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New chronological evidence for Yanshanian diagenetic mineralization in China's Altay orogenic belt

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Abstract Granitoids and related pegmatitic rare-metal deposits are widespread in China's Altay region, they used to be considered as Hercynian rocks and mineral deposits. Reported here are the ^{40}Ar-^{39}Ar ages of potassium-rich minerals (muscovite and microcline) in the Koktokay pegmatitic rare-metal orefield and whole-rock as well as quartz fluid-inclusion Rb-Sr isochron ages of granite and ores in the Shangkelan pegmatite rare-metal orefield. The ages indicate that there are Yanshanian Diagenetic Mineralization events happening in China's Altay orogenic belt and that formation of the famous Koktokay No.3 pegmatitic rare-metal deposit endured about 30 Ma of magmatic crystallization differentiation.

Keywords: Yanshanian diagenetic mineralization, isochronological evidence, Altay orogenic belt.

1 Formation and evolution of the China's Altay orogenic belt

As a very important part of the Central-Asia Super Orogenic Belt, the China's Altay orogenic belt is a late Caledonian folded belt consisting of Ordovician-Silurian detrital sediments[1]. With zircon U-Pb ages and whole-rock Sm-Nd isochron ages, predecessors[2] concluded that the crystalline basement in the Altay orogenic belt consist of newly-produced continental crusts resulting from crust-mantle differentiation 2.0—1.8 Ga, 1.5—1.4 Ga and 1.0—0.9 Ga ago. During the Early Paleozoic era, the China's Altay area endured a transform process from a stable continental margin to an active one, and began the collision-orogenic process in the Late Paleozoic. At the end of Paleozoic era, this area began intracontinental evolution, and most geologists used to believe that the area has been in a structural stillstand with weak magmatism since then. Chronological studies of granitoids and related pegmatitic rare-metal deposits in the China's Altay region have been carried out by a group of scholars[3—11], but almost all the data they got reflect Hercynian tectonomagmatic events of the region, only a little explained as the Yanshanian magmatic events[2]. Besides, most of the published ages (usually dated with whole-rock K-Ar method) are little creditable. Recent studies carried out by the authors show that the Indosinian and Yanshanian magmatism was quite strong and a considerable amount of mineral resources were formed, which is of great significance for reconsidering the geological evolution history of the Altay Orogenic Belt. Reported here is some new isochronological evidence of the Yanshanian diagenetic mineralization.

2 Geological characteristics of some typical Yanshanian deposits

(ⅰ) The Koktokay No.3 pegmatitic rare-metal deposit. The pegmatitic rare-metal deposits in Koktokay area are usually considered by predecessors[8—11] to be related to the Aler composite granite batholith. Along the contact zone of the batholith, there exist thousands of granitic pegmatitic dikes brokenly situated in groups, constituting a zoning of tens of kilometers long and the most important pegmatite district in the China's Altay orogenic belt, among which the Koktokay No.3 dike is the most typical one which is a superlarge composite rare-metal deposit with excellent structural zoning. The Koktokay No.3 dike (from rim to core) was divided into nine structural zones[8—11] according to mineral assemblages: (Ⅰ) graphic pegmatite zone; (Ⅱ) sugary albite zone; (Ⅲ) massive microcline zone; (Ⅳ) muscovite-quartz zone; (Ⅴ) foliated albite-spodumene zone; (Ⅵ) quartz-spodumene zone; (Ⅶ) muscovite-foliated albite zone; (Ⅷ) foliated albite-lepidolite zone; and (Ⅸ) massive quartz-microcline zone. Basides, some scholars distinguished a quartz-pollucite zone which was not well-developed and can only be found locally.

A great deal of chronological studies of granitoids and related deposits in the Koktokay area have been carried out since the 1960s by predecessors: Lei et al.[8] summed up the isotopic age of the granitic pegmatitic dikes and suggested that the rare-metal mineralization in the Koktokay area mainly happen during the middle-late Hercynian movement as far as to the Indosian period; Zou and his colleagues[9] systematically studied the chronological ages of the Koktokay No.3 pegmatitic dike and its mineralization age, concluding that: (ⅰ) structural zones of the dike were the product of about 100 Ma of magmatic crystallization differentiation: pegmatitic magma began to crystallize 330 Ma ago after its emplacement till the formation of the foliated albite-lepidolite zone (Ⅷ) 200 Ma age; (ⅱ) crystallization of the dike began at its rim and finished at the core; (ⅲ) the K-Ar age (120 Ma) of the microcline from the massive quartz-microcline zone (Ⅸ) do not reflect its real crystallization age because of big error.Although age dating of pegmatitic rare-metal mineralization in Koktokay area began at the 1960s and some conclusions have been reached based on a group of chronological data, except for a Rb-Sr whole isochron[9] ((331.9 ± 1.5) Ma), all the other ages are K-Ar ones which were mainly dated from the 1960s to the 1970s by several isotopic laboratories. Because of bad test conditions at that time, the ages are little creditable, such as three K-Ar ages[10] of muscovite from sugary albite zone (Ⅱ) of the Koktokay No.3 dike are quite different (292, 194.51, 198.51 Ma), much larger than the errors resulting from the dating method. Hence, all the data published need to be proved.

(ⅱ) The Shangkelan pegmatite rare-metal deposit. The Shangkelan pegmatite rare-metal deposit locates in the northern limb of the Kelan synclinorium, to the northern side of the Abagang fault, NE Aleitai City, Xinjiang Uygur Autonomous Region, China. Mineralized pegmatite veins in the ore district are distributed along the contact zone of the Shangkelan muscovite-albite granitic body and the Devonian system with greisen dikes between the granite and the pegmatite. The pegmatite and greisen dikes resulted from crystallization differentiation of magma and post-magmatic alteration, respectively. The Shangkelan muscovite-albite granitic body covers an area of 3 km^2 and consists mainly of albite (~55%), quartz (30%), muscovite (10%) and biotite ($\leq$5%) with a little apatite, beryl and wolframite seen with naked eyes. Hu[2] dated the granitic body with whole-rock Rb-Sr isochron technique, gaining an age of (183± 38)Ma(2σ).

3 Isochronological evidence for Yanshanian diagenetic mineralization

(ⅰ) Dating methods. With whole-rock and fluid-inclusion Rb-Sr dating technique as well as fast-neutron activation analyses of potassium-rich minerals, the authors respectively dated fresh granite and quartz from the Shangkelan river bank, muscovite and microcline from the Koktokay mining area. The Rb-Sr isotopic analyses were carried out with mass spectrum MAT-261 in the Research and Test Center, Chinese Academy of Geological Sciences, and samples were prepared with the method reported by Li Huaqin[12,13]. Isotopic analyses of argon were finished with gas mass spectrum MM-1200B in the Opening Laboratory of Isotope Geology, former Ministry of Geology and Mineral Resources. The purity of minerals for ^{40}Ar-^{39}Ar dating is more than 99.5%, and neutron irradiation was carried out in the nuclear reactor 49-2 in the Academy of Atomic Energy of China.

(ⅱ) Result and discussion. Shangkelan pegmatite rare-metal orefield: Rb-Sr data for muscovite-albite granitic body and fluid inclusions in quartz from the pegmatite vein of the Shangkelan orefield are listed in tables 1 and 2. Two sets of data show good linear relationships, and give an age of (181± 9.2) Ma and (177± 17)Ma(2 σ), respectively (figs. 1 and 2), suggesting that both the emplacem ent of the granitic body and rare-metal mineralization happen during the early Yanshanian period.

Table 1 Whole-rock Rb-Sr compositions of the Shangkelan muscovite-albite granite body

Sample No.	Sample name	Rb (10^{-6})	Sr (10^{-6})	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 1\sigma$
SN1-3	whole rock	393.9	16.30	70.92	0.886 87 ±0.000 02
SN1-5	whole rock	394.3	12.30	94.72	0.945 84 ±0.000 02
SN1-7	whole rock	400.4	9.989	119.1	1.019 82 ±0.000 10
SN1-9	whole rock	580.0	5.973	302.9	1.486 38 ±0.000 10
SN1-4	whole rock	471.3	7.363	193.3	1.194 53 ±0.000 07

Table 2 Rb-Sr compositions of quartz fluid inclusions from the Shangkelan rare-metal deposit

Sample No.	Sample name	Rb (10^{-6})	Sr (10^{-6})	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 1\sigma$
SN2-1	fluid inclusions	4.349	3.411	3.679	0.718 75 ±0.000 01
SN2-7	fluid inclusions	3.495	0.397 3	25.53	0.773 53 ±0.000 02
SN2-5	fluid inclusions	10.06	3.515	8.270	0.732 63 ±0.000 02
SN2-10	fluid inclusions	8.704	2.304	10.92	0.738 00 ±0.000 02
SN2-4	fluid inclusions	3.069	2.070	4.281	0.720 78 ±0.000 04
SN2-9	fluid inclusions	14.99	3.718	11.67	0.741 61 ±0.000 06

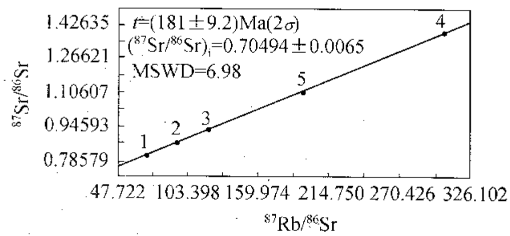

Fig. 1. Whole-rock Rb-Sr isochron of the Shangkelan muscovite-albite granite.

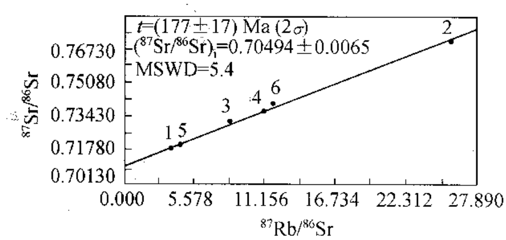

Fig. 2. Quartz fluid-inclusion Rb-Sr isochron of ores from the Shangkelan orefield.

Koktokay orefield: Muscovite from graphic pegmatite zone and from foliated albite-spodumene zone as well as microcline from massive quartz-microcline zone in the Koktokay No.3 dike have been dated with the ^{40}Ar-^{39}Ar fast-neutron activation method (tables 3—5, fig. 3—5).

Table 3 ^{40}Ar-^{39}Ar fast-neutron activation analytical data of muscovite from graphic pegmatite zone of the Koktokay No.3 dike

Heating stage	T/℃	($^{40}Ar/^{39}Ar$)m	($^{36}Ar/^{39}Ar$)m	($^{37}Ar/^{39}Ar$)m	$^{39}Ar/E^{-1}4$ (mole)	^{39}Ar(%)	Age/Ma
1	400	16.424 8	0.032 2	0.018 0	40.2	0.27	165.1 ±10.3
2	500	14.144 8	0.023 6	0.014 4	54.2	0.63	171.1 ±6.1
3	600	9.763 5	0.007 8	0.002 6	179.6	1.84	177.0 ±3.3
4	700	8.769 8	0.004 1	0.001 2	3 019.1	22.12	179.5 ±2.2
5	740	7.622 8	0.000 5	0.000 9	1 278.5	30.71	177.4 ±1.8
6	780	7.689 4	0.000 8	0.000 0	410.8	33.47	117.1±3.1
7	860	7.580 0	0.000 7	0.001 1	1 213.3	41.62	175.5 ±1.7
8	890	7.642 0	0.000 6	0.000 0	391.8	44.25	177.1 ±2.5
9	930	7.752 5	0.000 3	0.000 4	891.3	50.24	182.0 ±1.8
10	990	7.703 2	0.000 1	0.000 5	5313.6	85.93	182.1 ±1.8
11	1 025	9.848 2	0.007 5	0.000 7	396.3	88.60	180.9 ±2.6
12	1 080	9.812 5	0.007 3	0.001 9	1 239.1	96.92	181.9 ±2.1
13	1 200	11.462 6	0.012 6	0.015 8	308.6	98.99	183.6 ±4.5
14	1 400	11.089 5	0.016 5	0.061 8	149.9	100.00	149.3 ±6.2

Table 4 ^{40}Ar-^{39}Ar fast-neutron activation analytical data of muscovite from foliated albite-spodumene zone of the Koktokay No.3 dike

Heating stage	T/℃	($^{40}Ar/^{39}Ar$)m	($^{36}Ar/^{39}Ar$)m	($^{37}Ar/^{39}Ar$)m	$^{39}Ar/E^{-14}$ (mole)	^{39}Ar(%)	Age/Ma
1	400	14.428 9	0.016 9	0.012 7	58.9	0.28	223.6 ±9.5
2	500	11.072 3	0.009 4	0.006 8	95.0	2.29	196.1 ±4.1
3	690	8.444 3	0.003 1	0.002 1	771.9	13.78	178.8 ±2.5
4	740	7.934 6	0.001 5	0.000 8	1224.0	32.00	178.2 ±2.2
5	780	7.866 9	0.001 3	0.000 7	2475.5	68.85	177.9 ±1.7
6	830	8.104 4	0.002 1	0.000 0	219.1	72.11	177.9 ±1.8
7	890	7.992 3	0.001 8	0.000 1	695.8	82.47	177.3 ±2.1
8	960	7.896 2	0.001 5	0.001 3	508.9	90.04	177.1 ±2.0
9	1 050	7.761 8	0.001	0.002 1	481.1	97.20	177.7 ±2.0
10	1 140	7.902 9	0.001 4	0.000 1	154.7	99.50	178.2 ±1.7
11	1 230	41.047 6	0.122 3	0.091 5	6.2	99.60	118.9 ±80.6
12	1 330	23.396 8	0.040 7	0.069 5	14.2	99.81	263.7 ±85.6
13	1 400	17.913 3	0.058 1	0.301 5	12.9	100.00	190.0 ±21.6

Table 5 ^{40}Ar-^{39}Ar fast-neutron activation analytical data of microcline from massive quartz-microcline zone of the Koktokay No.3 dike

Heating stage	T/℃	($^{40}Ar/^{39}Ar$)m	($^{36}Ar/^{39}Ar$)m	($^{37}Ar/^{39}Ar$)m	$^{39}Ar/E^{-14}$ (mole)	^{39}Ar(%)	Age/Ma
1	400	11.487 9	0.021 4	0.128 5	1230.0	5.92	124.9 ±3.8
2	460	5.019 5	0.001 0	0.002 0	546.0	8.55	114.0± 0.3
3	540	4.883 5	0.000 1	0.000 1	2293.0	19.58	117.0± 1.1
4	610	4.892 9	0.000 0	0.003 7	703.0	22.96	115.7± 1.1
5	700	5.057 7	0.000 2	0.000 2	2387.0	34.44	120.8 ±1.2
6	780	5.286 9	0.000 5	0.001 2	1669.0	42.48	123.9 ±1.3
7	860	5.404 7	0.000 3	0.000 3	1393.0	49.18	127.8 ±1.3
8	960	5.694 0	0.000 2	0.000 0	4541.0	71.02	135.6 ±1.4
9	1 050	6.298 0	0.000 4	0.000 0	1592.0	78.68	147.7 ±1.8
10	1 125	6.329 1	0.000 3	0.000 6	2422.6	90.34	149.2 ±1.5
11	1 200	6.246 7	0.001 7	0.003 2	1184.0	96.03	138.1 ±1.5
12	1 300	6.591 3	0.000 8	0.015 5	476.0	98.32	152.2 ±1.8
13	1 400	10.073 1	0.009 4	0.089 4	348.0	100.00	173.8 ±3.9

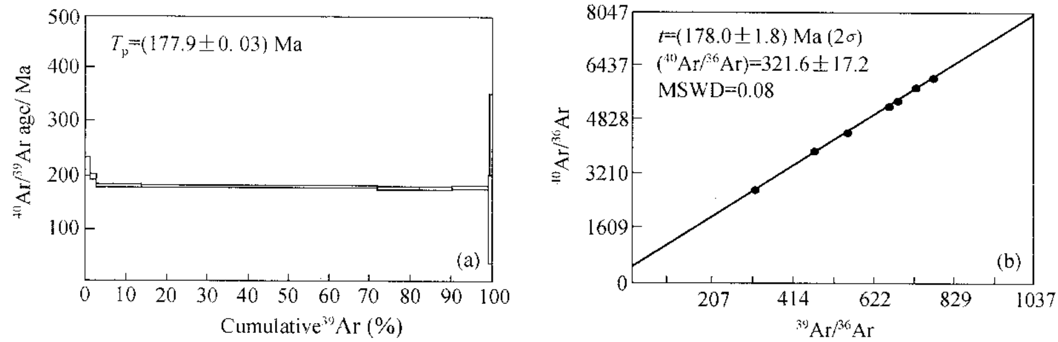

Fig. 3. ^{40}Ar-^{39}Ar age spectrum (a) and isochron (b) of muscovite from graphic pematite zone from the Koktokay No.3 dike.

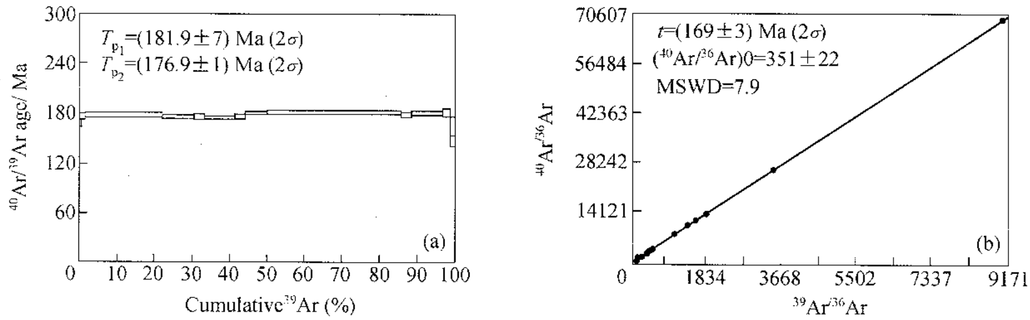

Fig. 4. ^{40}Ar-^{39}Ar age spectrum (a) and isochron (b) of muscovite from the foliated albite-spodumene zone from the Koktokay No.3 dike.

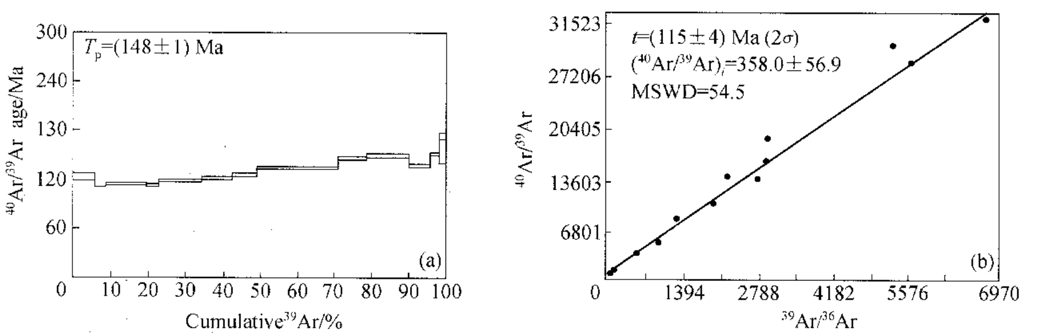

Fig. 5. ^{40}Ar-^{39}Ar age spectrum (a) and isochron (b) of muscovite from the massive quartz-microcline zone of the Koktokay No.3 dike.

Table 3 and fig. 3 show that: (ⅰ) the cumulative ^{39}Ar separated from muscovite from the graphic pegmatite zone is less than 3% at low temperatures (400—500℃) and high temperatures (1 230—1 400 ℃), so the apparent ages show no geological significance (Dalrymple et al.[14]); (ⅱ) the cumulative ^{39}Ar separated from muscovite is as high as 97% or more from 690 to 1 140℃, a stable age spectrum was formed (fig. 3(a)) with a plateau age of (177.9±0.03)Ma (2σ) given; (ⅲ) the age spectrum reflects a $^{40}Ar/^{39}Ar$ closed system hold since the crystallization of muscovite and the system has not been disturbed by post heat events; (ⅳ) coherence of plateau age and $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ isochron age shows no existence of excess argon; (ⅴ) initial $^{40}Ar/^{39}Ar$ (321±17) is a little bigger than the $^{40}Ar/^{39}Ar$ ratio (296) of current atmosphere, which might result from $^{40}Ar/^{36}Ar$ and $^{39}Ar/^{36}Ar$ test error because of low content of ^{36}Ar in the sample, or from entry of ^{40}Ar to crystal lattice by absorption and/or diffusion when and/or after crystallization of the muscovite[15]; and (ⅵ) both the plateau age and ^{40}Ar/^{36}Ar-^{39}Ar/^{36}Ar isochron age reflect the forming age of graphic pegmatite zone of the Koktokay No.3 dike.

From table 4 and fig. 4(a) we can find that there exist two stable age spectra respectively at 500—860℃ and 890—1 200℃, corresponding plateau age is (181.9±7.0)Ma(2σ) and (176.9±1.8)Ma(2σ), and the mean age is 179.4 Ma. With the ^{40}Ar/^{36}Ar and ^{39}Ar/^{36}Ar ratios at the temperature from 500 to 1 200℃, the authors got an isochron (fig. 4(b)) and an isochron age of (169±3)Ma(2σ) which is about 10 Ma less than the mean plateau age. The fact that the difference between the isochron age and plateau ages is far larger than the test error and that the initial ^{40}Ar/^{39}Ar (351±22) is an obviously bigger than the ^{40}Ar/^{39}Ar ratio (296) of current atmosphere indicate that there might be entry of ^{40}Ar to crystal lattice by absorption and/or diffusion when and/or after crystallization of the muscovite[15]. According to the geological fact that the foliated albite-spodumene zone was formed after the crystallization of the graphic pegmatite zone, the isochron age may be close to the forming age of the albite-spodumene zone. Besides, the ages show that the time interval between crystallization of the outmost zone and the middle zone of the Koktokay No.3 dike was very small and can be hardly distinguished with chronological methods.

It can be seen from table 5 and the age spectrum (fig. 5(a)) of microcline from the massive quartz-microcline zone of the Koktokay No.3 dike that: (ⅰ) at the temperature from 460 to 860℃, the plateau age increases slowly with temperature from 114 to 127 Ma with the cumulative ^{39}Ar as much as 49% or more (table 5); (ⅱ) three peaks of cumulative ^{39}Ar happen at the temperature from 960 to 1 125℃, the corresponding plateau age is (135.6±1.4) Ma, 147.7±1.8 Ma and (149.2±1.5) Ma (2σ), respectively; (ⅲ) a stable plateau appear at the temperature from 1 050 to 1 125℃ (fig. 5(a)), with the plateau age to be (148.0±1)Ma(2σ); (ⅳ) the apparent age and ^{40}Ar/^{39}Ar ratios change with temperature (table 5), which might result from loss of radiogenic argon because of disturbance of later heat events or from entry of ^{40}Ar to crystal lattice by absorption and/or diffusion when and/or after crystallization of the microcline; (ⅴ) the isochron (fig. 5(b)) may be a pseudoisochron (because the initial ^{40}Ar/^{39}Ar=358±56.9 is much higher than the ^{40}Ar/^{39}Ar ratio of the current atmosphere, which may suggest the existence of excess argon. Besides, the samples scatter in the isochron with MSWD=54.5, this kind of scattering should result much more from disturbance of ^{40}Ar/^{39}Ar system because of bad close condition provided by the crystal lattice of microcline than test errors), and isochron age has no geological significance just like the low-temperature apparent ages which are hardly creditable because of existence of excess argon (there are a series of conditions for loss of argon at low temperatures, the most possible ones are different activation energy states for separating argon from microcline, perthitization of microcline after crystallization and argon diffusion along the cleavage face {010} and {001} of microcline); (ⅵ) the high-temperature plateau age ((148.0±1) Ma) basically reflects the forming age of the massive quartz-microcline zone, or the upper limit of forming the Koktokay No.3 dike.

4 Conclusions

Rb-Sr isochron age for muscovite-albite granitic body and for quartz fluid inclusions from the Shangkelan rare-metal orefield as well as ^{40}Ar/^{39}Ar ages for muscovites and microcline from the Koktokay orefield are in good accordance with the field geological facts, suggesting that there exists Yanshanian diagenetic mineralization in the China's Altay region.

The world-famous Koktokay No.3 pegmatite dike with well-developed zoning was formed in a closed system of the deep crust through long period (about 30 Ma) of magmatic crystallization differentiation.

Granitic pegmatite veins are widespread in the China's Altay region, and their forming ages used to be considered to be in the Hercynian Period (according to the chronological data reported before). With the whole-rock and fluid-inclusion Rb-Sr dating technique and ^{40}Ar/^{39}Ar fast-neutron activation analyses of potassium-rich minerals (muscovite and microcline), the authors recently got a great deal of Indosian and Yanshanian diagenetic mineralization ages (such as the Dakelasu and Xiakelasu pegmatite vein (220—240 Ma ago)). Hence, the forming age of pegmatite veins in the China's Altay orogenic belt needs further study, which is of great significance for understanding the evolution history of the Altay Orogenic Belt.

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