Nd isotopic characteristics of Proterozoic metasedimentary rocks and constraints on their provenance in the eastern segment of Central Tianshan Belt, Xinjiang*

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Abstract Sm-Nd isotopic characteristics, $\varepsilon_{Nd}(t)$ values and Nd model ages (T_{DM}) of Proterozoic metasedimentary rocks in the eastern segment of Central Tianshan Belt (ESCTB), Xinjiang, are used to constrain the sedimentary provenance as well as to evaluate their tectonic implications. $\varepsilon_{Nd}(t)$ and T_{DM} values of these samples range from −4.00 to +6.36 and from 1.29 to 2.29 Ga, respectively. These feature values are distinguished from those of Archean Tarim Craton. Their average $\varepsilon_{Nd}(t)$ values of the Weiya, the Kumishi and the south to the Dikar samples are −2.46, +2.06 and +1.37, respectively. Nd model ages of the Weiya samples vary between 1.86 and 2.29 Ga, but those of the Kumishi and the south to the Dikar samples show a significant concentration at 1.6~1.9 Ga and the youngest Nd model age is 1.29 Ga. Those Nd isotopic characteristics suggest that these metasedimentary rocks could be derived from a significant proportion of Paleoproterozoic crustal source and a participation of young arc materials, rather than Archean Tarim Craton. Furthermore, the data also indicate that these two sources were paleogeographically separated. Thus we can deduce that the Kumishi and the south to the Dikar metasedimentary rocks were formed proximal to the arc side of the back-arc basin, but the Weiya metasedimentary rocks were closer to the continental side of the back-arc basin.

Keywords: Nd isotopic features, metasedimentary rocks, Xingxingxia group, provenance and forming time, Tectonic setting, the ESCTB of Xinjiang.

Sm-Nd isotopic investigations on clastic sedimentary rocks have been widely used not only to trace the provenance but also as the important indicators of the crustal evolution and the regional tectonic divisions[1~7]. It is believed that Nd isotopic composition can indicate the nature of the sediment sources, and the Nd model ages of the fine-grained sediments generally represent an average crustal residence age derived from different sources[7~9]. Although the Nd model age of the sedimentary rocks can not be regarded as the age of a specifically geological event, it can reflect the basic characteristics of sedimentary source regions. Sedimentary rocks usually consist of materials derived from various sources. Their Nd isotopic composition and Sm/Nd ratios are unaffected by weathering, sedimentary transport and diagenesis, so they will record varying proportions in the chemical and isotopic compositions of different provenance components[3,6,8,10,11]. Although some reports mentioned secondary disturbance of Sm-Nd isotopic system during weathering, sediment sorting, diagenesis[12~15], the primary Sm-Nd system has not been remarkably changed. As already pointed out by Goldschmidt[16], rare earth elements are mainly retained in clay minerals during weathering and sedimentation, only very small amounts being carried by solutions. Therefore, they are transported almost totally into the fine-grained clastic sedimentary rocks, indicating that differentiation of Sm-Nd could almost be neglected[7,10,11]. Gleason et al.[17] suggested that Nd isotopes are ideal for establishing provenance differences because of (1) their sensitivity to differences in crustal age, (2) the coherent behavior of rare earth elements (REEs) in clastic sediments during transport[10], and (3) the low mobility of REEs during diagenesis and metamorphism. Hence, it is possible for selecting Nd isotopic characteristics of fine-grained sedimentary rocks to trace back their provenance and to discuss the crustal growth and evolution[4,7].

The metasedimentary rocks are widely exposed in Proterozoic Xingxingxia group in the eastern segment of Central Tianshan Belt (ESCTB) and are the major component of Proterozoic Xingxingxia group.

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The aims of this contribution are to systemically analyze Sm-Nd isotopic characteristics of metasedimentary rocks from Xingxingxia group and to determine the nature of their source regions and their tectonic implications.

1 Geological setting

The ESCTB uplifted zone is characterized by a lot of Precambrian metamorphic blocks and is overlain by the unmetamorphosed Paleozoic and Mesozoic clastic sedimentary strata. The Precambrian metamorphic blocks are widespread in ESCTB which are composed of Xingxingxia group and Tianhu group. These rocks in Xingxingxia and Tianhu groups in ESCTB have been widely deformed and metamorphosed from greenschist to amphibolite facies, particularly, granulite facies in some locations[18]. The main lithological assemblage of Xingxingxia group consists of amphibolites and various parametamorphic schists, which was intruded by the Meso-Neoproterozoic and Paleozoic granitoids[19, 20]. The parametamorphic rocks include garnet biotite schist, kyanite garnet biotite schist, kyanite mica schist, mica quartz schist, staurolite mica schist, cordierite biotite schist, gneiss and some marbles. Guo et al.1) reported a zircon U-Pb age of (1216 ±74) Ma from mica schist in the Weiya area, which is interpreted as metamorphic age, and another U-Pb age of (1218 ±17) Ma from crystallization zircons of granitic gneiss intruded into mica schists. In addition, a discordant U-Pb upper intercept age of (1750 ±25) Ma from detrital zircons of kaynite biotite schist in the Kumishi area was also reported, which reflects the formation age of the protoliths1).

2 Analytical method and results

Nd isotope analysis of all samples, collected from the Kumishi, the Weiya and the south to the Dikar areas (Fig. 1 and Table 1), was carried out at the Isotope Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences. Mass analyses were performed using a VG354 thermal ionization mass spectrometer. For details of the analytical techniques, procedures and data normalization for the Sm-Nd isotope analyses refer to Refs.[21, 22].

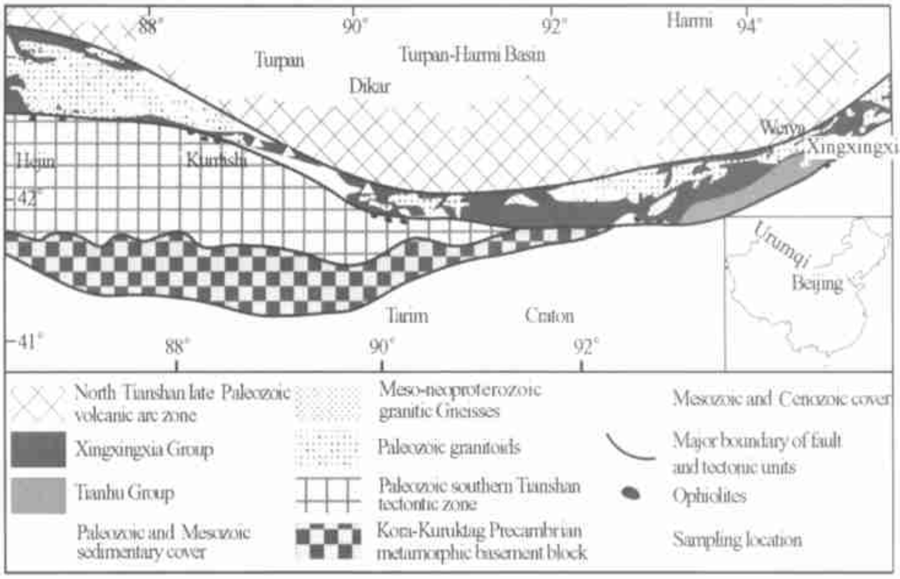

Fig. 1. Tectonic frame map of the Eastern Tianshan Orogen and the sampling locations (revision based on Guo et al.1), 2001).

Table 1. Simplified sample descriptions and sampling locations

Sample No.	Latitude	Longitude	Lithology	Mineral assemblage
			Kumishi area	
KM2105-2	42°19′42″	88°24′00″	Garnet biotite schist	Grt+Bt+Mus+Kfs+Qtz
KM2106-1	42°19′33″	88°24′45″	Kyanite biotite schist	Ky+Bt+Pl+Qtz+/-Mus+/-Grt
KM2106-2	42°19′34″	88°24′46″	Biotite schist with staurolite	Stau+Ky+Pl+Qtz+/-Mus+/-Grt

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1) Guo, Z. J. et al. The basement characteristics, uplifting processes and mineralization remote scene in the early Precambrian complexes in the eastern Tianshan upwelling belt, Xinjiang, China. Report of "305" Project (in Chinese), 2001.

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Sample No.	Latitude	Longitude	Lithology	Mineral assemblage
KM2107-1	42°19′27″	88°24′35″	Biotite schist with kyanite	Ky+Bt+Pl+Qtz+/-Mus+/-Grt
KM2107-2	42°19′27″	88°24′35″	Biotite schish	Bt+Mus+Kfs+Qtz
KM2112-2	42°14′11″	88°48′32″	Staurolite garnet biotite schist	Stau+Grt+Pl+Qtz+/-Mus
KM2113-1	42°13′23″	88°48′06″	Garnet biotite schist	Grt+Bt+Mus+Kfs+Qtz
KM2114-2	42°12′33″	88°47′26″	Garnet mica schist	Kfs+Pl+Bt+Grt+Stau+Qtz
KM2127-2	42°19′12″	88°25′56″	Staurolite biotite quartz schist	Stau+Grt+Pl+Qtz+/-Mus
KM2127-3	42°19′12″	88°25′56″	Kyanite biotite quartz schist	Ky+Bt+Pl+Qtz+/-Mus+/-Grt
KM2127-5	42°19′12″	88°25′56″	Garnet staurolite kyanite biotite schist	Grt+Stau+Ky+Qtz+Bt+Kfs
The south to the Dikar area				
DK2101-2	41°47′47″	89°59′19″	Hornblend plagioclast gneiss	Hbl+Pl+Qtz+Bt+/-Kfs
DK2102-2	41°48′20″	90°00′08″	Hornblend plagioclast gneiss	Hbl+Pl+Qtz+Bt+/-Kfs
DK2103-1	41°48′36″	90°00′21″	Mica quartz schist	Bt+Mus+Kfs+Qtz
DK2104-1	41°48′54″	90°00′44″	Biotite schist	Bt+Mus+Kfs+Qtz
DK2106-1	41°49′15″	90°00′56″	Mica quartz schist	Bt+Mus+Kfs+Qtz
DK2107-1	41°50′00″	90°01′44″	Kyanite mica schist	Ky+Bt+Pl+Qtz+/-Mus+/-Grt
DK2107-2	41°50′00″	90°01′44″	Kyanite cordierite biotite schist	Pl+Bt+Cord+Qtz+Ky
DK2108-1	41°51′01″	90°02′33″	Biotite plagioclast gneiss	Bt+Pl+Kfs+Qtz+/-Mus
Weiya area				
WY2103-2	41°41′35″	94°12′10″	Staurolite mica schist	Stau+Pl+Qtz+Mus
WY2103-4	41°41′35″	94°12′10″	Garnet mica schist	Grt+Pl+Qtz+Mus
WY2104-1B	41°41′15″	94°12′19″	Staurolite mica schist	Stau+Pl+Qtz+Mus
WY2104-1C	41°41′15″	94°12′19″	Staurolite mica schist	Stau+Pl+Qtz+Mus
WY2104-2	41°41′15″	94°12′19″	Garnet cordierite biotite schist	Cord+Grt+Qtz+Bt+Kfs

Nd isotopic data of totally twenty-four samples analyzed are listed in Table 2 and plotted in Figs. 2 and 3. The Nd model ages for the samples in ESCTB range from 1.29 to 2.30 Ga (Table 2). T_{DM} for the samples from the Weiya area is between 1.86 and 2.29, 2.05 Ga on average, suggesting that there is Paleoproterozoic or much older crust in the provenance. T_{DM} values for the samples from the Kumishi and the south to the Dikar areas, however, mainly concentrate between 1.6 and 1.9 Ga, 1.66 Ga on average. The youngest T_{DM} value is 1.29 Ga, which is close to the time of island arc magmatism (ca. 1.2 Ga)1). The depositional age of the sediments must be equal to or younger than the youngest depleted mantle model age; moreover, a magma crystallization age of (1218±17) Ma of granitoids intruded into these metasedimentary rocks, indicating that the depositional age of the metasedimentary rocks of Proterozoic Xingxingxia group must be in the range of 1.2~1.3 Ga, corresponding to the Jixian system in the North China Craton. Therefore, we adopt $\varepsilon_{Nd}(t)=\varepsilon_{Nd}(1.2\,Ga)$ to discuss the characteristics of the provenance.

Table 2. Nd isotopic data of Xingxingxia group metasedimentary rocks

Sample No.	Sm (μg/g)	Nd (μg/g)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	2σ	$\varepsilon_{Nd}(0)$	$f_{Sm/Nd}$	$\varepsilon_{Nd}(t)$	T_{DM}(Ga)
KM2105-2	4.58	23.69	0.1168	0.512308	11	−6.4	−0.41	5.86	1.32
KM2106-1	8.11	41.51	0.1182	0.512112	9	−10.3	−0.40	1.81	1.65
KM2106-2	15.05	79.53	0.1144	0.512071	10	−11.1	−0.42	1.59	1.65
KM2107-1	4.87	23.91	0.1231	0.512042	10	−11.6	−0.37	−0.32	1.86
KM2107-2	4.85	24.70	0.1187	0.512054	11	−11.4	−0.40	0.60	1.75
KM2112-2	3.25	15.87	0.1239	0.512295	11	−6.7	−0.37	4.51	1.45
KM2113-1	9.61	48.59	0.1196	0.512009	10	−12.3	−0.39	−0.42	1.84
KM2114-2	4.47	23.24	0.1163	0.512121	9	−10.1	−0.41	2.28	1.61
KM2127-2	6.48	32.49	0.1205	0.512073	9	−11.0	−0.39	0.69	1.76
KM2127-3	6.47	32.14	0.1218	0.512047	12	−11.5	−0.38	−0.02	1.82
KM2127-5	7.02	35.35	0.1201	0.512345	8	−5.7	−0.39	6.08	1.31

To be continued

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1) Liu, S. W. et al. Neoproterozoic granitic gneisses at Gangou-Chumishi, eastern Tianshan, northwestern China: its petrogenesis and tectonic implications (to be published)

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Sample No.	Sm (μg/g)	Nd(μg/g)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	2σ	$\varepsilon_{Nd}(0)$	$f_{Sm/Nd}$	$\varepsilon_{Nd}(t)$	T_{DM}(Ga)
DK2101-2	5.23	26.15	0.1209	0.512201	14	−8.5	−0.39	3.13	1.56
DK2102-2	4.35	21.34	0.1232	0.512384	8	−5.0	−0.37	6.36	1.29
DK2103-1	5.95	30.15	0.1193	0.511998	10	−12.5	−0.39	−0.59	1.85
DK2104-1	6.88	36.06	0.1154	0.512150	11	−9.5	−0.41	2.98	1.55
DK2106-1	5.91	32.02	0.1116	0.512053	9	−11.4	−0.43	1.67	1.63
DK2107-1	10.49	53.19	0.1193	0.511879	10	−14.8	−0.39	−2.92	2.04
DK2107-2	6.87	34.00	0.1221	0.512060	12	−11.3	−0.38	0.19	1.81
DK2108-1	7.77	40.51	0.1160	0.512009	9	−12.3	−0.41	0.13	1.78
WY2103-2	8.37	45.85	0.1104	0.511885	9	−14.7	−0.44	−1.43	1.86
WY2103-4	7.95	34.32	0.1402	0.512040	11	−11.7	−0.29	−2.99	2.29
WY2104—1B	6.98	35.27	0.119	60.511826	10	−15.8	−0.39	−4.00	2.14
WY2104—1C	4.07	21.18	0.1161	0.511904	11	−14.3	−0.41	−1.94	1.94
WY2104-2	8.45	40.79	0.1252	0.511976	8	−12.9	−0.36	−1.93	2.02

Note: $\varepsilon_{Nd}=[(^{143}Nd/^{144}Nd)_s/(^{143}Nd/^{144}Nd)_{CHUR}-1]\times 10000$,
$f_{Sm/Nd}=[(^{147}Sm/^{144}Nd)_s/(^{147}Sm/^{144}Nd)_{CHUR}]-1$,
$(^{143}Nd/^{144}Nd)_{CHUR}=0.512638$ and $(^{147}Sm/^{144}Nd)_{CHUR}=0.1967$,
$T_{DM}=1/\lambda\times\ln\{1+[(^{143}Nd/^{144}Nd)_s-0.51315]/[(^{147}Sm/^{144}Nd)_s-0.2137]\}$,
where S=sample, $t=1.2$ Ga.

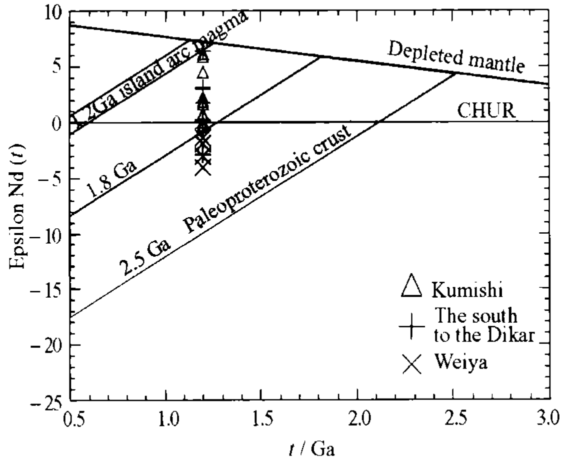

Fig. 2. t-$\varepsilon_{Nd}(t)$ diagram of the metasedimentary rocks. Epsilon Nd values are calculated using the referenced age of 1.2 Ga.

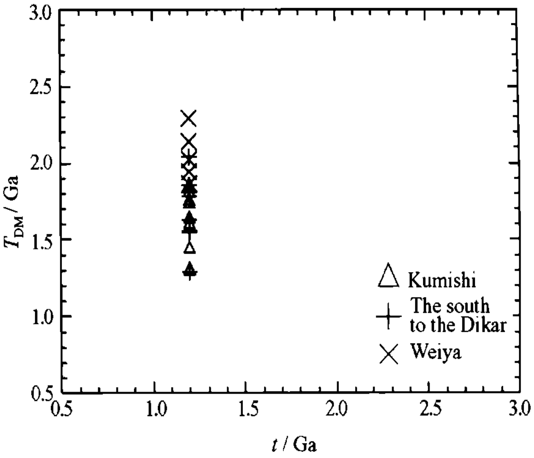

Fig. 3. t-T_{DM} diagram.

The $\varepsilon_{Nd}(t)$ values for all samples range from −4.0 to +6.4, and most values fall in the range −2.0 to +3.2 (Table 2). The $\varepsilon_{Nd}(t)$ values for the five samples from the Weiya area are smaller than −1.4, presenting average value of −2.46. The samples from the Kumishi and the south to the Dikar areas range from −2.93 to +6.36 (averaged 1.37) and from −0.42 to +6.08 (averaged 2.06), respectively. All of samples from the Kumishi and the south to the Dikar areas display an average $\varepsilon_{Nd}(t)$ value of 1.77. The $\varepsilon_{Nd}(t)$ values for the samples from the Kumishi and the south to the Dikar areas are bigger than −1, but those of the samples from the Weiya area are smaller than −1.4. Although three samples from the Kumishi area (KM2105-2, KM2112-2 and KM2127-5) and one sample from the south to the Dikar area (DK2102-2) have similar ^{147}Sm/^{144}Nd ratios (0.111~0.141, Table 2) to others, they have significantly higher $\varepsilon_{Nd}(t)$ values (>4.5).

3 Discussion

3.1 Provenance

In general, sediments derived from an old craton will display the characteristics of more negative ε_{Nd} values (for example, for Archean crust, $\varepsilon_{Nd}<-20$), and from younger crust will present less negative ε_{Nd}, or even positive ε_{Nd} (for example, for recent island arc volcanic rocks, $\varepsilon_{Nd}>2$)[4, 23]. According to the research of Hu et al.[20], the Nd isotopic analysis of Archean gray gneisses, schists and Proterozoic granitoids in the Tarim Craton indicated that the youngest Nd T_{DM} is older than 2.7 Ga, and $\varepsilon_{Nd}(t)$ values by our recalculation concentrate in the range of

−23 ~ −8. In contrast, the samples from Proterozoic Xingxingxia group in ESCTB display T_{DM} ranging from 1.29 to 2.30 Ga, and higher $\varepsilon_{Nd}(t)$ values (> −4.0), which indicates that the Nd isotopic composition of these samples is evidently different from that of the Tarim Craton. So far, neither has there been the report about the Archean age nor existence of Archean T_{DM} value in ESCTB. Hence, these metasedimentary rocks of Xingxingxai group could not be mainly derived from the Archean Tarim craton, but one or more accreted terrain(s) of which accreted time and tectonic background are under further studies. We can notice from Table 2 that these samples show a narrow range of Sm/Nd ratios (0.111 ~ 0.141), but display a wide range of $\varepsilon_{Nd}(t)$ values, which suggests that the source regions can be more than one[5]. Three samples (KM2105-2, KM2112-2 and KM2127-5) from the Kumishi area and one sample from the south to the Dikar area (DK2102-2) display the relatively high positive $\varepsilon_{Nd}(t)$ values, indicating they were derived from the place where young island arc material might be predominant. On the t-$\varepsilon_{Nd}(t)$ plot (Fig. 2), all the sample data points fall inside or close to the field of the Paleoproterozoic crust and between evolutional lines of the Paleoproterozoic crust and 1.2 Ga island arc magma rocks. This suggests that there are two derivations for these sediments, one is an older crust with an age of more than 1.8 Ga, the other is the Mesoproterozoic juvenile materials. All of these indicate that these sediments are the mixing products in a various proportion of these two end members. Almost all the data of the Weiya samples fall within the field of the Paleoproterozoic crust with average Nd model age of 2.05 Ga. In contrast, apart from sample DK2107-1 falling into the field of the Paleoproterozoic crust, the others from the Kumishi and the south to the Dikar are distributed between evolutional lines of the Paleoproterozoic crust and 1.2 Ga island arc magma rocks, with 1.64 Ga and 1.69 Ga average Nd model age, respectively. These changes of $\varepsilon_{Nd}(t)$ and T_{DM} indicate an increased flux of young materials, from the Weiya area, through the south to the Dikar area, to the Kumishi area.

The Nd model ages of metasedimentary rocks in Xingxingxia group and a discordant U-Pb upper intercept age ((1750±25) Ma) from detrital zircons of metasedimentary rock in the Kumishi area show that the sediments could be derived from a significant proportion of Paleoproterozoic crust and a various proportion of participation of juvenile materials. Four samples with relatively high $\varepsilon_{Nd}(t)$ values (KM2105-2, KM2112-2 and KM2127-5 from the Kumishi area and DK2102-2 from the south to the Dikar area) display the relatively young Nd model ages. Except sample WY2103-4 with a $^{147}Sm/^{144}Nd$ ratio of 0.1402, the other samples show $^{147}Sm/^{144}Nd$ ratios ranging from 0.11 to 0.13, indicating little differentiation/fractionation of Sm/Nd ratios during sedimentation and/or earlier source magma processes[3, 6]. Thus, it indicates small disturbance probability of Sm-Nd isotopic system. Even if there is disturbance in Sm-Nd isotopic system, its influence on Sm/Nd ratios of the samples is very small. The Nd model ages also strongly support that the samples from the Kumishi and the south to the Dikar areas contain a component of younger detrital material. Farmer et al.[5] suggested two obvious possibilities for this case: (1) high ε_{Nd} arc components and (2) high ε_{Nd} components derived from younger Precambrain crust. Samples KM2105-2, KM2112-2, KM2127-5 and DK2102-2 have $\varepsilon_{Nd}(t)$ values ranging from +4.5 to +6.4, with Nd model ages of 1.3 ~ 1.5 Ga. This range of Nd model age corresponds to the rocks of the Grenvillian orogenic belt[17, 24]. In addition, the major tectono-magmatism in ESCTB, occurring at about 1.2 Ga, may correspond to the amalgamation of Rodinia1), and the relatively young clastic component could be derived from the arc magmatic material. Hence, the sediment provenance of the Xingxingxia group metasedimentary rocks of ESCTB could be derived from a significant proportion of Paleoproterozoic source region and a participation of younger island arc.

3.2 Tectonic implications

Nd isotope could be used not only to determine the provenance of the sedimentary rocks, but also to recognize their ancient tectonic implications[7, 25]. The Nd isotopic compositions ($\varepsilon_{Nd}(t) = -4.0$ ~ $+6.4$) and Nd model ages ($T_{DM} = 1.29$ ~ 2.30 Ga) of the samples from ESCTB reveal that these metasedimentary rocks formed from various proportional mixing of the materials from older Paleoproterozoic continental blocks and younger arc, and Paleoproterozoic components could occupy the highest

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1) See footnote on page 910

proportion. Whole Xingxingxia group has been widely deformed and metamorphosed to various degrees, from greenschist to amphibolite facies, particularly, granulite facies in some locations, which is very likely to be the Grenvillian accreted terrain(s) and to derive from the amalgamation of Rodinia. This is also supported by the metamorphic zircons U-Pb age of (1216 ±74) Ma from the paragneiss and the magma crystallization zircon U-Pb age of (1218 ±17) Ma from the granitic rocks intruding into these paragneisses. The isotopic signature of these samples also indicates that these two sources were palaeogeographically separated. The samples from the Kumishi and the south to the Dikar areas show lower Nd model ages (T_{DM} = 1.29 ~ 2.04 Ga) and higher $\varepsilon_{Nd}(t)$ (> −1) values, indicating that they could yield proximal to the arc side of the back-arc basin, but those from the Weiya area show higher Nd model ages (T_{DM} = 1.86 ~ 2.29 Ga) and lower $\varepsilon_{Nd}(t)$ (= −4.00 ~ −1.43) values, suggesting these metasedimentary rocks were formed close to the continental side of the back-arc basin.

4 Conclusions

In summary, we can get some conclusive remarks from Nd isotopic characteristics of the Xingxingxia group metasedimentary rocks in ESCTB: (1) The depositional time of Xingxingxia group metasedimentary rocks could be in the range of 1.2 ~ 1.3 Ga, corresponding to the Jixian system; (2) these sediments could be derived from a significant proportion of Paleoproterozoic source and a participation of young materials, rather than the Tarim Craton; (3) these sediments were probably deposited in a back-arc basin tectonic setting, the metasedimentary rocks from the Kumishi and the south to the Dikar areas could yield proximal to the island arc side, but those from the Weiya area could form closer to the continental sides.

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References

1 McLennan, S. M. et al. Geochemical and Nd-Sr isotopic composition of deep-sea turbidites: crustal evolution and plate tectonic associations. Geochimica et Cosmochimica Acta, 1990, 54: 2015.

2 McLennan, S. M. et al. Early Proterozoic crustal evolution: Geochemical and Nd-Pb isotopic evidence from metasedimentary rocks, southwestern North America. Geochimica et Cosmochimica Acta, 1995, 59: 1153.

3 Jahn, B. M. et al. Evolution of the Kaapvaal Craton as viewed from geochemical and Sm-Nd isotopic analyses of intracratonic pelites. Geochimica et Cosmochimica Acta, 1995, 59: 2239.

4 Patchett, P. J. et al. Continental drainage in North America during the Phanerozoic from Nd isotopes. Science, 1999, 283: 671.

5 Farmer, G. L. et al. Nd isotope constraints on sources of Neoproterozoic to Early Cambrian siliciclastic sedimentary rocks in northern Sonora. Journal of South American Earth Science, 2001, 14: 437.

6 Chen, B. et al. Nd isotopic characteristics of the Paleozoic metasedimentary rocks of Altai orogen of Xingjiang and their constraints on the crustal evolution. Science in China (Series D) (in Chinese), 2001, 31(3): 226.

7 Chen, B. et al. Geochemical and isotopic studies of the sedimentary and granitic rocks of the Altai orogen of northwest China and their tectonic implications. Geological Magazine, 2002, 139: 1.

8 McCulloch, M. T. et al. Sm-Nd and Rb-Sr chronology of continental crust formation. Science, 1978, 200: 1003.

9 Miller, J. F. et al. Evolution of continental crust in the Central Andes: constraints from Nd isotope system. Geology, 1989, 17: 615.

10 Taylor, S. R. et al. The Continental Crust: Its Composition and Evolution, Oxford: Blackwell Scientific Publication, 1985.

11 McLennan, S. M. Rare earth elements in sedimentary rocks: Influence of provenance and sedimentary processes. Reviews in Mineralogy, 1989, 21: 169.

12 Nesbitt, H. W. Mobility and fractionation of rare earth elements during weathering of a granodiorite. Nature, 1979, 279: 206.

13 Zhao, J. X. et al. Sm-Nd and U-Pb Zircon isotopic constraints on the provenance of sediments from the Amadeus Basin, central Australia: evidence for REE fractionation. Geochimica et Cosmochimica Acta, 1992, 56: 921.

14 McDaniel, D. K. et al. Resetting of neodymium isotopes and redistribution of REEs during sedimentary processes: the Early Proterozoic Chelmsford Formation, Sudbury Basin, Ontario, Canada. Geochimica et Cosmochimica Acta, 1994, 58: 931.

15 Morey, G. B. et al. Rare earth elements in weathering profiles and sediments of Minnesota: implications for provenance studies. Journal of Sedimentary Research, 1997, 67: 105.

16 Goldschmidt, V. M. Geochemistry. Oxford: Oxford Univ. Press, 1954.

17 Gleason, J. D. et al. Nd isotopes link Ouachita turbidites to Appalachian sources. Geology, 1994, 22: 347.

18 Chen, Y. B. et al. REE and Sm-Nd isotopic characteristics of Weiya granulites in Eastern Tianshan, NW China. Geochimica (in Chinese), 1997, 26 (4): 70.

19 Gu, L. X. et al. Rb-Sr geochronology of granites in the eastern section of the mid-Tianshan belt and its tectonic evolution. Journal of Guilin College of Geology (in Chinese), 1990, 10 (1): 49.

20 Hu, A. Q. et al. Crustal evolution and Phanerozoic crust growth in northern Xinjiang: Nd isotopic evidence. Part I: Isotopic characterization of basement rocks. Tectonophysics, 2000, 328: 15.

21 Qiao, G. S. Normalization of isotopic dilution analysis. Science in China (Series A), 1988, 31: 1263.

22 Liu, S. W. et al. Geological and isotopic geochemical constraints on the evolution of the Fuping Complex, North China Craton. Precambrian Research, 2002, 117: 41.

23 Michard, A. et al. Nd isotopes in French Phanerozoic shale: external vs. internal aspects of crustal evolution. Geochimica et Cosmochimica Acta, 1985, 49: 601.

24 Boghossian, N. D. et al. Nd isotopes and the source of sediments in the miogeocline of the Canadian Cordillera. Journal of Geology, 1996, 104: 259.

25 Hemming, S. R. et al. Geochemical and Nd/Pb isotopic evidence for the provenance of the Early Proterozoic Virginia Formation, Minnesota. Implication for the tectonic setting of the Animikie basin. Journal of Geology, 1995, 103: 147.