Geochemistry evidence for depositional settings and provenance of Jurassic argillaceous rocks of Jiyuan Basin, North China

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This paper aims to discuss the depositional settings and provenances for the Jurassic in Jiyuan basin, North China, based on the rare earth element (REE) and trace element features of 16 Jurassic argillaceous rock samples from the Anyao, Yangshuzhuang and Ma'ao Formations, respectively. Generally, geochemical analysis results show that chondrite-normalised REE distribution patterns of all the three formations are characterised by light-REE (LREE) enrichment, moderately negative Eu anomalies, slightly negative Ce anomalies, and strong fractionation between LREE and heavy-REE (HREE). Trace element proxies V/(V+Ni), Ce_{anom} index, Ce/La, Sr/Ba, and Sr/Cu indicate a weak oxidation–reduction environment, progressively decreasing reducibility and water depth from the bottom up during Jurassic in Jiyuan basin. Palaeoclimate varied from humid in the Early Jurassic to arid in the Middle Jurassic, corresponding with the variations of palaeoredox and palaeosalinity. The provenances of Jurassic rocks in Jiyuan basin are mainly from felsic sources related to active continental margin and continental island arc. The Early–Middle Jurassic (Anyao and Yangshuzhuang Formations) provenances are mainly derived from North Qinling and partially from the eroded recycled felsic sedimentary covers of Taihang Mountain. In the late stage of Middle Jurassic (Ma'ao Formation), Taihang Mountain has been the primary source to Jiyuan basin. We conclude that the Jurassic rocks of Jiyuan basin reveal the progressive uplift and denudation processes of the Taihang Mountain.

1. Introduction

The North China Craton (NCC) is bound by the Qinling–Dabie orogen to the south, the Yinshan orogen to the north, the Longshoushan belt to the west and the Sulu HP–UHP metamorphic belt to the east (Zhang 1997, 2002, 2004; Zhao *et al.* 2005; Zhang *et al.* 2008; Zhai and Santosh 2011) (figure 1a). The NCC is divided into Eastern and Western blocks, separated by the Trans-North China Orogen (Zhao *et al.* 2001), and consists of Archean to Palaeoproterozoic basement overlain

by Mesoproterozoic to Cenozoic cover (Zhai and Santosh 2011; Zhao and Cawood 2012; Zhao and Zhai 2012). Mesozoic geodynamics of the eastern NCC was considered to be controlled by subduction of the Palaeo-Pacific plate underneath the Asian continent and subsequent closure of the Palaeo-Asian ocean (Davis *et al.* 2002; Griffin *et al.* 1998; Wu *et al.* 2005a, b; Zhu *et al.* 2012). The NCC has experienced lithosphere thinning, intense magmatism, structural deformation since Mesozoic, which indicates the destruction of the NCC (Zhu *et al.* 2012), followed by the development

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Figure 1. Simplified geological maps of Jiyuan basin, North China, showing: (a) tectonic setting of Jiyuan basin, North China (after Zhang *et al.* 2008) and (b) distribution of the Jurassic in western Henan Province, North China, and location of the section (modified from Zhang *et al.* 2005).

of the Mesozoic basins, e.g., Ordos Basin, Bohai Bay Basin, North Yellow Sea Basin and Jiyuan Basin (Li *et al.* 2012). During the Middle to Late Jurassic, the tectonic regime underwent significant transformation which related to the change of sedimentary environment (Dong *et al.* 2000, 2007; Luo *et al.* 2006; Zhang *et al.* 2008). Jiyuan basin is located adjacent to the north-west margin of the southern NCC, and regarded as a Triassic–Jurassic syn-orogenic basin (figure 1a) (Liu *et al.* 2013; Yang *et al.* 2012, 2014a, b). In the past two decades, many investigations have been carried out on the tectonic settings (Zhang 1997; Yang *et al.* 2012, 2014a, b) and sedimentary facies (Hu *et al.* 2004a, b; Zhang *et al.* 2005) of the Jurassic in the Jiyuan basin. Previous work has largely focused on the sedimentary environment of Early–Middle Jurassic (Anyao Yangshuzhuang Formations), whereas little work has been concentrated on the sedimentary environment of late stage of Middle Jurassic (Ma’ao Formation). The provenance of Jurassic rocks in Jiyuan basin is still poorly known, and further work needs to be conducted on the basin–range coupling relationship. The discussion of Jiyuan basin during Jurassic provides insights into the evolution of the NCC.

In this paper, we present trace element (including REE) data of argillaceous rocks to discuss the depositional settings, sedimentary provenances and tectonic settings of Jiyuan basin and the NCC tectonic evolution during Jurassic.

2. Location and geological setting

2.1 Geological background

The east–west-trending Jiyuan basin is bounded by the Taihang Mountains to the north, the North Qinling Orogen to the south (Zhang 1997; Yang *et al.* 2012). It was developed during the Late Palaeozoic–Middle Triassic, based on the large inland basin of North China (Wu 1985; Wu *et al.* 2000; Yang *et al.* 2012). It is marked by marine carbonate rocks from the Cambrian to Middle Ordovician, lack of strata from the upper Ordovician to Lower Carboniferous, coal-bearing strata of marine-terrigenous facies from the Middle Carboniferous to Permian, and red clastic deposits of fluvial facies from the Early to Middle Triassic. The Jiyuan basin remained in a steadily shrinking condition from the Late Triassic to Middle Jurassic, bearing the upper Triassic (including the Chunshuyao and Tanzhuang Formations) and Lower-Middle Jurassic (including the Anyao, Yangshuzhuang, and Ma’ao Formations) from the bottom up (Wu *et al.* 2000; Yang *et al.* 2012).

2.2 Stratigraphy and depositional settings

The study area comprised well-exposed Jurassic formations located in the Chengliu Town of Jiyuan

City in northwestern Henan Province, North China (figure 1b). The Upper Triassic–Middle Jurassic System are well exposed and widely distributed in Chengliu. The Jurassic rocks are subdivided into three sedimentary formations from bottom to top, i.e., Anyao, Yangshuzhuang, and Ma’ao, respectively (Hu 1991; Wu *et al.* 2000; Yang *et al.* 2014a) (figure 2).

The Anyao Formation contains mainly celadon mudstones interbedded with calcareous siltstones (figure 3a, b). Multiple types of Bouma succession (Wu 1985; Buatois *et al.* 1996), scouring structures and trace fossils, including Fodinichnia and Pasichnia (Wu 1985; Buatois *et al.* 1996; Hu *et al.* 2002) occurred in the Lower-Middle part, indicating a semi-deep to deep lacustrine turbidite environment. Wave ripples occurred in the fine-grained sandstones of the upper part, suggesting shallow lacustrine facies.

The overlying Yangshuzhuang Formation is characterised by feldspathic quartz sandstones interbedded with gray-yellow mudstones, and celadon mudstones and interbedded with feldspathic and lithic sandstones from bottom to up (figure 3c), bearing tabular cross-bedding, parallel bedding, wavy bedding, and asymmetric ripple marks.

The overlying unconformity stratum is the Ma’ao Formation. Riverbed conglomerates with a distinct scoured surface (figure 3d) occurred at the bottom of the Ma’ao Formation. The lower part contains mainly celadon lithic sandstones with parallel beddings (figure 3e), foreset beddings (figure 3f) and wedge cross-beddings (figure 3g), indicating intense water energy. The upper part is marked by purple mudstone interbedded with celadon mudstone with parallel beddings, small-scale cross beddings, current beddings, and lamelli-branch fossils (figure 3h) from the bottom up, showing shallow-shore lacustrine facies (figure 3i, j).

3. Samples and methods

Sixteen Jurassic argillaceous rock samples were collected from the location as shown in figure 2, including four samples from the Anyao Formation, two from the Yangshuzhuang Formation, and 10 from the upper part of the Ma’ao Formation.

All the samples were ground to 200 mesh by an agate mortar after natural drying. Trace element and REE determinations of the powder samples were analysed using Agilent 7500a ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, using the method of Qi *et al.* (2000). The analytical precision of the REE and trace element concentrations was better than 95%. Detection limits were ≤ 2 ppm for most trace

Figure 3. Jurassic outcrops in Jiyuan basin, North China. (a, b) Outcrops of Anyao Fm. showing deep to semi-deep water deposits. (c) Outcrops of the Upper Yangshuzhuang Fm. (d) Riverbed conglomerates from the lower section of Ma'ao Fm. (e) Parallel bedding. (f) Foreset bedding. (g) Wedge cross-bedding. (h) Dashed circles show lamellibranch fossils from upper section of Ma'ao Fm. (i) Outcrops of Ma'ao Fm. showing shallow lacustrine facies deposits. (j) Outcrops of Ma'ao Fm. showing shore lacustrine facies deposits.

elements. The detection limits for Ba, Cr, Rb, Sr, and V are 5 ppm.

4. Results

The trace and rare earth element analysis results and other related chondrite-normalized geochemical parameters of the 16 Jurassic argillaceous rock samples from the Jiyuan basin are listed in table 1.

The total REE contents (ΣREE) of samples from the Anyao Formation range from 151.7 to 246.0 ppm (average 183.7 ppm), which is higher than the average value for the upper continental crust (UCC) (average 148.14 ppm) (Rudnick and Gao 2014). Samples in the Yangshuzhuang Formation appear to have higher ΣREE values (287.6 and 251.8 ppm) than the average values of UCC. The ΣREE values of samples from the Ma'ao Fm. approached the average UCC value, ranging greatly from 79.6 to 192.9 ppm (average 142.3 ppm). The minimum value 79.6 ppm, which corresponds to sample MA-5 (shell limestone), might have resulted from the dilution on REE concentrations by bioclasts and calcites.

All the REE data are compared with chondrite and UCC (figure 4). The chondrite-normalised REE distribution pattern (figure 4a) is characterised by relative enrichment of LREE and nearly flat HREE patterns, presenting a V-shaped curve. Samples exhibit moderately negative Eu anomalies (range: 0.56–0.69 ppm, average 0.64 ppm) and slightly negative Ce anomalies (range: 0.83–1.01 ppm, average: 0.90 ppm), except for sample MA-8. The values of the LREE/HREE ratio range between 7.9 and 10.4 with an average of 9.1, the $(\text{La}/\text{Yb})_{\text{N}}$ ratio range from 7.92 to 13.9 with an average of 9.5, the $(\text{La}/\text{Sm})_{\text{N}}$ ratios range between 2.85 and 5.96 with an average of 4.0, indicating strong fractionation between LREE and HREE. The $(\text{Gd}/\text{Yb})_{\text{N}}$ ratios range from 1.07 and 2.19, with an average of 1.61, revealing slight fractionation of HREE.

Compared with UCC, the REE of the Anyao Formation is flat. The REE of the Yangshuzhuang Formation is characterised by enrichment in LREE and slightly negative Eu anomalies with the REE contents of the approximately twice average value of UCC. The REE of the Ma'ao Formation is flat with slightly positive Eu anomalies. As shown in figure 4, the REE patterns of Anyao Formation vary greatly and partially show affinity with the Yangshuzhuang Formation. Compared with Yangshuzhuang Formation, the Eu anomalies in Anyao Formation is much stronger. The REE pattern of Yangshuzhuang Formation shows an obvious difference from the Anyao and Ma'ao Formations.

5. Discussion

Trace elements (including REEs) of fine-grained clastic rocks are relatively stable in the later diagenesis and weathering processes, thus making them reliable tools for tracing the provenances and depositional settings (Bhatia and Taylor 1981; Bhatia and Crook 1986; McLennan and Taylor 1991; McLennan *et al.* 1993, 1995; Gu *et al.* 2002; Zhang 2004; Zhang *et al.* 2012).

5.1 Depositional environments

5.1.1 Palaeoredox

Palaeoredox conditions of ancient and modern sedimentary basins can be evaluated using various geochemical proxies (Cullers 1994, 2000; Rimmer 2004; Tribouillard *et al.* 2006; Huang *et al.* 2015). Vanadium (V) is a redox-sensitive element and is enriched in reducing sediments (Calvert and Pedersen 1993; Crusius *et al.* 1996; Dean *et al.* 1997; Algeo and Maynard 2004), making the $\text{V}/(\text{V}+\text{Ni})$ ratio an important proxy for palaeoredox reconstruction (Hatch and Leventhal 1992; Jones and Manning 1994; Rimmer 2004; Miao *et al.* 2007; Yan *et al.* 2009; Huang *et al.* 2015). In average, the $\text{V}/(\text{V}+\text{Ni})$ ratio in the Anyao Formation is 0.75 (range from 0.66 to 0.80), lower than that of Yangshuzhuang Formation (0.82), and higher than that of the Ma'ao Formation (range from 0.59 to 0.74 with an average of 0.67). The ratios suggest that all the three formations were formed in weakly stratified water columns. The lower part of the Anyao Formation records semi-deep to deep lacustrine environments (Wu 1985; Buatois *et al.* 1996; Hu *et al.* 2002), which should have strong water column stratification. However, abundant turbidite trace fossils occurred in the lower part of the Anyao Formation (Wu 1985), due to the frequent turbidite current, which may have caused weak water column stratification and provides enough oxygen for trace makers. Water depth in the Ma'ao Formation varied frequently, relating to the variation of redox condition (figure 2). The $\text{Ce}_{\text{anom}}(\text{Ce}=\text{Ce}_{\text{N}}/(\text{La}_{\text{N}}\times\text{Pr}_{\text{N}})^{0.5})$ has also proved to be a robust palaeoredox indicator (Elderfield and Greaves 1982). The Ce_{anom} index of Anyao Formation ranges from -0.03 to -0.09 , reflecting a weak oxidation–reduction condition with the reducibility gradually weakening (Elderfield and Greaves 1982). The Ce_{anom} indices of both the samples of Yangshuzhuang Formation are -0.08 and the Ce_{anom} index of the Ma'ao Formation, varies greatly from 0.01 to -0.1 , indicating a weak oxidation–reduction environment (Elderfield and Greaves 1982). The Ce/La ratios suggest that all the three formations were formed in weakly

Table 1. Trace and rare earth element data of the argillaceous rocks from the Jurassic in Jiyaan basin, North China.

Sample	AY-1	AY-2	AY-3	AY-4	YSZ-1	YSZ-2	MA-1	MA-2	MA-3	MA-4	MA-5	MA-6	MA-7	MA-8	MA-9	MA-10
REEs (ppm)																
La	31.10	33.20	39.40	57.00	59.50	71.60	24.80	30.30	37.60	34.90	18.40	33.70	40.40	35.70	25.50	25.10
Ce	63.90	66.80	72.30	99.50	105.00	125.00	46.80	49.70	74.40	72.30	32.60	67.90	84.70	81.80	48.20	48.20
Pr	7.41	7.85	8.21	11.60	11.60	13.00	5.44	5.27	7.12	7.71	3.77	7.37	9.11	8.87	5.72	5.63
Nd	28.10	29.50	30.50	42.80	42.10	44.70	20.20	19.10	24.40	29.10	14.10	28.00	33.70	35.50	21.50	21.40
Sm	5.28	5.72	5.57	7.62	6.94	6.89	3.92	3.43	4.27	5.65	2.58	5.61	6.43	7.19	4.19	4.30
Eu	0.93	1.13	1.10	1.53	1.41	1.31	0.82	0.79	0.81	1.08	0.55	1.08	1.24	1.47	0.84	0.88
Gd	4.71	5.23	5.07	7.00	6.53	6.51	3.27	3.65	3.34	4.97	2.29	4.66	5.21	6.19	3.48	3.51
Tb	0.71	0.84	0.79	1.11	1.04	1.00	0.52	0.56	0.58	0.80	0.35	0.76	0.81	0.98	0.54	0.57
Dy	3.91	4.80	4.61	6.85	6.39	6.02	3.00	3.17	3.69	4.68	1.95	4.12	4.68	5.62	3.14	3.22
Ho	0.75	0.97	0.94	1.41	1.35	1.34	0.58	0.68	0.76	0.99	0.41	0.85	0.89	1.07	0.61	0.66
Er	2.21	2.78	2.75	4.22	4.20	4.26	1.60	1.77	2.42	2.74	1.05	2.41	2.48	2.85	1.73	1.83
Tm	0.32	0.41	0.42	0.63	0.67	0.67	0.25	0.23	0.38	0.44	0.17	0.35	0.39	0.42	0.27	0.28
Yb	2.01	2.77	2.82	4.11	4.41	4.63	1.65	1.41	2.65	2.85	1.20	2.38	2.51	2.69	1.71	1.76
Lu	0.31	0.39	0.41	0.62	0.68	0.69	0.23	0.20	0.39	0.42	0.17	0.33	0.38	0.39	0.24	0.27
ΣREE	151.70	162.40	174.90	246.00	251.80	287.60	113.10	120.3	162.80	168.60	79.60	159.5	192.90	190.70	117.70	117.60
LREE/HREE																
(La/Yb) _N	9.10	7.87	8.76	8.42	8.91	10.40	9.11	9.24	10.40	8.37	9.41	8.99	10.05	8.37	8.97	8.65
(La/Sm) _N	10.01	7.76	9.04	8.97	8.73	10.01	9.73	13.90	9.18	7.92	9.92	9.16	10.41	8.59	9.65	9.23
(Gd/Yb) _N	3.38	3.33	4.06	4.29	4.92	5.96	3.63	5.07	5.05	3.54	4.09	3.45	3.60	2.85	3.49	3.35
δEu	1.98	1.60	1.52	1.44	1.25	1.19	1.68	2.19	1.07	1.48	1.61	1.66	1.76	1.95	1.72	1.69
δCe	0.56	0.63	0.63	0.64	0.64	0.59	0.69	0.68	0.64	0.62	0.68	0.63	0.64	0.66	0.66	0.68
Ce/Ce*	0.92	0.90	0.86	0.83	0.85	0.86	0.87	0.82	0.97	0.96	0.84	0.93	0.96	1.01	0.87	0.88
	0.95	0.94	0.90	0.87	0.88	0.87	0.91	0.85	0.93	0.95	0.88	0.94	0.96	1.0	0.91	0.92
Trace elements (ppm)																
Sc	7.80	15.10	16.60	20.60	21.50	20.90	8.73	4.70	14.10	10.00	6.68	10.10	14.80	8.91	9.22	8.59
V	53.80	110.0	127.00	121.00	158.00	147.00	55.10	32.60	105.00	67.00	46.00	78.70	108.00	52.20	65.70	56.10
Ni	17.60	32.60	32.50	61.80	34.10	33.00	25.60	23.00	37.00	28.10	19.80	35.40	53.00	27.00	29.50	33.80
Cu	9.34	33.80	32.40	31.70	25.70	17.60	19.40	12.20	39.50	20.70	17.10	33.50	21.80	30.60	26.30	34.90
Co	21.70	18.50	16.00	22.40	11.90	14.20	8.81	6.64	11.40	5.73	5.16	11.30	16.20	9.97	11.80	11.60
Rb	55.40	140.0	172.00	182.00	160.00	148.00	86.20	36.60	162.00	73.70	53.00	81.40	153.00	74.80	103.00	87.60
Sr	146.0	159.0	96.70	55.30	139.00	139.00	238.00	299.00	77.50	103.00	365.00	260.00	98.70	158.00	272.00	326.00
Zr	277.0	159.0	153.00	236.00	238.00	269.00	81.00	51.80	187.00	263.00	59.70	119.00	131.00	186.00	83.70	115.00
Cs	2.30	7.74	9.34	19.40	9.91	9.19	5.11	2.06	9.67	3.72	2.92	4.75	9.32	4.56	6.04	5.22
Ba	199.0	420.0	524.00	696.00	431.00	438.00	436.00	279.00	513.00	280.00	232.00	344.00	343.00	262.00	407.00	342.00
Hf	6.99	4.28	4.18	6.31	6.94	7.62	2.39	1.43	5.19	7.05	1.75	3.31	3.72	4.97	2.43	3.27
Th	9.67	14.20	15.60	20.30	16.30	18.80	8.41	4.59	15.30	12.20	6.06	10.60	15.20	10.30	9.09	8.58
U	1.89	2.68	2.75	3.28	4.34	5.21	1.89	6.27	5.53	3.28	1.78	3.97	2.66	2.32	2.57	3.62

Table 1. (Continued.)

Sample	AY-1	AY-2	AY-3	AY-4	YSZ-1	YSZ-2	MA-1	MA-2	MA-3	MA-4	MA-5	MA-6	MA-7	MA-8	MA-9	MA-10
Ratios																
Th/U	5.12	5.30	5.67	6.19	3.76	3.61	4.45	0.73	2.77	3.72	3.40	2.67	5.71	4.44	3.54	2.37
Rb/Sr	0.27	0.38	0.47	1.55	0.31	0.15	0.72	2.09	0.12	0.36	1.06	1.15	3.29	1.78	0.88	0.38
Sr/Cu	15.6	4.70	3.00	1.70	5.40	7.90	12.20	24.50	2.00	5.00	21.40	7.80	4.50	5.20	10.30	9.30
Sr/Ba	0.73	0.38	0.18	0.08	0.32	0.32	0.55	1.07	0.15	0.37	1.57	0.76	0.29	0.60	0.67	0.95
Ce _{anom}	-0.03	-0.04	-0.07	-0.09	-0.08	-0.08	-0.06	-0.10	-0.02	-0.02	-0.08	-0.03	-0.02	0.01	-0.06	-0.06
Ce/La	2.05	2.01	1.84	1.75	1.76	1.75	1.89	1.64	1.98	2.07	1.77	2.01	2.10	2.29	1.89	1.92
V/(V+Ni)	0.75	0.77	0.80	0.66	0.82	0.82	0.68	0.59	0.74	0.70	0.70	0.69	0.67	0.66	0.69	0.62

Note: All elements in ppm; 'N' represents chondrite-normalised value, from Boynton (1984), 'A' represents the shale-normalised value of North America, from Haskin *et al.* (1968); $L = La + Ce + Pr + Nd + Sm + Eu$, $HREE = Gd + Tb + Dy + Ho + Er + Tm + Yb + Lu$, $REE = L + H$; $\delta Ce = Ce_N / (La_N * Pr_N)^{0.5}$; δEu represents Eu anomaly, $\delta Eu = Eu_N / (Sm_N * Gd_N)^{0.5}$; $Ce/Ce^* = Ce_A / (La_A * Pr_A)$.

oxidising-reducing conditions (sub-oxic conditions) (Bao *et al.* 2011). As shown in figure 2, regional oxidising strengthened quickly, since the late stage of Middle Jurassic (Ma'ao Formation).

5.1.2 Palaeosalinity

The Sr/Ba ratios were used to indicate the palaeosalinity conditions (e.g., Zheng and Liu 1999; Custodio 2002; Liu and Zhou 2007). The Sr/Ba ratios in the Anyao Formation decrease gradually from 0.73 to 0.08, the Sr/Ba ratios of both the samples of Yangshuzhuang Formation are 0.32, the Sr/Ba ratios in the Ma'ao Formation vary greatly from 0.15 to 1.57, indicating a decreasing salinity and an increasing freshwater environment in Anyao Formation, a freshwater environment in Yangshuzhuang Formation and an overall brackish environment (Zheng and Liu 1999; Custodio 2002; Liu and Zhou 2007). With water depth gradually shallowing, the salinity decreased as well, indicating a humid climate and open lacustrine environment with a large inflow of freshwater during the deposition of Anyao Formation. Palaeosalinity varied in the Ma'ao Formation, showing a similar trend to palaeoredox conditions. The negative correlation between Ce/La and Sr/Ba ($r=0.61$) suggests a relatively closed basin and the inverse relationship between water depth and salinity during the deposition of the Ma'ao Formation.

5.1.3 Palaeoclimate

Geochemical signature of sedimentary rocks provides important information on climate (Bhatia 1983; Bhatia and Crook 1986; Adegoke *et al.* 2014). The Sr/Cu ratio in lacustrine basins is used as a palaeoclimate proxy (Lerman 1978; Deng and Qian 1993; Liu and Zhou 2007; Cheng *et al.* 2010). The Sr/Cu ratios in the Anyao Formation range from 1.7 to 4.7 with an average of 3.1. The Sr/Cu ratios in Yangshuzhuang Formation are 5.4 and 7.9. The Sr/Cu ratios in the Ma'ao Formation range greatly from 2.0 to 24.5 with an average of 10.2. The Sr/Cu ratios suggest that the Anyao Formation mainly records a warm and humid climate, whereas the Yangshuzhuang and Ma'ao Formation indicate a quite arid climate (Cheng *et al.* 2010), as shown in figure 2. Samples MA-3, MA-4, and MA-7 show the frequent variations of climate in the late stage of Middle Jurassic. Additionally, Ce/La and Sr/Ba ratios in the Ma'ao Formation indicates the positive correlation between climate and salinity. As shown in figure 2, the Jiyuan basin was deposited in a warm-humid climate in Early Jurassic, whereas it became quite arid in the late stage of Middle Jurassic, corresponding with the variation of palaeoredox and palaeosalinity conditions.

5.2 Provenance analysis

5.2.1 Nature of source rocks

REE patterns have been used as the most reliable proxies of sediment provenance (Taylor and McLennan 1985; McLennan 1989; McLennan *et al.* 1995). The enrichment of LREEs, the negative Eu anomalies and the flat HREE patterns of the Jurassic argillaceous rock samples reveal derivation from the sources similar to UCC composed mainly of felsic components. The $(\text{Gd}/\text{Yb})_N$ ratio decreases steadily with decreasing of Gd content due to the geological evolution and elemental fractionation. Based on Cheng *et al.* (2010), the $(\text{Gd}/\text{Yb})_N$ ratio reveals that provenance of most samples were probably derived from Post-Archean source areas. As shown in figure 4(b), the provenances are mainly derived from the felsic sources, whereas the provenance for Ma'ao Formation shows an obvious difference when compared with Anyao and Yangshuzhuang Formations.

The immobile trace elements (e.g., Zr, Y, Th, Sc, Hf, La) in the sedimentary rocks have proved to be useful in determining source rocks (Gu *et al.* 2002; Taylor and McLennan 1985; Wani and Mondal 2011; Mondal *et al.* 2012). As shown in figure 5, the samples mostly lie in the field of felsic volcanic rocks. The La/Yb *vs.* REE plot (figure 5c) suggests that the source rocks were granites and some older sedimentary rocks. In spite of limited data, it is clearly shown that provenance varies in different formations. The provenance for Ma'ao Formation is obviously different from Anyao and Yangshuzhuang Formations. As shown in the plots of La/Th *vs.* Hf (figure 5a), samples from the Ma'ao Formation probably indicate a mixed provenance comprising

granites and felsic to intermediate volcanic components. Similarly, the La/Yb *vs.* REE plot (figure 5c) shows the different of provenance for Ma'ao Formation. Three of 10 samples in the Ma'ao Formation (MA-2, MA-9, MA-10) show high Co/Th ratios, reflecting the influence by intermediate volcanic components. Geochemistry reveals a mixed provenance comprising recycled sedimentary rocks and felsic rocks for Anyao Formation. The provenance for Yangshuzhuang Formation exhibits difference from the Anyao and Ma'ao Formations, as shown in figure 5(a, c).

5.2.2 Tectonic setting of Jurassic sedimentary rocks of Jiyuan basin

The Th–Co–Zr/10 and Th–Sc–Zr/10 (figure 6) plots have been used to discriminate tectonic environments (e.g., Bhatia and Crook 1986; Xu *et al.* 2010; Wang *et al.* 2012; Zhang and Liu 2015). As shown in figure 6, most samples plot in ACA field or within ACA and CIA fields, indicating the provenance of Jurassic sediments in Jiyuan basin mainly related to ACM and CIA. Tectonic setting of samples in Ma'ao Formation is quite different from Anyao and Yangshuzhuang Formations. Samples of the Yangshuzhuang Formation plot into different fields compared with Anyao Formation.

The Th/U ratios in the Anyao Formation range from 5.12 to 6.19, the Th/U ratios in the Yangshuzhuang Formation are 3.76 and 3.61 and the Th/U ratios in the Ma'ao Formation range greatly from 0.71 to 5.73 (average 3.38), whereas some of them range from 2.5 to 3.5. The Th/U ratios reveal that the Jurassic provenance in Jiyuan basin is marked by dominated sedimentary rock with

Figure 4. (a) Chondrite-normalized and (b) upper continental crust (UCC)-normalized spidergrams for Jurassic argillaceous rocks from the Jiyuan basin, North China. Chondrite values are from Boynton (1984); UCC values are from Rudnick and Gao (2014).

Figure 5. Plots of (a) Hf vs. La/Th (after Floyd and Leveridge 1987); (b) La/Sc vs. Co/Th (average compositions of references are from Condie (1993)); (c) Total REE vs. La/Yb (after Allègre and Minster 1978); and (d) Zr/Sc vs. Th/Sc (after McLennan *et al.* 1993) for Jurassic argillaceous rocks from Jiyuan basin, North China.

few island-arc volcanic rocks in the Early Jurassic (Anyao Formation), massive island-arc volcanic rocks with few mixed sedimentary rocks in the early stage of Middle Jurassic (Yangshuzhuang Formation) and dominated island-arc volcanic rocks with mixed recycled sedimentary rocks in the late stage of Middle Jurassic (Ma'ao Formation) (Bhatia and Taylor 1981).

In addition, the Th/U ratio gradually increases with increasing weathering, due to the oxidation and loss of U (Taylor and McLennan 1985; McLennan and Taylor 1991; McLennan *et al.* 1995). Th/U ratios >4 are thought to be related to weathering history (McLennan *et al.* 1995). As shown in the Th/U – Th plot (figure 7), the weathering of the Jurassic sedimentary rocks in Jiyuan basin gradually decreases from the bottom up (McLennan *et al.* 1993). The provenance for Ma'ao is quite different from Anyao and Yangshuzhuang Formations, showing variation from the source similar to UCC to the depleted mantle source (McLennan *et al.* 1993). Furthermore, combined with the La/Th

vs. Hf plot (figure 5a), the Jurassic provenance for Jiyuan basin changed gradually from sedimentary-rock-dominated to igneous-rock-dominated from the bottom up, probably due to the convention of tectonic regimes.

5.3 Constraints on tectonism and basin evolution

The tectonic evolution of Jiyuan basin during Jurassic were discussed on the basis of depositional settings analysis, provenance analysis and regional geology. During Early–Middle Jurassic (ca. 201–170 Ma), the subduction of Palaeo-Pacific plate relate to the destruction of NCC, followed by the development of the Jiyuan basins (Li *et al.* 2012; Zhu *et al.* 2012). Taihang Mountains began to uplift in the Middle Jurassic (ca. 175–150 Ma) (Wang and Li 2008). The initial uplift stage of Taihang Mountains corresponds to the deposition of Anyao and Yangshuzhuang Formations when the

Figure 6. Ternary plots of (a) Co–Th–Zr/10 and (b) Sc–Th–Zr/10 for tectonic discrimination (after Bhatia and Crook 1986). OIA = Oceanic Island Arc, ACM = Active Continental Margin, CIA = Continental Island Arc, PM = Passive Margin.

Figure 7. Plot of Th vs. Th/U for Jurassic argillaceous rocks from Jiyuan basin, North China (after McLennan *et al.* 1993).

Jiyuan basin belonged to the opening system of the large Ordos basin.

During the deposition of Anyao Formation, the southern fault of Jiyuan basin occurred strike-slip and extensional activities (Wu *et al.* 2000; Yang *et al.* 2012). The subsidence of Jiyuan basin

resulted in the deep-water turbidite deposits in Anyao Formation, corresponding with weak extension tectonic regime of NCC. The provenances for Anyao Formation were mainly derived from the sedimentary cover and felsic rock basement of North Qinling, and partially from the recycled felsic sedimentary covers of northern Taihang Mountains.

In the early stage of Middle Jurassic (ca. 174 Ma), the accommodation space of Jiyuan basin was filled rapidly with the water depth shallowed. The provenance for Yangshuzhuang Formation were mainly derived from the felsic volcanic rocks of North Qinling. Detrital zircon data from Anyao and Yangshuzhuang Formations also reveal that the basement of North Qinling had been the primary provenance for Jiyuan basin (Yang *et al.* 2014b). The unstable conglomerates disappeared southwardly, revealing that provenance for Jiyuan basin may also derive from the Taihang Mountains during the deposition of Yangshuzhuang Formation (Yang *et al.* 2014b).

With the subduction of Palaeo-Pacific plate (i.e., Izanagi) which contributes to the Mesozoic tectonic transmission of the North China in Middle Jurassic (ca. 170 Ma) (Isozaki and Nishimura 1989; Isozaki 1997; Maruyama *et al.* 1997; Hou *et al.* 2009),

Taihang Mountain entered into main orogenic episode. With the enhancing uplifting and eroding of Taihang Mountain, the Palaeoproterozoic–Archean basic components in the basement of NCC (Taihang Mountain) had been eroded and transported into surrounding basins (Zhai and Liu 2003; Zhai and Santosh 2011; Zhao and Zhai 2012). Jiyuan basin was isolated from the large Oros basin in the deposition of Ma’ao Formation. Jiyuan basin showed a lacustrine regressive deposition which underwent a conversion from lacustrine to fluvial facies at the bottom of the Ma’ao Formation, indicating the conversion of tectonic stress field of NCC and a rapid uplift of Jiyuan basin in the late stage of Middle Jurassic (ca. 168 Ma). The lithology of sandstone in Middle Jurassic varied from feldspar-quartz sandstone to lithic sandstone, and the colour of argillaceous rocks, which varied from celadon to purple, revealed the regional rapid uplift and deduction of Jiyuan basin (Li *et al.* 2014). The regional oxidising enhanced quickly and the palaeoclimate changed from humid to arid in Middle Jurassic, corresponding with the convention of tectonic regime of NCC. The felsic provenance for Ma’ao Formation were probably still derived from North Qinling, whereas the intermediate-basic volcanic rocks comprising depleted mantle components may derive from the basement of NCC (Taihang Mountain). Detrital zircons from the Ma’ao Formation also revealed that Taihang Mountain had been the primary source to the Jiyuan basin in the late stage of Middle Jurassic (Yang *et al.* 2012, 2014b).

6. Conclusion

Based on the geochemical data of the studied Jurassic argillaceous rocks collected from the Jiyuan basin, the main conclusions are as follows:

1. The trace element proxies $V/(V+Ni)$, Ce_{anom} index, Ce/La , Sr/Ba , and Sr/Cu reveal that Jiyuan basin was deposited in a weakly oxidizing–reducing condition (sub-oxic condition) with reducibility decreasing and water depth gradually shallowing from the bottom up during Jurassic. Both the Anyao and Yangshuzhuang Formations record a freshwater environment, whereas the Ma’ao Formation records a brackish water environment with frequent variations in salinity. The palaeoclimate changed from warm and humid to arid and hot in Middle Jurassic.
2. Provenance for the Jurassic argillaceous rocks in Jiyuan basin are mainly derived from felsic volcanic rocks and relate to active continental margin and continental island arc, with felsic source gradually reducing and basic components increasing from the bottom up.
3. In the Early–Middle Jurassic (Anyao and Formations), North Qinling has provided the main provenance for the Jurassic sedimentary rocks in Jiyuan basin. The subduction of Palaeo-Pacific plate in Middle Jurassic related to the uplift of Taihang Mountain. Taihang Mountain has been the primary source to the Jiyuan basin in the late stage of Middle Jurassic.

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