4.94
Ho	0.44	0.61	0.56	0.54	0.73	0.4	0.81	0.77	0.76	0.74	0.69	0.75	0.71	0.66	0.72	0.56	0.79	0.69	1.5	1.11	0.58	1.06	1.5	1.11	0.58	1.06
Er	1.28	1.8	1.63	1.57	2.12	1.19	2.26	2.29	2.2	2.21	2.02	2.15	2.06	1.88	2.07	1.63	2.13	1.94	4.81	3.29	1.95	3.35	4.81	3.29	1.95	3.35
Tm	0.19	0.26	0.22	0.22	0.3	0.18	0.29	0.32	0.28	0.31	0.29	0.31	0.29	0.27	0.29	0.23	0.26	0.26	0.78	0.49	0.32	0.53	0.78	0.49	0.32	0.53
Yb	1.24	1.73	1.6	1.52	2.00	1.21	2	2.27	1.96	2.18	1.91	1.97	1.94	1.76	1.97	1.52	1.78	1.76	5.45	3.04	2.23	3.57	5.45	3.04	2.23	3.57
Lu	0.18	0.26	0.21	0.22	0.3	0.19	0.27	0.31	0.27	0.3	0.28	0.28	0.28	0.26	0.30	0.23	0.24	0.26	0.82	0.42	0.34	0.53	0.82	0.42	0.34	0.53
ΣREE	119.5	127.1	151	132.53	221.1	140.6	183.6	175.4	186.6	159.3	183.2	184.1	179.24	196	357.32	300.25	353.67	337.08	195.06	136.2	106.26	145.84	195.06	136.2	106.26	145.84
L/H	12.2	9.6	12.2	11.33	13.8	15.5	10.5	10.8	11.6	10.1	12.1	11.2	11.95	13.1	20.95	22.75	18.52	20.74	7.89	7.96	11.45	9.10	7.89	7.96	11.45	9.10
(La/Yb) _N	16.1	12.7	16.2	15.00	19.3	20.2	16.5	12.5	17.3	11.8	16.2	15.5	16.16	18.9	34.22	36.94	34.77	35.31	5.46	5.58	7.31	6.12	5.46	5.58	7.31	6.12
δEu	0.75	0.68	0.81	0.75	0.87	0.79	0.83	0.71	0.77	0.72	0.83	0.84	0.80	0.85	0.82	0.93	0.98	0.91	0.27	0.34	0.49	0.37	0.27	0.34	0.49	0.37
δCe	0.94	0.83	0.91	0.89	0.94	0.97	0.75	0.95	0.85	0.94	0.94	0.92	0.91	0.92	0.93	0.93	0.96	0.94	0.95	1.09	1.13	1.06	0.95	1.09	1.13	1.06
La/Yb	22.41	17.68	22.63	20.91	26.97	28.17	23.07	17.46	24.12	16.52	22.65	21.64	22.58	26.32	47.71	51.50	48.47	49.23	7.61	7.77	10.19	8.52	7.61	7.77	10.19	8.52
Cr	33.14	59.32	29.84	40.77	30.04	24.62	38.9	22.96	41.12	35.98	26.94	68.84	36.18	38.06	52.80	7.50	52.84	37.71	6.68	8.7	3.79	6.39	6.68	8.7	3.79	6.39
Co	2.4	7.4	1.89	3.90	9.04	4.77	6.15	7.03	6.13	2.5	5.35	11.99	6.62	7.14	9.57	9.42	11.96	10.32	1.34	0.33	1.38	1.02	1.34	0.33	1.38	1.02
Ni	9.12	29.54	8.16	15.61	10.17	10.21	12.54	11.74	11.68	9.93	9.01	17.79	11.63	13.71	18.32	8.62	32.42	19.79	8.77	3.9	2.96	5.21	8.77	3.9	2.96	5.21
Cu	9.14	8.95	4.62	7.57	4.62	3.95	8.34	23.92	6.98	6.51	4.99	10.78	8.76	19.61	11.55	6.24	16.43	11.41	20.46	16.02	3.4	13.29	20.46	16.02	3.4	13.29

Zn	33.12	42.92	20.4	32.15	70	46.36	42.02	57	44.18	32.61	49.59	69.5	51.41	96.76	385.20	74.78	65.46	175.15	44.2	26.4	111.98	60.86
Ga	8.07	11.98	11.43	10.49	17.67	14.69	15.49	12.48	14.43	12.3	16.57	17.36	15.12	17.46	18.13	17.70	19.37	18.40	14.57	16.43	14.52	15.17
Rb	33.14	58.68	60.66	50.83	62.86	78.84	78.88	78.82	46.54	59.55	48.99	44.64	62.39	62.1	101.38	83.56	2.08	85.67	97.5	65.28	110.16	90.98
Sr	101	193.9	194.2	163.03	353.6	61.8	132.5	88.6	284.2	186.6	539.5	254.2	237.63	527.2	485.00	631.00	1026.80	714.27	152.02	51.3	137.62	113.65
Y	12.98	19.19	14.49	15.55	20.82	11.1	21.3	19.57	22.14	18.9	19.48	20.84	19.27	18.57	20.00	15.54	22.36	19.30	43.06	30.5	16.08	29.88
Zr	153.9	298.4	170.6	207.63	356.6	172.5	211.8	241	243.8	284.2	234.6	279.8	253.04	309.6	356.40	205.80	291.80	284.67	171.62	192.06	165.7	176.46
Nb	9.26	12.48	11.1	10.95	15.28	10.02	12.55	13.41	10.95	12.05	12.97	12.33	12.45	13.67	19.26	10.35	18.83	16.15	18.15	10.05	15.01	14.40
Cs	0.55	3.69	1.01	1.75	0.8	1.58	4.51	1.28	0.46	2.18	0.79	0.6	1.53	2.04	0.91	1.50	0.62	1.01	0.33	0.42	1.24	0.66
Ba	808	344	1420	857.33	873	762	389	860	445	770	1113	982	774.25	774	2480.00	2332.00	2720.00	2510.67	677.2	547.8	742.6	655.87
Hf	3.74	7.32	4.19	5.08	8.59	4.08	4.95	5.92	5.76	6.94	5.44	6.79	6.06	7.65	8.66	5.11	6.67	6.81	4.75	5.03	4.14	4.64
Ta	0.64	0.92	0.74	0.77	0.9	0.58	1.27	0.85	0.69	0.86	0.81	0.74	0.84	0.87	1.25	0.62	1.11	0.99	1.34	0.72	0.93	1.00
Pb	8.09	9.61	14.95	10.88	15.74	9.46	11.58	80.94	10.91	11.5	14.6	7.23	20.25	21.14	22.72	17.02	24.24	21.33	24.1	17.69	29.58	23.79
Th	4.28	6.99	5.17	5.48	6.81	5.3	7.64	6.01	7.11	6.7	7.07	6.06	6.59	6.27	21.70	12.12	9.54	14.45	16.46	5.24	7.2	9.63
U	0.75	1.44	0.83	1.01	1.11	0.78	1.75	1.45	1.84	0.99	1.32	1.03	1.28	1.35	3.14	1.76	1.40	2.10	3.54	0.63	0.75	1.64
Sc	2.95	6.26	4.56	4.59	7.66	4.73	9.28	5.73	8.87	6.9	6.07	10.23	7.43	7.23	6.65	7.01	9.56	7.74	3.24	2.55	3.38	3.06
Th/U	5.73	4.85	6.24	5.61	6.14	6.8	4.37	4.16	3.85	6.78	5.37	5.91	5.42	4.65	6.91	6.89	6.81	6.87	4.65	8.32	9.57	7.51
La/Sc	9.46	4.9	7.96	7.44	7.05	7.23	4.97	6.92	5.33	5.23	7.12	4.16	6.00	6.4	14.13	11.17	9.03	11.44	12.82	9.26	6.72	9.60
Th/Sc	1.45	1.12	1.13	1.23	0.89	1.12	0.82	1.05	0.8	0.97	1.16	0.59	0.93	0.87	3.26	1.73	1.00	2.00	5.09	2.05	2.13	3.09
La/Th	6.51	4.38	7.01	5.97	7.93	6.45	6.03	6.6	6.66	5.39	6.12	7.02	6.53	7.38	4.33	6.46	9.04	6.61	2.52	4.51	3.16	3.40
Rb/Sr	0.33	0.3	0.31	0.31	0.18	1.27	0.6	0.89	0.16	0.32	0.09	0.18	0.46	0.12	0.21	0.13	0.07	0.14	0.64	1.27	0.8	0.90
Zr/Y	11.86	15.55	11.77	13.06	17.13	15.54	9.94	12.32	11.01	15.03	12.04	13.43	42.90	16.68	17.82	13.24	13.05	14.70	3.99	6.3	10.3	6.86

Note: L/H=LREE/HREE; $\delta\text{Eu}=(\text{Eu}/0.087)/\{[(\text{Sm}/0.231)+(\text{Gd}/0.306)]\}/2$; $\delta\text{Ce}=3\times(\text{Ce}_{\text{sample}}/\text{Ce}_{\text{shale}})/[2\times(\text{La}_{\text{sample}}/\text{La}_{\text{shale}})+\text{Nd}_{\text{sample}}/\text{Nd}_{\text{shale}}]$; Chondrite standard values are derived from Boynton (1984); J=JDW; R = 10 RZ.

Table 3. LA-ICP-MS U–Pb zircon age data for the granitic gneiss conglomerates from the base of the Zhucheng Basin.

Spot					Isotopic ratios						Age (Ma)			
	U	Th	Th/U	Pb (total)	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ
	(ppm)	(ppm)		(ppm)										
Sample 13WL-6 (E119°13'42'', N35°44'57''), $^{206}\text{Pb}/^{238}\text{U}$ age: 790 ± 8.4 Ma, MSWD=3.1														
1.1	125.71	129.08	1.03	29.75	0.0656	0.0037	1.1462	0.0569	0.1276	0.0025	775	27	774	15
2.1	235.78	330.29	1.40	63.39	0.0688	0.0035	1.2076	0.0643	0.1241	0.0018	804	30	754	11
3.1	149.27	196.91	1.32	44.94	0.0703	0.0037	1.3347	0.0694	0.1344	0.0023	861	30	813	13
4.1	360.52	773.90	2.15	147.46	0.0684	0.0030	1.2643	0.0525	0.1323	0.0022	830	24	801	13
5.1	181.99	140.80	0.77	38.12	0.0645	0.0033	1.1515	0.0567	0.1275	0.0023	778	27	773	13
6.1	116.97	129.96	1.11	29.47	0.0643	0.0040	1.1524	0.0688	0.1280	0.0025	778	32	777	14
7.1	97.79	93.58	0.96	23.12	0.0689	0.0050	1.2472	0.0800	0.1332	0.0029	822	36	806	17
8.1	136.50	142.79	1.05	31.28	0.0648	0.0037	1.1556	0.0677	0.1263	0.0024	780	32	767	14
9.1	146.39	142.04	0.97	33.17	0.0667	0.0037	1.1943	0.0638	0.1281	0.0027	798	30	777	15
10.1	123.59	123.98	1.00	28.66	0.0673	0.0041	1.1785	0.0702	0.1265	0.0023	791	33	768	13
11.1	127.85	113.20	0.89	28.40	0.0621	0.0042	1.1524	0.0745	0.1333	0.0026	778	35	807	15
12.1	153.54	161.73	1.05	36.91	0.0689	0.0036	1.2399	0.0618	0.1304	0.0025	819	28	790	14
15.1	107.12	105.71	0.99	25.12	0.0684	0.0041	1.2290	0.0682	0.1307	0.0022	814	31	792	13
17.1	96.12	87.54	0.91	21.20	0.0662	0.0038	1.2358	0.0738	0.1341	0.0027	817	34	811	15
20.1	151.39	156.94	1.04	35.04	0.0658	0.0035	1.1603	0.0637	0.1276	0.0023	782	30	774	13
21.1	87.77	83.06	0.95	20.47	0.0659	0.0049	1.1461	0.0729	0.1281	0.0027	775	34	777	16
23.1	338.94	307.82	0.91	80.89	0.0700	0.0027	1.3342	0.0499	0.1380	0.0019	861	22	833	11
24.1	59.42	82.64	1.39	17.97	0.0724	0.0075	1.3248	0.1266	0.1326	0.0036	857	55	803	20
25.1	107.21	106.59	0.99	24.41	0.0632	0.0043	1.1213	0.0745	0.1293	0.0025	764	36	784	14
26.1	139.86	139.48	1.00	31.88	0.0657	0.0034	1.1652	0.0613	0.1285	0.0025	784	29	780	14
27.1	130.08	132.96	1.02	31.48	0.0654	0.0036	1.2048	0.0683	0.1316	0.0023	803	31	797	13
28.1	97.70	90.56	0.93	21.20	0.0638	0.0041	1.1363	0.0743	0.1278	0.0028	771	35	775	16
29.1	52.99	67.13	1.27	14.58	0.0681	0.0068	1.1542	0.1016	0.1275	0.0033	779	48	774	19
30.1	113.69	107.81	0.95	26.71	0.0635	0.0048	1.1571	0.0858	0.1287	0.0027	781	40	780	16
31.1	107.45	108.03	1.01	24.36	0.0696	0.0045	1.2104	0.0751	0.1251	0.0028	805	35	760	16
31.2	372.62	697.42	1.87	137.19	0.0660	0.0047	1.1348	0.0796	0.1273	0.0038	770	38	773	22
33.1	109.59	93.17	0.85	25.07	0.0697	0.0045	1.2576	0.0772	0.1342	0.0036	827	35	812	20
34.1	54.42	92.31	1.70	17.90	0.0638	0.0056	1.1549	0.0983	0.1297	0.0029	780	46	786	17
35.1	99.72	84.74	0.85	22.07	0.0665	0.0043	1.1971	0.0756	0.1319	0.0029	799	35	799	17
36.1	146.48	135.30	0.92	33.05	0.0636	0.0042	1.1068	0.0678	0.1266	0.0026	757	33	768	15
37.1	176.07	185.99	1.06	43.82	0.0670	0.0035	1.2750	0.0674	0.1378	0.0028	835	30	832	16
38.1	88.98	75.69	0.85	18.80	0.0642	0.0044	1.1402	0.0769	0.1280	0.0026	773	37	776	15
39.1	101.14	101.50	1.00	27.99	0.0681	0.0043	1.3604	0.0857	0.1445	0.0027	872	37	870	15
41.1	56.66	54.94	0.97	12.79	0.0650	0.0054	1.0947	0.0888	0.1224	0.0028	751	43	744	16
41.2	61.26	111.43	1.82	21.85	0.0659	0.0077	1.1505	0.1163	0.1282	0.0034	777	55	777	20
43.1	85.73	132.48	1.55	26.80	0.0650	0.0052	1.1947	0.0863	0.1354	0.0029	798	40	819	16
44.1	108.80	99.42	0.91	24.59	0.0655	0.0049	1.1854	0.0876	0.1311	0.0028	794	41	794	16
45.1	60.11	83.77	1.39	17.15	0.0659	0.0053	1.2057	0.1030	0.1318	0.0040	803	47	798	23
46.1	71.79	89.73	1.25	19.62	0.0619	0.0051	1.0959	0.0796	0.1311	0.0030	751	39	794	17
48.1	61.17	49.91	0.82	14.41	0.0656	0.0053	1.3427	0.1216	0.1466	0.0046	864	53	882	26

4.2 Geochemical characteristics of the major elements

4.2.1 Characteristics and comparison of the chemical components

(1) LWZ Fm and QGZ Fm

The data were divided into three groups: the LWZ Fm, QGZ Fm and Fajiyang Formation (FJY Fm). However, the FJY Fm had only one sample, which

is not representative. The samples in the first two groups were carefully selected and included more than three samples, and the test results are of relatively high scientific value. The sandstones of LWZ Fm all show medium- and fine-grained clastic texture, moderate sorted or poor sorted and fair roundness – mainly of angular and subangular. The clastic constituents are composed of quartz (27–61 vol%), feldspar (3–30 vol%), debris (15–70 vol%) and minor muscovite and accessory minerals.

Table 4. LA-ICP-MS U–Pb zircon age data for the Proterozoic granitic gneiss and Mesozoic intrusive rocks in the Jiaonan Orogen.

Spot	Isotopic ratios										Age (Ma)			
	U	Th	Pb (total) (ppm)	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$						
	(ppm)	(ppm)		Th/U	1σ	1σ	1σ	1σ	1σ	1σ				
Sample 10RZ-14 (E119°5'55.5'', N35°27'57''), $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age: 771±6.4 Ma (MSWD=0.21)														
2.1	89.2	149	1.67	18.1	0.0865	0.0033	1.5096	0.0577	0.1264	0.0016	934	23	767	9
3.1	83.9	79.1	0.94	14.6	0.0703	0.0030	1.2388	0.0522	0.1275	0.0015	818	24	774	9
4.1	93.2	99.2	1.06	16.3	0.0667	0.0028	1.1614	0.0452	0.1268	0.0014	783	21	770	8
5.1	99.3	118	1.19	17.7	0.0632	0.0026	1.0980	0.0456	0.1262	0.0015	752	22	766	9
6.1	57.6	75.5	1.31	16.4	0.0672	0.0031	1.1827	0.0570	0.1276	0.0020	793	27	774	11
7.1	44.3	56.6	1.28	16.5	0.0668	0.0041	1.1456	0.0675	0.1257	0.0019	775	32	764	11
9.1	125	157	1.25	10.6	0.0632	0.0023	1.1078	0.0402	0.1273	0.0014	757	19	772	8
15.1	71.4	84.6	1.18	15.3	0.0599	0.0035	1.0488	0.0577	0.1280	0.0017	728	29	777	10
Sample JDW-11 (E119°15'10.6'', N35°43'12''), $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age: 751±6.3 Ma (MSWD=1.9)														
1.1	97.8	93.03	1.05	16.2	0.0680	0.0034	1.1673	0.0553	0.1246	0.0018	785	26	757	10
2.1	250.8	207.24	1.21	39.3	0.0680	0.0013	1.1553	0.0234	0.1233	0.0016	780	11	749	9
3.1	185.1	193.31	0.96	30.6	0.0681	0.0014	1.1742	0.0260	0.1251	0.0016	789	12	760	9
4.1	279.5	923.36	0.30	48.5	0.0674	0.0013	1.1564	0.0240	0.1244	0.0016	780	11	756	9
5.1	196.0	185.88	1.05	30.7	0.0660	0.0015	1.1049	0.0260	0.1214	0.0016	756	13	739	9
6.1	72.6	78.11	0.93	12.1	0.0644	0.0023	1.1180	0.0405	0.1259	0.0017	762	19	764	10
7.1	156.8	130.79	1.20	24.5	0.0667	0.0016	1.1525	0.0286	0.1253	0.0016	778	14	761	9
8.1	393.3	582.25	0.68	69.9	0.0658	0.0013	1.1188	0.0230	0.1234	0.0016	762	11	750	9
9.1	206.0	209.14	0.99	33.4	0.0674	0.0014	1.1551	0.0256	0.1242	0.0016	780	12	755	9
10.1	165.4	179.12	0.92	27.7	0.0642	0.0034	1.0946	0.0564	0.1237	0.0018	751	27	752	10
11.1	121.0	132.68	0.91	19.6	0.0663	0.0020	1.1013	0.0332	0.1205	0.0016	754	16	734	9
12.1	147.2	193.37	0.76	25.3	0.0661	0.0018	1.1244	0.0310	0.1234	0.0016	765	15	750	9
13.1	156.5	191.92	0.82	26.2	0.0650	0.0038	1.0715	0.0602	0.1196	0.0018	739	30	728	10
14.1	171.1	172.28	0.99	27.3	0.0645	0.0016	1.0937	0.0285	0.1231	0.0016	750	14	748	9
15.1	205.3	141.96	1.45	33.3	0.0667	0.0033	1.1275	0.0539	0.1226	0.0017	767	26	745	10
16.1	103.8	93.41	1.11	16.8	0.0641	0.0035	1.1135	0.0581	0.1259	0.0018	760	28	764	10
17.1	140.4	153.94	0.91	23.9	0.0681	0.0017	1.2178	0.0309	0.1296	0.0017	809	14	786	10
18.1	55.9	60.96	0.92	9.1	0.0618	0.0032	1.0579	0.0546	0.1242	0.0017	733	27	755	10
19.1	197.8	182.94	1.08	30.3	0.0664	0.0016	1.0990	0.0266	0.1201	0.0016	753	13	731	9
Sample 10RZ-20 (E119°5'27'', N35°23'2''), $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age: 126±3.0 Ma (MSWD=2.9)														
1.1	24.0	31.6	1.32	0.6	0.0484	0.0225	0.1218	0.0566	0.0183	0.0006	117	51	117	4
2.1	44.3	66.6	1.50	1.2	0.0483	0.0235	0.1274	0.0617	0.0191	0.0006	122	56	122	4
3.1	51.2	93.5	1.83	1.5	0.0485	0.0157	0.1255	0.0405	0.0188	0.0005	120	36	120	3
4.1	26.1	34.3	1.31	0.7	0.0487	0.0339	0.1307	0.0909	0.0195	0.0008	125	82	124	5
5.1	31.7	44.3	1.40	1.2	0.1069	0.0415	0.2711	0.1042	0.0184	0.0010	244	83	118	7
6.1	56.5	72.8	1.29	1.5	0.0484	0.0120	0.1323	0.0328	0.0198	0.0004	126	29	126	3
7.1	26.7	37.4	1.40	1.7	0.0571	0.0272	0.1367	0.0648	0.0174	0.0006	130	58	111	4
8.1	49.3	67.9	1.38	1.3	0.0486	0.0255	0.1266	0.0663	0.0189	0.0007	121	60	121	4
9.1	45.2	78.5	1.74	1.4	0.0641	0.0227	0.1809	0.0638	0.0205	0.0006	169	55	131	4
10.1	41.2	83.3	2.02	1.2	0.0484	0.0217	0.1277	0.0573	0.0192	0.0006	122	52	122	4
11.1	68.4	134.9	1.97	2.1	0.0486	0.0079	0.1348	0.0218	0.0201	0.0004	128	19	128	2
13.1	27.7	44.5	1.61	1.0	0.0488	0.0353	0.1482	0.1072	0.0220	0.0008	140	95	141	5
14.1	59.8	95.8	1.60	1.7	0.0488	0.0079	0.1388	0.0223	0.0206	0.0004	132	20	132	3
15.1	71.7	142.3	1.99	1.5	0.0484	0.0078	0.1303	0.0210	0.0195	0.0004	124	19	125	3
16.1	32.8	43.3	1.32	0.9	0.0487	0.0200	0.1356	0.0555	0.0202	0.0006	129	50	129	4
17.1	39.2	62.9	1.61	1.1	0.0485	0.0131	0.1361	0.0368	0.0204	0.0005	130	33	130	3
18.1	35.8	51.3	1.43	1.0	0.0490	0.0161	0.1360	0.0446	0.0201	0.0006	129	40	128	3

Figure 5. Zircon U–Pb concordia diagram of (a) the granitic gneiss at the base of the Laiyang Group's conglomerates, (b and c) the Neoproterozoic granites in the Jiaonan Orogen, and (d) the Mesozoic syenite in the Jiaonan Orogen.

The sandstones of QGZ Fm are similar to those of LWZ Fm, and all of medium and fine grained clastic texture, poor sorted and of poor roundness – with obvious angles. The sandstones of QGZ Fm consisted of quartz (30–57 vol%), feldspar (15–57 vol%), debris (8–55 vol%) and minor muscovite and heavy minerals.

The LWZ Fm has a higher SiO_2 content (average 72.87 wt.%) than the QGZ Fm (average 70.26 wt.%), but the other major element contents, apart from CaO, are lower in the former than in the latter (table 1). The Al_2O_3 content in the LWZ Fm is between 11.83 and 12.48 wt.%, averaging 12.11 wt.%; the K_2O content is between 1.94 and 2.63 wt.%, averaging 2.16 wt.%; the Na_2O content is between 2.88 and 4.55 wt.%, averaging 3.56 wt.%; the $\text{Fe}_2\text{O}_3^{\text{T}} + \text{MgO}$ content averages 3.74 wt.%; and the TiO_2 content is between 0.37 and 0.56 wt.%, averaging 0.46 wt.%. The Al_2O_3 content in the QGZ Fm is between 12.02 and 16.17 wt.%, averaging 13.93 wt.%; the K_2O content is between 1.81 and 3.48 wt.%, averaging

2.47 wt.%; the Na_2O content is between 2.52 and 6.27 wt.%, averaging 4.34 wt.%; and the $\text{Fe}_2\text{O}_3^{\text{T}} + \text{MgO}$ content averages 5.84 wt.%.

Comparing the major element data of the LWZ Fm and QGZ Fm with the previously studied average (Bhatia and Crook 1986) chemical compositions of ocean island sandstones, continental island arc sandstones, active continental margins and passive continental margins (table 2), the characteristics of the LWZ Fm in the lower Laiyang Group are most similar to those of active continental margin sandstones, whereas those of the QGZ Fm in the upper Laiyang Group are most similar to those of continental island arcs.

(2) Comparison of the Laiyang Group with the Proterozoic and Mesozoic intrusive rocks

We also compared the major element compositions of the Laiyang Group's sandstones (including LWZ, QGZ and FJY Formations) to those of the Neoproterozoic granitic gneisses in the Jiaonan Orogen (table 1, figure 6). The TiO_2 , $\text{Fe}_2\text{O}_3^{\text{T}}$, MnO and

Figure 6. Hacker variable diagram of the Laiyang Group's sandstones from the Zhucheng Basin.

MgO contents of the Laiyang Group's sandstones are markedly higher than in the Neoproterozoic granitic gneisses, whereas the SiO_2 and K_2O contents are lower in the former than in the latter. The other major element concentrations are similar (table 1, figure 6). The SiO_2 concentrations of the Laiyang Group's sandstones are higher than those of the Mesozoic syenite in the Jiaonan

Orogen, but the other major element concentrations are all lower (table 1).

(3) Factors influencing the chemical compositions of the sandstones

Correlations exist between the quartz grains, feldspar debris and unstable rock debris present in sandstones and between the various elements in

the sandstones (Bhatia 1983). Hence, this paper studied the correlations between the major element geochemical data from the LWZ Fm, QGZ Fm and Neoproterozoic granitic gneisses (figure 6).

The SiO_2 content exhibits an obvious negative linear correlation with TiO_2 , Fe_2O_3 , MgO , and Na_2O in the sandstones of each formation in the study area (figure 6). The plot of the Neoproterozoic granitic gneiss samples and the plot of the sandstone samples are on the same oblique line, indicating that the quartz grains in the sandstones and the silicate minerals in the granitic gneiss influence the chemical properties of the whole rock to a great extent. This plot also highlights the similar compositions of the source regions of the LWZ Fm and QGZ Fm. However, the correlations of SiO_2 with Al_2O_3 and K_2O are not clear (figure 5), which may be attributed to residual Al_2O_3 minerals and the loss of K ions due to weathering in the source region.

4.2.2 Types of sandstones

Sandstones are generally geochemically classified by the major element oxide concentrations. For example, the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio can distinguish quartz arenite with abundant silicon from mudstones with abundant aluminium (Herron 1988), and this ratio can also reflect constituent enrichments in quartz, clay minerals and feldspar (Cox and Lowe 1995). The $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ ratio can distinguish lithic sandstones from feldspar sandstones (arkoses and subarkose), which can indicate the stability of mafic minerals in sandstones during the course of weathering (Heron 1988). The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio can reflect chemical maturity (Pettijohn *et al.* 1972). Previous researchers have established the geochemical classification of sandstones according to these ratios (Herron 1988) (figure 6).

For the LWZ Fm and QGZ Fm, the average $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios are 6.02 and 5.04, respectively;

Figure 7. Geochemical classification diagram (Herron 1988) of the major elements of the Laiyang Group's sandstones from the Zhucheng Basin.

the $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$ ratios are 1.21 and 1.76, respectively; and the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios are 0.63 and 0.65, respectively (table 1). In the $\log(\text{SiO}_2/\text{Al}_2\text{O}_3)$ – $\log(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ classification diagram, most of the sample points fall in the Fe sandstone area (figure 7a). In the $\log(\text{SiO}_2/\text{Al}_2\text{O}_3)$ – $\log(\text{Na}_2\text{O}/\text{K}_2\text{O})$ classification diagram, most of the sample points fall in the greywacke area, with a small number of sample points falling in the lithic sandstone area (figure 7b). These results suggest that the sandstones in the Zhucheng Basin did not experience intense weathering and were deposited near the source area or experienced rapid diagenesis. Additionally, abundant mafic components may be present in the source area.

4.2.3 Sandstone chemical alteration and source area paleo-weathering

During the course of rock weathering, deposition and diagenesis, the oxide concentrations of unstable elements (such as CaO, Na_2O , K_2O , and MgO) and relatively stable elements (such as Al_2O_3 , ZrO_2 , and TiO_2) can change (Cox *et al.* 1995). Several indices of sandstone chemical alteration and paleo-weathering based on the major element oxide contents have been proposed by previous researchers. Frequently used indicators include the Chemical Index of Alteration (CIA) (McLennan *et al.* 1993), the Chemical Index of Weathering (CIW) (Harnois 1988), the Plagioclase Index of Alteration (PIA) (Fedo *et al.* 1995) and the Index of Chemical Constituent Variation (ICV) (Cox *et al.* 1995) (table 5).

Based on these indices, similarities and differences exist between the LWZ Fm and QGZ Fm. Their ICV average values are 0.99 and 1.01, respectively, which are close to 1.0 and do not differ significantly. Generally, first-cycle sediments are characterised by the presence of less resistant minerals and rock fragments. If this material is reworked through a second cycle, the less resistant minerals will be eliminated, or altered to more stable products. When the ICV values are greater than 1.0, the sandstones are likely first-cycle sediments, whereas ICV values less than 1.0 indicate that the sandstones are likely recycled sediments or first-cycle sediments that have experienced intense weathering (Cox *et al.* 1995). The ICV values of the LWZ Fm are between 0.95 and 1.02, suggesting that the source area did not experience intense weathering. The ICV values of the QGZ Fm are between 0.86 and 1.30, indicating that great variations in the degree of weathering are present in the source rocks of the QGZ Fm; certain source rocks were relatively intensely weathered, whereas others were not.

All the other indices for the LWZ Fm are lower than those for the QGZ Fm. For instance, the LWZ Fm's CIA (average: 47) and CIW (average: 51) values are lower than those of the QGZ Fm (50 and 5, respectively). Previous researchers have considered CIA values between 45 and 55 to indicate no weathering, whereas a value of 100 indicates intense weathering and the complete loss of alkaline-earth metals (such as Ca, Mg and Sr) (McLennan 1993; Jason and Michale 2003). The average value of the upper crust is 47 (McLennan 1993). Therefore, the weathering in the source areas of the LWZ Fm and QGZ Fm was very weak, but the weathering of the latter was slightly more intense than that of the former, which is also reflected by the PIA. The PIA average values of the QGZ Fm and LWZ Fm are 64 and 60, respectively. Generally, the PIA values are about 50 for fresh rocks and values close to 100 for clay minerals such as kaolinite, illite, and gibbsite (Fedo *et al.* 1995). These data suggest that the source area is nearby the Zhucheng Basin, and the rock in the source area has not undergone intense weathering, which indicates the intense uplift occurred in the source area of the Zhucheng Basin. Furthermore, the source area of the LWZ Fm likely rose more rapidly during the deposition of the LWZ Fm than that of the QGZ Fm because the CIA value is similar to the average value of the upper crust and suggests the lack of apparent weathering in the source area. The above

Table 5. Chemical alteration and weathering features of the LWZ Fm and QGZ Fm from the Zhucheng Basin.

Sample no.	CIA	CIW	PIA	ICV
LWZ Fm				
JDW-71	45	48	58	1.02
JDW-74	49	54	63	0.99
JDW-82	46	52	59	0.95
Average	47	51	60	0.99
QGZ Fm				
JDW-28	51	55	64	1.15
JDW-29	52	57	65	1.01
JDW-77	43	47	55	1.30
JDW-78	58	69	73	0.76
JDW-79	48	52	61	0.99
JDW-80	48	52	61	0.99
JDW-81	50	58	64	1.03
JDW-83	51	57	65	0.86
JDW-85	49	54	63	0.97
Average	50	56	64	1.01

Note: $\text{CIA} = [\text{Al}_2\text{O}_3 / (\text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{Al}_2\text{O}_3)] \times 100$ (McLennan 1993), $\text{CIW} = [\text{Al}_2\text{O}_3 / (\text{CaO}^* + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3)] \times 100$ (Harnois 1988), $\text{PIA} = [(\text{Al}_2\text{O}_3 - \text{K}_2\text{O}) / (\text{CaO}^* + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3 - \text{K}_2\text{O})] \times 100$ (Fedo *et al.* 1995), $\text{ICV} = (\text{Fe}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}^* + \text{MgO} + \text{MnO} + \text{TiO}_2) / \text{Al}_2\text{O}_3$ (Cox *et al.* 1995).

conclusion is consistent with the high exhumed rate of 2.0 km Ma^{-1} from before *c.* 128 to 123 Ma in Jiaonan Orogen (Ni *et al.* 2016).

The intensity and trend of the source area's weathering can also be shown on A–CN–K and A–CNK–FM diagrams (McLennan *et al.* 1993) (figure 8). The difference in these two diagrams lies in the consideration of the mafic components. Feldspar and alkaline aluminosilicate minerals are generally considered to transform into clay minerals during rock weathering, unstable oxides (such as CaO, Na₂O and K₂O) are easily lost, and stable oxides (such as Al₂O₃) increase proportionately (McLennan *et al.* 1993). As a result, if the rocks do not experience potassic alteration, the rock weathering trend will be parallel to the A–CN edge in the A–CN–K diagram, expanding in the directions of kaolinite, illite, and white mica (figure 8).

All the sample points are plotted in the A–CN–K and A–CNK–FM diagrams. In the A–CN–K diagram, all the sample points are close to plagioclase, far from potassium feldspar. Additionally, majority of the sample points are under or in the vicinity of the plagioclase–potassium feldspar boundary, indicating that the plagioclase contents are higher than the potassium contents in the samples; thus, the weathering of feldspar in the rocks was very weak (CIA values mostly lower than 50%). The rock weathering trends are generally oriented in the direction of illite (figure 8a) and are parallel to the A–CN edge, suggesting that the rocks did not experience potassium metasomatism. The plotted points are close to granodiorite and andesite, consistent with the ferruginous sandstones in the geochemistry classification of the samples discussed above. The sample points are more disperse in the A–CNK–FM diagram (figure 8b) than in the A–CN–K diagram, because

the samples contain variable quantities of mafic components. However, the sample points are still close to granodiorite and in the vicinity of the potassium feldspar–FM line, demonstrating that the rocks did not undergo obvious weathering, which is consistent with the results from the A–CN–K diagram.

4.3 Trace element geochemistry

4.3.1 LWZ Fm and QGZ Fm

The trace element and REE contents of the Laiyang Group's sandstones are listed in table 2. The trace element contents of the Laiyang Group's sandstones in the Zhucheng Basin are lower than those of the upper continental crust (Rudnick and Gao 2003), with the exception of Rb, Zr and Ba, which are higher. In particular, Co, Ni, Sr and Ta are obviously lower than in the upper continental crust and trend towards acidity. The trace element contents in the LWZ Fm in the Lower Laiyang Group are obviously higher than those in the QGZ Fm in the Upper Laiyang Group, with the exception of Cr, Ni, Cs and Ba.

In the primitive mantle-normalised spider diagram of the trace elements (figure 9), the Laiyang Group in the Zhucheng Basin exhibits overall enrichment in the large ion lithophile elements Rb, Ba and K and REEs La and Ce; depletion in the inactive elements P, Ti, Y, Yb and Lu; intermediate concentrations of Zr and Hf; and variable Sr concentrations. The individual spider diagrams for the LWZ Fm and QGZ Fm (figure 9a) are generally similar, but the LWZ Fm curve is primarily below the QGZ Fm, with the exception of Rb, Ba, Th and U. This difference is more obvious in REE-normalised distribution pattern diagrams. On both the chondrite-normalised (figure 10a) and North

Figure 8. (a) A–CN–K and (b) A–CNK–FM diagrams of the major elements of the Laiyang Group's sandstones from the Zhucheng Basin (McLennan *et al.* 1993). Note: A = Al₂O₃, CN = CaO + Na₂O, K = K₂O, FM = Fe₂O₃ + MgO, CIA = Chemical Index of Alteration. All the samples are calculated in mole numbers.

Figure 9. Primitive mantle-normalized spider diagram of the trace elements (normalized data derived from Sun and McDonough (1989)). (a) Laiyang Group's sandstones from the Zhucheng Basin and the Laiyang Depression; (b) intrusive rocks from the Jiaonan Orogen; and (c) comparison of the LWZ Fm with the Proterozoic intrusive rocks and several Mesozoic stocks.

American Shale Composite normalised diagrams (figure 10b), the sample curves of the QGZ Fm are primarily above those of the LWZ Fm, except for one unseparated broken line. This difference may indicate that the sediments experienced chemical

element separation and migration during the deposition of these formations and that the elevation difference between the basin and provenance decreased during the sedimentation of the QGZ Fm. This process allowed sufficient time for the REEs in the sediments to become separated, and they were subsequently preserved in the basin.

Light REEs are enriched on the REE chondrite-normalised diagram for the Laiyang Group's sandstones in the Zhucheng Basin (figure 10a). By contrast, the heavy REEs are relatively depleted, and weak negative Eu anomalies are present. The REE content of the Laiyang Group's sandstones is almost identical to that of the North American Shale Composite (figure 10b), with slight depletion in the heavy REEs and slightly higher Eu contents, indicating that the sandstones in the LWZ Fm and QGZ Fm in the Laiyang Group experienced a relatively complete sedimentary cycle. Critically, heavy earth elements are not enriched, demonstrating that the geochemical properties of the samples were not greatly affected by water-rock reactions that might diminish their ability to discriminate provenances and tectonic settings.

4.3.2 Laiyang Group, Neoproterozoic granitic gneiss and Mesozoic intrusive rocks

The curved shape of the trace element plot for the Laiyang Group from the Zhucheng Basin is similar to that of the Neoproterozoic granitic gneiss in the Jiaonan Orogen (figure 9a, b). For instance, the Neoproterozoic granitic gneisses are enriched in the large ion lithophile elements Rb, Ba, U and K, the REEs La and Ce, and the elements Y, Yb and Lu, and they are depleted in typical inactive elements, such as Sr, P and Ti.

On the spider diagrams, the trace elements of the Laiyang Group are also similar to those of the syenite that intruded in the early Cretaceous, but the values of the former are slightly lower than those of the latter (figure 9c). Each value for the LWZ Fm is between that of the Neoproterozoic granitic gneiss and that of the Lower Cretaceous diorite.

In the REE chondrite-normalised diagrams, the light REE contents of the LWZ Fm are similar to those of the Neoproterozoic granitic gneisses, and both exhibit negative Eu anomalies. The normalised heavy REE values of the Neoproterozoic granitic gneisses are flat and generally higher than those of the LWZ Fm. The Cretaceous syenite features large variations in its normalised values, which are obviously higher than those of the other two rock types, and the light REEs exhibit poor differentiation (figure 10c).

The REE differences between the LWZ Fm, the Neoproterozoic granitic gneiss and the Lower Cretaceous syenite in the North American Shale

Figure 10. Comparison of the REE-normalized distribution pattern diagrams of the Laiyang Group's sandstones with the Proterozoic and Mesozoic intrusive rocks. (a) Chondrite normalization of the Zhucheng Basin sediments; (b) North American Shale Composite normalization of the Zhucheng Basin sediments; (c) chondrite-normalized comparison of the Proterozoic and Cretaceous intrusive rocks and the LWZ Fm from the Zhucheng Basin; and (d) North American Shale Composite-normalized comparison of the Proterozoic and Cretaceous intrusive rocks and the LWZ Fm from the Zhucheng Basin. The standardized data are from Sun and McDonough (1989).

Composite-normalised diagram are similar to those in the chondrite-normalised diagram (figure 10d). In particular, the Neoproterozoic granitic gneisses feature a negative Eu anomaly.

The above comparison shows that the Laiyang Group sandstones have a substantial affinity to the Jiaonan Orogen's Neoproterozoic granitic gneiss and that the sandstones are unrelated to the Mesozoic intrusive rocks. These findings are consistent with the zircon geochronology of the Laiyang Group's conglomerates.

5. The tectonic setting and provenance

5.1 Tectonic setting

Under supergene conditions, the migration of major and trace elements in sediments is controlled by various factors, of which the tectonic setting and provenance are the most important (Bhatia 1983).

For clastic sedimentary rocks, the stability of the provenance's tectonic setting controls the derivation of sediments and determines the relative stay duration of major and trace elements at the earth's surface due to weathering denudation, consolidation diagenesis, and then controls the fractionation of major and trace elements. These processes produce different geochemical features in sedimentary rocks (Adeigbe and Jimoh 2013). Hence, the analysis and interpretation of the geochemical features of clastic rocks is an effective way to determine the tectonic setting and provenance of sediments (Ejeh *et al.* 2013; Ikhane *et al.* 2014).

The major element $K_2O/Na_2O-w(SiO_2)\%$ discrimination diagram is based on the correlation of SiO_2 and K_2O/Na_2O and is used to discriminate between several tectonic settings. This type of diagram does not list continental island arcs due to the similarities in the SiO_2 , K_2O and Na_2O signatures of inactive continental margins and continental

Figure 11. Tectonic discrimination diagram of the major elements in the Laiyang Group's sandstones from the Zhucheng Basin. (a) $\text{K}_2\text{O}/\text{Na}_2\text{O}$ - $w(\text{SiO}_2)$ discrimination diagram (Roster and Korsch 1986); (b) F_1 - F_2 discrimination diagram for major elements (Roster and Korsch 1988); (c) $\text{Fe}_2\text{O}_3+\text{MgO}$ - $\text{TiO}_2\%$ discrimination diagram (Bhatia 1983); (d) $\text{Fe}_2\text{O}_3+\text{MgO}$ - $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O})$ discrimination diagram (Bhatia 1983).

island arcs (Roster and Korsch 1988). According to this diagram, the plotted points of the sandstones from the LWZ Fm and QGZ Fm fall in the active continental margin area, far from the passive continental margin and ocean island arc areas (figure 11a).

Based on the $\text{Fe}_2\text{O}_3+\text{MgO}$ - $w(\text{TiO}_2)\%$ and $\text{Fe}_2\text{O}_3+\text{MgO}$ - $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O})$ discrimination diagrams (Bhatia 1983) (figure 11b, c), the majority of the sample points for the LWZ Fm and QGZ Fm lie in the active continental margin and continental island arc provenance fields. The sedimentary sequence from the LWZ Fm to the QGZ Fm transitions from the active continental margin field to the continental island arc field (figure 11b, c). The major element oxide contents of the rocks in the LWZ Fm and QGZ Fm also exhibit a similar trend with respect to the values of active continental margins and continental island arcs (table 1).

In addition to major elements, trace elements are also used to discriminate tectonic settings, such

as in the $\text{Th}-\text{Sc}-\text{Zr}/10$ diagram and the $\text{La}-\text{Th}-\text{Sc}$ diagram (Bhatia and Crook 1986). These diagrams can clearly discriminate between the tectonic settings of ocean island arcs, continental island arcs, active continental margins and passive continental margins. According to these diagrams, the Laiyang Group's sandstones in the Zhucheng Basin primarily plot within the continental island arc field, although a few points fall outside this area (figure 12).

Despite the difference in the results, the discussed diagrams generally indicate that the source rocks of the sediments in the Laiyang group were formed in an active continental margin and/or continental arc setting. Uplifted basement is known to act as a denudation area of active continental margins, and incised magmatic arc is the source areas of continental island arcs (Bhatia 1983). The observed provenance properties indicate that the source areas of the sediment in the Zhucheng Basin experienced intense uplift during the deposition of

the Laiyang Group and that the magmatic arc, which was originally deeply buried in the basement, began to experience denudation. These results are consistent with the results obtained from the previously discussed sandstone chemical alteration indices and source area paleo-weathering estimates in this paper.

5.2 Provenance

It is important to discover the provenance of the Laiyang Group's sandstones in the Zhucheng Basin. The paleocurrent directions indicate the provenance should be in the south-east direction of the basin. The zircon geochronologic data from the conglomerates at the base of the Laiyang Group

indicate that the rocks exposed in the source area during the early stages of basin formation were primarily Neoproterozoic granitic gneiss (table 3). The ages of the Neoproterozoic granitic gneisses that crop out in the Jiaonan Orogen are between 739 and 819 Ma (Hacker *et al.* 2006; Huang *et al.* 2006). The age of the granitic gneisses in conglomerates is close to that of the Neoproterozoic granitic gneiss in the Jiaonan Orogen. Combined with the paleocurrent directions and the age of the granitic gneiss in conglomerates, the Jiaonan Orogen was the most important provenance of sediment in the Laiyang Group in the Zhucheng Basin. This conclusion is supported by the similarities in both the major element and trace element concentrations between the Laiyang Group's sandstones and the

Figure 12. Trace element discrimination diagram for the Laiyang Group's sandstones from the Zhucheng Basin.

Figure 13. Multivariable function and discrimination diagram of the provenance properties of the major elements of the Laiyang Group's sandstones from the Zhucheng Basin.

Jiaonan Orogen's Neoproterozoic granitic gneiss. It must be mentioned that, since we found the zircon with the age of 882 ± 26 Ma, there might be other source rocks.

The younger intrusions in the Jiaonan Orogen formed primarily in the Early Cretaceous (~126 and 116 Ma) (Yang *et al.* 2005; Hacker *et al.* 2009) (table 4) and featured widely different trace element patterns relative to the Laiyang Group. These results suggest that the Cretaceous intrusive rock was emplaced while the basin was subsiding and was not exposed at the surface.

In addition to geochronologic differences, the established F_1 – F_2 discrimination function diagram, based on the oxides of Ti, Al, Mg, Ca, Na and K, is commonly used to effectively discriminate between mafic, intermediate and felsic magmatic rocks and quartz sedimentary rocks (figure 13) (Roster and Korsch 1988; Ejeh *et al.* 2013; Zhang *et al.* 2014).

We analysed the correlations between the Laiyang Group's sandstone samples from the Zhucheng Basin, established a discrimination equation and plotted the points (figure 13). The results show that most of the sample points fall into the felsic igneous rock provenance field, and a few sample points fall into the intermediate rock provenance field. Although the sandstone samples are divided into two provenances, the sample points are tightly grouped near the provenance field of intermediate rocks, indicating that the provenance of the Laiyang Group in the Zhucheng Basin is primarily intermediate-acid igneous rocks. This finding is consistent with the conclusion that the sandstones are primarily ferruginous sandstones and clastic sandstones (according to the geochemical classification diagram for the sandstone's major elements; figure 7) and contain abundant plagioclase (according to the A–CN–K diagram; figure 8).

Figure 14. Regional Mesozoic depositional, tectonic and magmatic events in east China. The Ar–Ar ages are from Zhao *et al.* (1998), Yang *et al.* (2005), Webb *et al.* (2006), Hacker *et al.* (2009), and Guo *et al.* (2013). The depositional stage of the Zhucheng Basin is from Zhang *et al.* (2008), the extensional rate of the Liaonan MCC is from Liu *et al.* (2005), the extensional rate of the Jiaobei Block is from Charles *et al.* (2011a, 2013), and the subsidence rate is from Ren *et al.* (2002).

The rocks in the Jiaonan Orogen are mainly composed of ultrahigh-pressure metamorphic rocks from the Paleoproterozoic Fenzishan Group and Neoproterozoic granitic gneiss and granitic gneiss (Ni *et al.* 2013). Granitic gneiss is the largest component of the ultrahigh-pressure metamorphic complex, accounting for 75% of the entire complex's outcropping area (Liu *et al.* 2008; Zheng *et al.* 2010). This observation agrees with the results obtained from the geochemical discrimination diagram, indicating that the sandstone's provenance includes intermediate rocks and felsic igneous rocks. The Fenzishan Group and granitic gneiss were the source rocks, which is consistent with the conclusion that the sediments' provenances included active continental margins and continental island arcs.

6. Tectonic implications

The geochemical features and provenance analysis of the major elements of the Laiyang Group's sandstones from the Zhucheng Basin indicate that the southern Sulu Orogen (the Jiaonan Orogen) experienced rapid uplift during rapid subsidence of the Zhucheng Basin at 135–125 Ma (the depositional period of the Laiyang Group) (Zhang *et al.* 2003). These events occurred approximately 60–80 Ma later than the ultrahigh-pressure metamorphism and continental collision events, which is longer than the generally accepted interval between continental collision and crustal remelting events (Thompson 1999). Therefore, the rapid uplift of this orogen is likely unrelated to the post-orogenic extension and is instead associated with a separate extensional event. A series of extensional features have been described in the northern Jiaodong area and include the formation and denudation of the Linglong MCC (130–124 Ma) (Charles *et al.* 2011a) and the uplift and denudation of the Jiaobei Uplift (140–110 Ma) (Zhang *et al.* 2006). Additionally, a series of metamorphic core complexes and detachment fault zones, including the Liaonan MCC (Liu *et al.* 2005, 2006, 2011) and the Waziyu MCC (Li *et al.* 2012) (figure 1), was developed on the opposite side of the Jiaodong peninsula. In fact, the development phase of the Laiyang Group in the Zhucheng Basin coincides with the intense destruction of the North China Craton (Liu *et al.* 2005; Zhu *et al.* 2011; Ni *et al.* 2014) (figure 14). During this period, widespread rifted basins developed in the North China Craton, resulting in the Xing'anling–Mongolia giant rift system (Meng 2003a; Meng *et al.* 2003b; Ni *et al.* 2011), Songliao rift system (Song *et al.* 2010; Zhang *et al.* 2011), Lower Cretaceous Bohai Bay rift system (Ren *et al.* 2002), and others (figure 1).

The rapid subsidence of the Zhucheng Basin during the formation of the Laiyang Group and

the rapid uplift of the southern Sulu Orogen are both the result of a single regional extensional event. During this event, rifted basins formed in the shallow crust, and the Wulian MCC developed in and was exhumed from the deeper crust. These tectonic phenomena are the result of the lithospheric thinning of the North China Craton and its peripheral areas.

7. Conclusions

- The fluvial-lacustrine facies sedimentary rocks in the Laiyang Group and the volcanic rocks in the Qingshang Group formed during the Early Cretaceous in the Zhucheng Basin. The Linshansi Formation's conglomerates and the LWZ Fm, QGZ Fm and Fajiaoying Formation's sandstones and mudstones were successively deposited, forming the Laiyang Group.
- The major element contents of the LWZ Fm and QGZ Fm in the Zhucheng Basin are similar, but differences still exist. The LWZ Fm has higher SiO₂ contents (average: 72.87 wt.%) than the QGZ Fm (average: 70.26 wt.%), and the other major element contents, apart from CaO, are lower in the former than in the latter. The values of the LWZ Fm (lower Laiyang Group) in various indices are similar to the average values of active continental margins, whereas the values of the QGZ Fm (upper Laiyang Group) are similar to those of continental island arcs.
- The majority of the sandstone samples from the Laiyang Group in the Zhucheng Basin are ferruginous sandstones and greywackes, although a few samples are lithic sandstones. Therefore, the sandstones did not experience intense weathering and were deposited near the source region or experienced rapid diagenesis. In addition, mafic material was abundant in the source areas. The tectonic setting discrimination diagram reveals that the provenance of the Laiyang Group includes features of active continental margins and continental island arcs.
- The trace element and REE contents of the LWZ Fm and QGZ Fm in the Zhucheng Basin are similar. In the primitive mantle-normalised trace element spider diagram, the Laiyang Group is relatively enriched in the large ion lithophile elements Rb, Ba and K and REEs La and Ce and is depleted in the inactive elements P, Ti, Y, Yb and Lu, with intermediate amounts of Zr and Hf and various Sr contents. In the chondrite-normalised diagram, the Laiyang Group is relatively enriched in the light REEs and relatively depleted in the heavy REEs, with negative Eu anomalies. The trace element and REE characteristics of the Laiyang Group are similar to

those of the Neoproterozoic granitic gneisses in the Jiaonan Orogen but are significantly different from those of the Lower Cretaceous intrusions.

- The zircon age of the granitic gneiss material in the conglomerates at the base of the Laiyang Group is 790 ± 8.4 Ma, close to the ages of the Neoproterozoic granitic gneisses in the Jiaonan Orogen (739–819 Ma). Clearly, these ages differ significantly from those of the Lower Cretaceous intrusions, revealing that the Neoproterozoic granitic gneisses in the Jiaonan Orogen may be the main provenance of the Laiyang Group in the Zhucheng Basin.
- The chemical alteration and paleo-weathering indices (CIA, CIW, PIA and ICV) suggest that the source rocks generally did not experience weathering during the depositional period of the Laiyang Group. The Jiaonan Orogen experienced rapid uplift during the depositional period of the Laiyang Group in conjunction with the high exhumed rate of 2.0 km Ma^{-1} from before *c.* 128 Ma to 123 Ma in Jiaonan Orogen.
- The rapid subsidence of the Zhucheng Basin during the formation of the Laiyang Group and the rapid uplift of the Jiaonan Orogen both resulted from a single regional extensional event. Rifted basins and the Wulian MCC also formed during this event. These tectonic phenomena represent significant shallow structural responses to the lithospheric thinning of the North China Craton and its peripheral areas.

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