Research Article

Genesis of the Bieyesamas Monzogranite of the Altay Mountain, Xinjiang, Northwestern China, and Its Rare Metal Resource Potential

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Lying in the Altay Orogenic Belt in Xinjiang, Northwestern China, the Bieyesamas monzogranite pluton is located in the North Altay Terrane. It is one of the important granitic batholiths with a large amount of rare metal pegmatite dikes. According to LA-ICP-MS zircon U-Pb isotopic dating, the $^{206}\text{Pb}/^{238}\text{U}$ weighted average age of the Bieyesamas monzogranite is 451.1 ± 5.1 Ma (MSWD = 6.0), indicating the formation age of Late Ordovician. The Bieyesamas monzogranite has secondary minerals such as garnet and tourmaline. The geochemical analysis shows that the pluton is characterized by high SiO_2 (70.45%~75.44%), Al_2O_3 (14.04%~17.14%), potassium and alkaline ($\text{K}_2\text{O} = 4.20\% \sim 4.78\%$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 7.90\% \sim 8.99\%$), A/CNK (1.16~1.28), and high corundum (2.33%~5.08%) being found in CIPW standard minerals, belonging to high-K calc-alkaline peraluminous series. The pluton is enriched in LREE, depleted in HREE (LREE/HREE = 5.99~9.65), with obviously negative Eu anomaly ($\delta\text{Eu} = 0.44 \sim 0.60$), while the trace elements are characterized by Rb, K, Nb, Ta, Hf, and U enrichment and Ba, Sr, Ti, and Zr depletion, as well as with high differentiation index (DI = 93.24%). Zircon $\varepsilon\text{Hf}(t)$ values range from 2.89 to 7.69, with the corresponding two-stage model ages ($T_{\text{DM}2}$) of 941~1257 Ma. The mineral assemblage, geochemical characteristics, and zircon Hf isotope indicate the pluton experienced the highly fractionated process and belongs to highly fractionated S-type granite, which was formed by partial melting of the Meso- to Neoproterozoic crustal material. In the Bieyesamas monzogranite, the average contents of rare metals are obviously higher ($\text{Li} = 550 \times 10^{-6}$, $\text{Be} = 10.18 \times 10^{-6}$, $\text{Nb} = 18.91 \times 10^{-6}$, $\text{Ta} = 2.14 \times 10^{-6}$, $\text{Rb} = 500 \times 10^{-6}$, and $\text{Cs} = 149.9 \times 10^{-6}$) than the other rocks and Clark values of crust, which indicates that the Bieyesamas pluton has the enrichment potential of rare metals. The metallogenic geological conditions are superior in the Bieyesamas area of the Altay Mountain, and rare metal deposits and ore spots are widely distributed. In particular, the newly discovered rare metal deposits are characterized by large-scale mineralization, high grade and industrial utilization value, etc. It is preliminarily predicted that they have reached the medium-scale deposits. Therefore, the Bieyesamas area is one of the key areas for rare metal prospecting breakthroughs in the future, with great potential for rare metal mineral resources.

1. Introduction

The Altay Orogenic Belt is located in the western part of the Central Asian Orogenic Belt, in the transition zone between the Siberian Block and the Kazakhstan-Jungare Block [1], with a total length of about 2000 km, extending nearly east-west through China, Mongolia, Russia, and Kazakhstan (Figure 1(a)), and stretching about 500 km in northern

Xinjiang, NW China [2]. The Altay Orogenic Belt is adjacent to the West Sayan Ridge ancient island arc belt to the north and is bounded to the Junggar Orogenic Belt by the Ertix-Mainobo suture zone [3] (Figure 1(b)). The Altay Orogenic Belt is an accretionary orogenic belt, which has undergone two-way accretion of the Paleozoic oceanic crust and intra-continental orogeny of the Middle Cenozoic, forming a series of continental blocks, island arcs, and accretionary

FIGURE 1: Geotectonic position (a) and distribution of intrusive rocks (b) in the Altay area of Xinjiang, Northwestern China. Main faults: F1, Hongshanzui Fault; F2, Abagong Fault; F3, Kezijaier Fault; F4, Ertix Fault.

complex [4], as well as a large number of intermediate-acid intrusive rocks [5], with at least 40% volume of the intrusive rocks exposed [6], and intrusive rocks were formed over a wide range of ages, including Ordovician-Silurian (479–421 Ma), Devonian (410–370 Ma), Carboniferous (368–313 Ma), Permian (300–252 Ma), and Triassic (247–202 Ma) [7]. The massive development of intrusive rocks provides a unique physical source condition for the formation of pegmatites within the Altay Orogenic Belt, and nearly 100,000 pegmatite veins have been identified in Altay, forming an important rare metal mineralization belt in China [8–16].

The most famous rare metal deposit in the Altay Mountains of Xinjiang is the No. 3 pegmatite vein of Koktokay, but it is currently shut down due to resource depletion. In the northeastern part of the Altay Mountains, a batholith two-mica granite has been developed in the Bieyesamas area, and medium-sized spodumene ore has been reported here [17]. In 2017, the author carried out mineral exploration in the Bieyesamas area of Altay, relying on the geological resource survey and evaluation project, and newly discovered dozens of granitic pegmatite veins, all of which showed rare metal mineralization such as lithium, beryllium, niobium, tantalum, rubidium, and cesium, thus indicating that the area has a large prospecting potential [18]. Ding et al. studied the genetic relationship between the ore-bearing pegmatites and granite enclosing rocks of the Bieyesamas deposit and concluded that the two rocks are products of different tectonic settings in different periods [19]. Yang et al. carried out a study on the geochemical characteristics of granite rocks and their geological significance of the Bieyesamas deposit

and concluded that its genetic type is highly differentiated I-type granite [20]. Recently, we carried out petrology, geochronology, Lu-Hf isotope, and geochemistry studies on the Bieyesamas monzogranite and considered it as S-type granite. Meanwhile, based on the study of the metallogenic geological background, we further explored the prospect of rare metal finding and mineralization potential in the region, which provide new information for the regional tectonic evolution of the Altay Orogenic Belt, and at the same time, it is of great indicative significance for the search and exploration of rare metals in northeastern Altay.

2. Regional Geological Background

The fracture zones and different terrain in the Altay region of Xinjiang all spread in a northwestern-southeastern direction, with the Hongshanzui Fault (F1), the Abagong Fault (F2), and the Kezijaier Fault (F3) distributed from north-east to south-west, dividing the Altay Orogenic Belt into the North Altay Terrane, the Central Altay Terrane, and the Qionghuer-Abagong Terrane [21]. To the south, it is adjacent to the Junggar Orogenic Belt, and between them is the Ertix-Mainobo suture zone and the Ertix Fault (F4) (Figure 1(b)). Tectonically, the Bieyesamas pluton is located within the North Altay Terrane.

The stratigraphic distribution of the North Altay Terrane consists mainly of Devonian and Carboniferous systems (Figure 1(b)), including the Middle-Upper Devonian Mangdaiqia Formation, Upper Devonian-Lower Carboniferous Kumasu Formation, and Lower Carboniferous Hongshanzui

Formation. The Mangdaiqia Formation contains fine clastic rocks represented by gray-light and gray-green sandstone, siltstone, with generally large outcrop thickness, stable extension, and obvious rhythmic characteristics. It shows dominant fine sandstone-siltstone cycle, with local intercalation of a fine sandstone-mudstone cycle, and the fine sandstone and siltstone are interbedded. The main lithologies of the Upper Devonian-Lower Carboniferous Kumasu Formation are fine siltstone, fine- to medium-grained litharenite, phyllite, and radiolarian siliceous rocks. The Lower Carboniferous Hongshanzui Formation is gray and gray-black dacite, altered breccia tuff with a thin layer of medium- to fine-grained tuffaceous sandstone and siltstone, feldspathic litharenite, mudstone, etc. [19]. The intrusive rocks of the North Altay Terrane are widely developed, accounting for more than 60% of the area. The intrusive rocks are mainly Early Devonian medium-grained granodiorite and fine-grained monzogranite, Late Carboniferous monzogranites, and biotite syenogranites. The vein rocks are mainly pegmatites with rare metal minerals [20].

The volcanic activity in the region is not well developed, and the exposed area of volcanic rocks is about 152 km²; the rock type is mainly felsic volcanic lava, with a small amount of intermediate-felsic volcanoclastic rocks. The volcanic rocks mainly occurred in the Lower Carboniferous Hongshanzui Formation, and there is also a small amount in the first section of the Middle-Upper Devonian Mangdaiqia Formation. There are also many types of metamorphic rocks, affected by regional metamorphism, thermal contact metamorphism, and kinetic metamorphism. Among them, the metamorphic degree of the Middle-Upper Devonian Mangdaiqia Formation reaches a low green-schist phase, and its metamorphic mineral combination is sericite + chlorite + quartz. The Upper Devonian-Lower Carboniferous Kumasu Formation is characterized by the occurrence of chlorite. The Lower Carboniferous Hongshanzui Formation also underwent low green-schist phase metamorphism, and its mineral combination is chlorite + epidote + quartz.

3. Characteristics of Rare Metal Resources in the Altay

More than 100,000 pegmatite veins containing rare metals, industrial minerals, or gemstones have been discovered in the Altay region of Xinjiang, which is rich in nonmetallic resources such as industrial muscovite, ceramic feldspar, and gemstones, as well as being a well-known pegmatite-type rare metal-rich area in China and abroad.

The Altay pegmatite-type rare metal deposits are mainly produced in the Central Altay Terrane and the Qiongkuier-Abagong Terrane (Figure 1(b)), and most of them are distributed in nine pegmatite catchment areas [22]. The main diagenetic periods of rare metal deposits include the Caledonian, Hercynian, Indosinian, and Yanshanian periods. These deposits are characterized by increasing mineralization elements, mineral assemblages, and pegmatite mineral structural zones from early to late stages, and the deposits are gradually expanding in size and type [23].

Altay pegmatite-type rare metal deposits include a variety of rare metal mineralization types and genesis [24], among which the pegmatites of metamorphic differentiation genesis are mainly REE-Nb type, produced in the northern section of the Qiongkuier-Abagong Terrane (Figure 1(b)), and belong to the Caledonian and Hercynian periods, basically without internal part-band structure, small in scale, and the mineral composition and the enclosing black mica granodiorite gneiss are basically consistent. The mixed metasomatic pegmatite deposits are mainly of industrial muscovite (small amount of Be and Nb) type, produced in the southern section of the Central Altay Terrane and belong to the Caledonian. The high-temperature gas-liquid pegmatite deposits are mainly of Be-(Mo or W) type, produced in the Central Altay Terrane; no chronological data are available, but the related granite bodies belong to the Hercynian and Yanshanian periods. The pegmatites of remelting magmatic differentiation are mainly Be-(Nb-Ta), Li-(Nb-Ta), and Li-Be-Nb-Ta-Cs rare metal types, which are produced in the Central Altay Terrane and the Qiongkuier-Abagong Terrane, and belong to the Hercynian, Indosinian, and Yanshanian periods of mineralization, and these deposits are large in scale and have well-developed internal structural zones and constitute the most important pegmatite-type rare metal deposits in the Altay region (Figure 1(b)).

The distribution of rare metal deposits within the North Altay Terrane is relatively less, and only the pegmatitic spodumene ore of the Bieyesamas has been found [17], but new deposits have been gradually discovered through mineral exploration in recent years [18].

4. Petrography

The Bieyesamas batholith extends in the northwest direction, and the exposed area is more than 1000 km², which can be divided into two structural belts of internal medium-coarse grained and outward medium and fine-grained, but there is no obvious boundary between the two belts, and the relationship is gradually transition. This granitic batholith consists of two-mica monzogranite. The rocks show typical massive structure and granular texture (Figure 2(a)).

The minerals are mainly composed of alkali feldspar (~40%), plagioclase (~20%), quartz (~25%), muscovite (~12%), and biotite (<3%, Figures 2(b)–2(d)), with minor garnet and tourmaline (Figures 2(e) and 2(f)). Secondary minerals such as sericite and chlorite also can be seen. The species of alkaline feldspar is microcline or cryptoperthite, and mineral crystals are euhedral and subeuhedral, with the myrmekitic texture and the tartan twinning (Figure 2(b)).

Muscovite is mainly primary mineral. Muscovite crystals are euhedral flakes (Figures 2(c) and 2(d)), with scattered distribution and undulating extinction. In Figure 2(b), muscovite is irregular and symbiosis with quartz and plagioclase, etc., showing secondary feature.

Garnet crystals are subeuhedral granular (Figure 2(e)), indicating that its material source is from the crust. Tourmaline crystals are commonly light blue-green strip or granular (Figure 2(f)), with obvious polychromaticity.

FIGURE 2: Field photographs (a, b) and microphotographs (c–f) of Bieyesamas monzogranite. Abbreviations: Mc: microcline; Pl: plagioclase; Qtz: quartz; Ms: muscovite; Bi: biotite; Tur: tourmaline; Grt: garnet.

5. Analytical Methods

5.1. Zircon U-Pb and Lu-Hf Isotope Analyses. A 2 kg weight sample was collected for zircon selection, and the crushed sample and zircon selection were done by the Laboratory of Langfang Regional Geological Survey Institute, Hebei Province, China. Zircon in situ isotope measurements was carried out at the Key Laboratory for the Study of Focused Magmatism and Giant Ore Deposits, Ministry of Natural Resources, Xi'an, China. Zircon with good crystalline shape and no obvious inclusions and fissures were fixed with DECON epoxy resin, carefully polished until the zircon core was exposed, and then subjected to zircon micrographs (reflected and transmitted light) and CL microimaging studies. The zircon was analyzed by CL-photography using the XL30 SFEG electron beam produced by FEI. LA-ICP-MS U-Pb isotope analysis of zircon microregions was performed using an Agilent 7500 ICP-MS and a Lambda Physik Compex 102 ArF excimer laser (working substance ArF, wavelength 193 nm), and an inline GeoLas 200 M optical system from MicroLa.

The laser beam spot diameter was 30 μm , and the laser peeling depth was 20–40 μm . Helium detection was the carrier gas for the peeling material, and the instrument was tuned with NIST SRM 610 synthetic silicate glass standard as the reference material; single-point peeling sampling was performed; GJ-1 specimens were tested once before and after every 6 test samples, and 1 test before and after every 12 test points for NIST 610 and 91500. Zircon ages were determined using 91500 and GJ-1 as external standards, and elemental contents were determined using NIST 610 as external standards. The in situ Lu-Hf isotope determination of zircon was performed on a British Nu Plasma HR multireceiver inductively coupled plasma mass spectrometer MC-ICP-MS equipped with a GeoLas 2005 laser exfoliation system with a laser exfoliation pulse frequency of 10 Hz and a laser beam spot diameter of 30 μm , and the same 91500 and GJ-1 external standards were used for the analysis. The age data were processed using ICPMSDataCal (version 10.2) program, and the age harmonics and weighted average age were calculated and plotted using Isoplot 3. The detailed analytical

FIGURE 3: Zircon CL images for microbeam analyzed spots and apparent U-Pb ages (a) and zircon U-Pb concordia diagram (b, c) of the Bieyesamas monzogranite. The yellow circle represents the U-Pb analysis spot; the red circle represents the Lu-Hf analysis spot.

TABLE 1: LA-ICP-MS U-Pb isotopic analyses for zircons from the Bieyesamas monzogranite.

Spot	Pb (10^{-6})	Th ($\times 10^{-6}$)	U ($\times 10^{-6}$)	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	Ratio $^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	Age/Ma $\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$
3	72.5	106.9	529.0	0.20	0.0541	0.0009	0.5460	0.0085	0.0729	0.0004	442.0	5.5	453.6	2.5
5	76.0	94.9	1123.0	0.08	0.0561	0.0005	0.5660	0.0050	0.0729	0.0005	455.0	3.4	453.7	2.9
7	36.7	45.8	291.8	0.16	0.0558	0.0009	0.5470	0.0095	0.0725	0.0007	442.0	6.0	451.2	4.2
9	32.0	43.6	150.3	0.29	0.0558	0.0013	0.5570	0.0135	0.0728	0.0007	448.0	9.0	453.0	4.3
10	78.6	89.3	543.0	0.16	0.0561	0.0006	0.5720	0.0060	0.0744	0.0005	458.9	3.8	462.5	3.0
11	62.9	80.3	308.0	0.26	0.0562	0.0011	0.5490	0.0110	0.0711	0.0007	443.0	7.0	442.7	4.0
18	15.4	21.5	300.8	0.07	0.0542	0.0009	0.5380	0.0090	0.0727	0.0006	436.0	6.0	452.2	3.4
21	96.2	145.4	879.0	0.17	0.0552	0.0006	0.5640	0.0065	0.0748	0.0009	453.7	4.1	465.0	5.0
22	38.3	56.9	875.0	0.07	0.0550	0.0006	0.5309	0.0047	0.0705	0.0003	432.2	3.2	439.2	2.1
24	59.8	105.0	269.0	0.39	0.0561	0.0010	0.5550	0.0095	0.0722	0.0009	447.0	6.0	449.0	5.5
25	36.7	64.5	210.0	0.31	0.0547	0.0013	0.5650	0.0130	0.0748	0.0011	453.0	8.5	465.0	6.0
26	37.3	62.2	347.0	0.18	0.0568	0.0009	0.5790	0.0085	0.0736	0.0006	463.0	5.5	457.6	3.7
28	83.9	135.0	530.0	0.25	0.0556	0.0008	0.5500	0.0085	0.0711	0.0008	444.0	6.0	443.0	5.0

procedures and data processing methods, as well as the instrument operating parameters, are described in Liu et al. and Yuan et al. [25, 26].

5.2. Whole Rock Major and Trace Elements. A total of six samples were collected in the field, all avoiding fractured

and altered areas to ensure that the samples taken were fresh, unweathered, and postaltered. The samples were determined for major elements, rare earth elements, and trace elements. The elemental composition analysis of the rocks was completed at the Xi'an Mineral Resources Inspection and Testing Center of the Ministry of Natural Resources, Xi'an, China.

TABLE 2: Lu-Hf isotopic analyses for zircons from the Bieyesamas monzogranite.

Spot	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 2\sigma$	Hf_i	$\varepsilon\text{Hf}(t)$	T_{DM1} (Ma)	T_{DM2} (Ma)	$f_{\text{Lu/Hf}}$
3	453.6	0.087068	0.001983	0.282687	0.000022	0.28267	6.36	823	1035	-0.94
5	453.7	0.144953	0.003384	0.282707	0.000024	0.28268	6.66	826	1016	-0.90
7	451.2	0.140618	0.003152	0.282679	0.000028	0.28265	5.70	862	1076	-0.91
9	453.0	0.074174	0.001686	0.282586	0.000022	0.28257	2.89	961	1257	-0.95
10	462.5	0.142499	0.003241	0.282641	0.000023	0.28261	4.54	921	1159	-0.90
11	442.7	0.104983	0.002387	0.282734	0.000022	0.28271	7.69	763	941	-0.93
18	452.2	0.075751	0.001693	0.282659	0.000019	0.28264	5.45	856	1093	-0.95
21	465.0	0.178410	0.004099	0.282707	0.000028	0.28267	6.68	842	1024	-0.88
22	439.2	0.169210	0.003969	0.282688	0.000022	0.28266	5.55	867	1075	-0.88
24	449.0	0.137328	0.002971	0.282730	0.000025	0.28270	7.51	781	958	-0.91
25	465.0	0.097624	0.002168	0.282615	0.000027	0.28260	4.01	932	1195	-0.93
26	457.6	0.115284	0.002604	0.282700	0.000023	0.28268	6.73	818	1015	-0.92
28	443.0	0.122911	0.002749	0.282659	0.000022	0.28264	4.95	881	1117	-0.92

Annotation: T_{DM1} , the one-stage model age; T_{DM2} , the two-stage model age.

The samples were tested by an X-ray fluorescence spectrometer (XRF-1800). 0.7 g of samples was weighed, added with an appropriate amount of boric acid, and melted into glass flakes at high temperature, and finally, the oxide content was determined by external standard method on an Axios 4.0 kW sequential XRF instrument from Panaco, Netherlands, with an analysis error better than 1%, in which the FeO content was determined by a wet chemical method. The analysis of trace and rare earth elements was accomplished by inductively coupled plasma mass spectrometry (ICP-MS). The samples were first crushed and ground finely to 200 mesh in an agate jar, 50 mg was taken in a Teflon flask, dissolved with HNO_3 and HF for 2 d, respectively, and then HClO_4 was added to further dissolve the samples, which were evaporated dry in a water bath and then diluted to 50 ml with 5% HNO_3 solution, and finally, the determination was carried out on a Thermoelectric Series II plasma mass spectrometer using the internal standard method with an analytic accuracy better than 5%.

6. Analysis Results

6.1. Zircon U-Pb Ages. The zircons in the monzogranite are light yellow-transparent long columns with some short columns, and the zircon particle size is mostly 100–200 μm (Figure 3(a)). The zircon cathodoluminescence (CL) images show that the zircon is morphologically intact, with good crystal shape, sharp and clear crystal ribs, and good overall luminescence; the zircon has a relatively clear oscillatory growth band, which is characteristic of magmatic origin (Figure 3(a)). The zircon was analyzed in 13 spots, and the zircon U-Pb isotope dating results are shown in Table 1. The Th content of zircon ranges from 21.5×10^{-6} to 145.4×10^{-6} ; the U content ranges from 210.0×10^{-6} to 1123.0×10^{-6} , with a wide fluctuation range; the Th/U ratio is mainly concentrated in the range of 0.07 to 0.39. The age data of the samples were processed with good harmony, with more concentrated $^{206}\text{Pb}/^{238}\text{U}$ ages between 439.2 ± 2.1 Ma and 465.0 ± 6.0 Ma (Figure 3(a), Table 1), and their

$^{206}\text{Pb}/^{238}\text{U}$ weighted average age is 451.1 ± 5.1 Ma (MSWD = 6.0, Figures 3(b) and 3(c)), which represents the age of crystallization of the Bieyesamas monzogranite. Therefore, the crystallization age of the magmatic zircon is Late Ordovician.

6.2. Zircon Lu-Hf Isotopic Compositions. In the present work, in situ Lu-Hf isotopic analysis was performed on 13 zircons in the Bieyesamas monzogranite (Table 2). Among them, $^{176}\text{Lu}/^{177}\text{Hf}$ ratios ranged from 0.001686 to 0.004099 with an average of 0.002775, indicating that the zircons accumulated little radiogenic Hf after formation, and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios can basically represent the Hf isotopic composition of the zircon system at the time of crystallization [27]. The $f_{\text{Lu/Hf}}$ values range from -0.95 to -0.88, which are significantly smaller than the $f_{\text{Lu/Hf}}$ values of salic crust (-0.72, [28]) and mafic crust (-0.34, [29]), so the age of the two-stage model better reflects the time when the source material was extracted from the depleted mantle or the average age of the source material in the crust. The upper crust mean composition (0.008) recommended by Taylor and McLennan [30] used in the paper was used to calculate T_{DM2} , and $\varepsilon\text{Hf}(t)$ and T_{DM2} were calculated using the U-Pb age at each point. Table 2 shows the results of Lu-Hf isotope analysis, where $^{176}\text{Hf}/^{177}\text{Hf} = 0.282586 \sim 0.282734$, and $\varepsilon\text{Hf}(t)$ is 2.89~7.69, with a mean value of 5.75, while the two-stage model age $T_{\text{DM2}} = 941 \sim 1257$ Ma, with a mean value of 1074 Ma, implying that the source of this monzogranite is mainly crustal material of the Meso- to Neoproterozoic.

6.3. Major Elements. The results of major elements are shown in Table 3. The SiO_2 contents of the Bieyesamas monzogranite are 70.45%~75.44%, which are relatively Si-rich; the Al_2O_3 contents are 14.04%~17.14%; the aluminum saturation index A/CNK values are between 1.16 and 1.28, which are in the range of peraluminous in the A/CNK-A/NK diagram (Figure 4(a)); the Na_2O contents are 3.12%~4.24%, K_2O contents are 4.20%~4.78%, $\text{K}_2\text{O}/\text{Na}_2\text{O} = 1.01 \sim 1.53$, full alkaline varies from 7.90%~8.99%, Rittman index δ varies

TABLE 3: Compositions of major element (%), trace element ($\times 10^{-6}$), and REE ($\times 10^{-6}$) of the Bieyesamas monzogranite.

Sample name	17B1 Monzogranite	17B3 Monzogranite	17B4 Monzogranite	17B5 Monzogranite	17B6-2 Monzogranite	17B8-2 Monzogranite
SiO ₂	74.93	74.32	75.44	74.39	70.45	74.35
TiO ₂	0.096	0.12	0.045	0.063	0.068	0.062
Al ₂ O ₃	14.15	14.04	14.14	14.37	17.14	14.5
Fe ₂ O ₃	0.34	0.42	0.17	0.29	0.16	0.31
FeO	0.47	0.65	0.26	0.52	0.57	0.51
MnO	0.047	0.034	0.016	0.046	0.074	0.045
MgO	0.25	0.36	0.12	0.21	0.17	0.19
CaO	0.66	0.82	0.51	0.62	0.69	0.58
Na ₂ O	3.52	3.12	3.84	4.05	4.24	4.19
K ₂ O	4.56	4.78	4.59	4.2	4.75	4.23
P ₂ O ₅	0.23	0.29	0.16	0.41	0.54	0.37
Loss on ignition	0.72	1.05	0.68	0.81	1.14	0.66
Total	99.97	100.00	99.97	99.98	99.99	100.00
K ₂ O + Na ₂ O	8.08	7.90	8.43	8.25	8.99	8.42
K ₂ O/Na ₂ O	1.30	1.53	1.20	1.04	1.12	1.01
TFeO/MgO	3.10	2.86	3.44	3.72	4.20	4.15
δ	2.04	1.99	2.19	2.17	2.94	2.26
A/CNK	1.19	1.19	1.16	1.16	1.28	1.16
A/NK	1.32	1.36	1.25	1.28	1.41	1.26
AI	0.76	0.73	0.80	0.78	0.71	0.79
Quartz (Qz)	35.90	36.46	34.83	34.24	27.24	33.23
Anorthite (An)	1.79	2.20	1.50	0.40	0.00	0.46
Albite (Ab)	30.01	26.68	32.72	34.56	36.29	35.69
Orthoclase (Or)	27.15	28.55	27.32	25.03	28.40	25.16
Corundum (C)	2.79	2.97	2.33	3.04	5.08	2.88
Hypersthene (Hy)	1.14	1.63	0.60	1.23	1.38	1.14
Ilmenite (Il)	0.18	0.23	0.09	0.12	0.13	0.12
Magnetite (Mt)	0.50	0.62	0.25	0.42	0.23	0.45
Apatite (Ap)	0.54	0.68	0.37	0.96	1.27	0.86
Total	99.99	100.02	100.01	100.00	100.02	99.99
Differentiation index (DI)	93.06	91.69	94.87	93.83	91.93	94.08
B	18.30	24.60	18.10	65.70	23.60	19.20
Be	9.18	9.92	11.00	9.42	9.99	11.60
Li	473	454	168	383	1400	422
Cs	90.50	70.30	26.60	62.30	566.00	83.60
Bi	0.38	0.24	0.59	3.37	21.00	3.51
Cu	6.38	5.92	1.93	2.97	11.60	3.75
Pb	21.80	21.00	23.20	21.40	25.90	21.40
Zn	32.40	30.40	6.78	31.30	130.00	32.20
Cr	5.02	4.76	2.86	3.05	3.04	3.58
Ni	3.00	1.65	1.08	0.51	0.67	0.95
Co	1.86	1.74	0.42	0.66	0.66	0.67
Rb	373	390	335	399	1000	502
Sr	35.80	51.90	35.20	28.20	27.30	28.70
Ba	78.20	89.20	62.60	66.00	88.20	71.70
Sc	9.02	6.69	6.80	9.05	8.78	9.15
Nb	25.32	14.65	12.39	19.90	24.04	17.16

TABLE 3: Continued.

Sample name	17B1 Monzogranite	17B3 Monzogranite	17B4 Monzogranite	17B5 Monzogranite	17B6-2 Monzogranite	17B8-2 Monzogranite
Ta	2.42	1.74	1.46	2.36	2.86	2.02
Zr	36.00	48.00	11.80	38.50	43.40	36.00
Hf	1.42	1.74	0.60	1.64	1.88	1.57
Ga	19.90	18.10	16.50	17.50	21.00	16.60
U	7.23	10.70	7.04	16.00	15.00	7.02
Th	6.87	7.96	1.88	3.04	3.62	4.01
La	15.10	10.90	2.94	5.33	6.23	6.56
Ce	29.30	22.30	5.37	11.00	13.20	13.30
Pr	3.42	2.65	0.60	1.28	1.54	1.64
Nd	12.60	10.10	2.09	4.83	6.12	6.32
Sm	2.56	2.18	0.47	1.21	1.52	1.60
Eu	0.45	0.28	0.16	0.23	0.26	0.24
Gd	2.02	1.73	0.42	1.30	1.54	1.42
Tb	0.31	0.26	0.08	0.19	0.22	0.20
Dy	1.80	1.52	0.48	1.12	1.25	1.12
Ho	0.35	0.30	0.09	0.21	0.24	0.21
Er	0.94	0.80	0.24	0.54	0.58	0.51
Tm	0.14	0.12	0.04	0.08	0.08	0.07
Yb	0.88	0.81	0.23	0.48	0.50	0.42
Lu	0.13	0.12	0.03	0.07	0.07	0.06
Y	10.10	8.17	2.46	5.62	6.22	4.96
Rb/Ba	4.77	4.37	5.35	6.05	11.34	7.00
Rb/Sr	10.42	7.51	9.52	14.15	36.63	17.49
10000Ga/Al	2.66	2.44	2.20	2.30	2.31	2.16
Σ REE	70.00	54.07	13.25	27.87	33.35	33.67
LREE	63.43	48.41	11.63	23.88	28.87	29.66
HREE	6.57	5.66	1.62	3.99	4.48	4.01
LREE/HREE	9.65	8.55	7.20	5.99	6.44	7.39
(La/Yb) _N	12.31	9.65	9.17	7.97	8.94	11.20
(La/Sm) _N	0.60	0.44	1.10	0.56	0.52	0.49
(Gd/Yb) _N	1.00	1.02	0.99	1.03	1.04	0.99
δ Eu	0.60	0.44	1.10	0.56	0.52	0.49
δ Ce	1.00	1.02	0.99	1.03	1.04	0.99

Annotation: A/CNK = $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ (mol); A/NK = $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ (mol); AI = $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$ (mol); differentiation index (DI) = Qz + Or + Ab.

from 1.99 to 2.94, and the SiO_2 - K_2O diagram reflects that the Bieyesamas pluton belongs to the high-K calc-alkaline series (Figure 4(b)); the CaO contents are 0.51%~0.82%, and the TiO_2 contents are low (0.045%~0.12%); the TFeO/MgO ratio ranges from 2.86 to 4.20, with an average of 3.58, indicating Fe-rich and Mg-poor. According to the CIPW standard mineral calculations, corundum (2.33% to 5.08%) occurs, showing peraluminous characteristics. The samples in the TAS diagram (Figure 4(c)) based on the results of the major element analysis fall in the granite region.

6.4. Trace Elements. The total rare earth elements (Σ REE) of the monzogranites ranged from $13.25 \times 10^{-6} \sim 70.00 \times 10^{-6}$, with an average of 38.70×10^{-6} , which is low. The

chondrite-normalized diagram shows a right inclined distribution pattern of rare earth elements (Figure 5(a)), indicating enrichment of light rare earth elements (LREE) and obvious fractionation of light and heavy rare earth elements (HREE, LREE/HREE of 5.99-9.65 and $(\text{La/Yb})_N$ of 7.97-12.31). Five sets of data show strong negative Eu anomalies (δ Eu of 0.44-0.60), indicating that the rock may have undergone a strong plagioclase segregation crystallization.

Trace elements primitive-mantle-normalized curves show that the rocks are relatively enriched in high field strength elements (such as Nb, Ta, Hf, and U) and large ionic lithophile elements (such as K and Rb), while poor in elements such as Ba, Sr, Ti, and Zr (Figure 5(b)). The contents of rare metal elements in Table 3 rock trace elements are all

FIGURE 4: Diagrams of A/NK-A/CNK (a, after [31]), K₂O-SiO₂ (b, after [32]), and TAS (c, after [33]) of the Bieyesamas monzogranite.

FIGURE 5: Chondrite-normalized REE distribution patterns (a) and primitive-mantle-normalized trace element distribution patterns (b) of the Bieyesamas monzogranite (after [34]).

high: Li contents are $168 \times 10^{-6} \sim 1400 \times 10^{-6}$, with an average of 550×10^{-6} ; Be contents are $9.18 \times 10^{-6} \sim 11.60 \times 10^{-6}$, with an average of 10.18×10^{-6} ; Ta contents are $1.46 \times 10^{-6} \sim 2.86 \times 10^{-6}$, with an average of 2.14×10^{-6} ; Rb contents are $1.46 \times 10^{-6} \sim 2.86 \times 10^{-6}$, with an average of 500×10^{-6} ;

the contents of Cs ranged from 26.6×10^{-6} to 566.0×10^{-6} , with an average of 149.9×10^{-6} ; the contents of Nb ranged from 12.39×10^{-6} to 25.32×10^{-6} , with an average of 18.91×10^{-6} . These indicate that the pluton has rare metal enrichment potential.

FIGURE 6: Discrimination diagrams of granite genetic types for the Bieyesamas monzogranite. (a) $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ vs. $((\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO})$ diagram (after [36]), (b) $10000\text{Ga}/\text{Al}$ vs. (TFeO/MgO) diagram (after [39]), and (c) Zr vs. TiO_2 diagram, FG-fractionated I-, S-type granite, OGT-unfractionated I-, S-type granite.

7. Discussion

7.1. Petrogenetic Type. Granite genetic types include I, S, M, and A. The Bieyesamas monzogranite was considered to be highly fractionated I-type in the study of Yang et al. [20]. In our study of the Bieyesamas monzogranite, we find that the lithological and elemental geochemical features indicate that the monzogranite has undergone a high degree of differentiation evolution, with a mean differentiation index DI of 93.24%, which is also reflected by the $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}) - ((\text{K}_2\text{O} + \text{Na}_2\text{O})/\text{CaO})$ diagram (Figure 6(a)). The identification of the highly fractionated granite often requires a combination of mineralogical and geochemical characteristics. Garnet and tourmaline are commonly seen among the secondary minerals of the rock, both of which are aluminum-rich minerals, and corundum (mean 3.18%) appears in the Cross Iddings Pirsson Washington (CIPW) norm minerals in Table 3, indicating S-type granite features rather than I-type granite. The Al-saturated characteristic value A/CNK ranges from 1.16 to 1.28, with an average of 1.19 and greater than 1.10, which is strongly peraluminous. However, the A/CNK values of A-type granites generally range from 1.0 to 1.1 [35] and are mainly weakly peraluminous granites, so the strong peraluminous character of the rock also indicates a closer affinity with S-type granites. The rock peralkaline index AI ranges from 0.71 to 0.80 with an average of 0.76, close to

that of highly fractionated S-type granites ($\text{AI} = 0.71$) and significantly lower than the average of 0.85 for A-type granites [36–38]; the $10000\text{Ga}/\text{Al}$ ratios of the rocks range from 2.16 to 2.66 with an average of 2.35, while the TFeO/MgO ratios are lower with an average of 3.46, while the A-type granites are more Fe-rich. The $10000\text{Ga}/\text{Al}$ - TFeO/MgO diagram (Figure 6(b)) shows that the rock samples all fall into the fractionated I- and S-type regions, which are further supported by the Zr - TiO_2 diagram (Figure 6(c)) distinguishes that the samples all fall into the S-type region. Therefore, combining mineralogical and geochemical indices, the Bieyesamas monzogranite should be a fractionated S-type granite.

7.2. Magma Origin and Evolution. The rare earth elements of the Bieyesamas monzogranite are in a right inclined distribution pattern, with trace elements relatively enriched in high field strength elements such as Nb, Ta, Hf, and U and large ionic lithophile elements such as K and Rb, while poor in Ba, Sr, Ti, and Zr, suggesting that the granite has undergone significant fractional crystallization. The strong enrichment of Rb indicates that the melting of continental crust material in magma is very full and the degree of partial melting is very high. Ti depletion is more closely related to the fractional crystallization of ilmenite than magnetite. The ilmenite content from the norm mineral calculation in Table 3 is very low (0.09%-0.23%), while magnetite content is higher

FIGURE 7: C/MF vs. A/MF and age (Ma) vs. $\epsilon\text{Hf}(t)$ diagram for the Bieyesamas monzogranite (after [42]).

(0.23%-0.62%). The loss of Ba and Sr should be related to fractional crystallization of plagioclase [40]. The Rb/Sr ratios of the rocks range from 7.51 to 36.63, with an average of 15.95, which is much higher than that of the upper continent crust (0.32), suggesting that the source components may have come from the upper continent crust [30]. The La/Ta ratios range from 2.01 to 6.26, with an average of 3.7, which is much smaller than the lower limit (25) of the La/Ta ratio, indicating that the magma should be of crustal origin and not mingled with mantle-derived material [41]. The slightly positive Eu anomalies and strong depletion of HREE in sample No.17B4 indicate the residue of garnet and plagioclase-free in the source caused by high pressure and resemble a crustal thickening regime. The source area of the Bieyesamas monzogranite is also reflected on the C/MF-A/MF diagram (Figure 7(a)) as a partial melt of metamorphic sandstone dominated by clasticite [42]. Combined with the widespread occurrence of garnet in the rock suggests that the Bieyesamas pluton is a partial melt of crust-derived material.

Zircon Hf isotope analysis is an important tool to discriminate the source area of granites [27]. $\epsilon\text{Hf}(t)$ values obtained in this paper range from 2.89 to 7.69 for monzogranite, with $T_{\text{DM2}} = 941\text{-}1257\text{ Ma}$. Zircon $\epsilon\text{Hf}(t)$ values for Bieyesamas monzogranite are positive and vary less than 5 ϵ units. The Hf isotope values are homogeneous. These characteristics may suggest that the granites originated from partial melting of the juvenile crust, which is consistent with the above-mentioned geochemical characteristics of the crustal origin of the rocks. In the age (Ma) vs. $\epsilon\text{Hf}(t)$ diagram (Figure 7(b)), the $\epsilon\text{Hf}(t)$ values show a trend from the vicinity of the chondrite to the line of evolution near the depleted mantle, which also indicates the involvement of juvenile components in the petrogenetic process. The zircon Hf isotope two-stage model age represents the time of extraction of protolithic material from the depleted mantle [27], and the granite T_{DM2} in this paper inferred that the Bieyesamas granite was formed by partial melting of the Meso- to Neoproterozoic crustal material.

TABLE 4: Values for sample by zircon saturation thermometer.

Number	Sample	M	D_{Zr}	T_{Zr} (°C)
17B1	Monzogranite	0.0262	13777.78	759
17B3	Monzogranite	0.0266	10333.33	783
17B4	Monzogranite	0.0266	42033.90	674
17B5	Monzogranite	0.0262	12883.12	764
17B6-2	Monzogranite	0.0254	11428.57	774
17B8-2	Monzogranite	0.0264	13777.78	759
Average				752

Annotation: T_{Zr} (°C) = $12900 / (3.80 + 0.85 \times (M - 1) + \ln D_{\text{Zr}}) - 273.15$; $D_{\text{Zr}} = 496000 / (\text{Zr content of the whole rocks})$; $M = (\text{Na} + \text{K} + 2\text{Ca}) / (\text{Al} \times \text{Si})$ (the cation numbers ratio). Let be $\text{Si} + \text{Al} + \text{Fe} + \text{Mg} + \text{Ca} + \text{Na} + \text{K} + \text{P} = 1$ (fraction of number of atoms) (after [43]).

The North Altay was in the early stage of subduction and accretionary orogenesis in the Ordovician, and the continental margin arc environment formed lasted until the Early Devonian, and the evolution of the arc was gradually mature. The Bieyesamas pluton is the product of the initial Ordovician continental margin arc background [20]. According to Wu et al. [27], most granites rise adiabatically, and in this process, the pressure of magma changes rapidly but the temperature changes slowly. Therefore, the early crystallization temperature of magma can approximately represent the temperature at its origin. According to the formula proposed by Watson and Harrison for estimating the zircon saturation thermometer based on the content of Zr in the trace elements of whole rock [43], the calculated zircon crystallization temperature ranges from 674°C to 783°C (average 752°C) (Table 4), indicating that the original magma temperature is high and the minimum temperature can reach 783°C. It indicates that the pluton belongs to high-temperature granite. The Bieyesamas pluton was produced by partial melting that occurred at higher temperatures.

FIGURE 8: Pegmatite dyke distribution map (a, b) of Bieyesamas mining area and mineral occurrence characteristics (c-e) (after [18]).

7.3. Rare Metal Resource Potential. The Bieyesamas pluton is a huge batholith with an exposed area of more than 1000 km². The edge of the pluton is biotite granite, and the interior is two-mica monzogranite. Numerous pegmatite veins are produced in the fine- and medium-grained two-mica monzogranite (Figure 8(a)), and spodumene minerals are widely developed in the pegmatite veins, while rare metals such as beryllium, niobium, and tantalum are mostly associated with spodumene minerals. The average content of Li is 550×10^{-6} , Be is 10.18×10^{-6} , Nb is 18.91×10^{-6} , Ta is 2.14×10^{-6} , Rb is 500×10^{-6} , and Cs is 149.9×10^{-6} in the two-mica monzogranite which is the direct envelope of the rare metal pegmatite veins. The rare metal contents are all significantly higher than other rock types and crustal Clark values (continent crustal element abundance values: Li = 20×10^{-6} , Be = 3.0×10^{-6} , Nb = 13.7×10^{-6} , Ta = 2.2×10^{-6} , Rb = 112×10^{-6} , and Cs = 7.3×10^{-6} , Taylor and McLennan [30]), indicating that the rock has rare metal enrichment potential. Due to the large size of the monzogranite and the long-term crystallization, thus it can provide a richer material source for rare metal enrichment mineralization, while the intermediate-acidic volatile-rich lava provides favorable conditions for later transformation, migration, and enrichment, showing the close relationship between intrusive rocks and rare-metal mineralization in the area.

The rare meta pegmatite veins in the Bieyesamas pluton develop different mineral structural belts from the outside to the center, and the common structural belts include quartz-muscovite structural belt, quartz-spodumene structural belt, quartz-cleavandite-spodumene structural belt

(Figure 8(b)), quartz-microcline-spodumene structural belt, and core quartz, and locally, there are also graphic texture belt and microcline belt, among which the quartz-microcline-spodumene belt is the main mineral-bearing structural belt. The spodumene commonly found in the structural belt is distributed in the form of plates, up to $1 \sim 2 \times 3 \sim 4$ cm (Figure 8(c)). Beryl is hexagonal columnar, grass green, light blue, opaque to translucent, 0.1~5.0 cm in diameter (Figures 8(d) and 8(e)), some of which reach the quality standard of aquamarine. Single crystals of niobium-tantalite are in the form of plates or thin plates, brown-black to black (Figure 8(e)). More specifically, the pegmatite veins of the deposit are almost entirely mineralized, with different degrees of mineralization in each structural belt. Although most veins have only one to two structural belts, spodumene and niobium-tantalite are relatively uniformly distributed in the structural belts, even though the outermost quartz-muscovite belt still contains mineral, only with slightly lower content and smaller grain size, which is very rare in pegmatites of the Altay region.

The Bieyesamas pegmatite-type rare metal deposit is located about 100 km northeast of the Koktokay town, Fuyun County in Xinjiang. Although this mine was discovered as a rare metal ore source in the early 1990s, few geological exploration work was carried out due to inconvenient transportation [17]. From 2017 to the present, the pegmatite veins developed in the Bieyesamas monzogranite have been identified as the most potential metallogenic section for rare metals by the Geological Investigation Project of the China Geological Survey. A total of 76 pegmatite veins were found, of

which 56 veins all have obvious lithium, beryllium, niobium, and tantalum mineralization (Figure 8(a)). The pegmatite veins are exposed on the surface for 100~1500 m in length, 0.1~40 m in width, 210°~245° in inclination, and 30°~45° in dip (gently inclined). After chemical analysis, 70% of the rare metal contents are found in fine independent minerals such as spodumene, beryl, and niobium-tantalite, and only 30% are distributed in rock-forming minerals, among which the content of rare elements such as Li_2O , Rb_2O , Cs_2O , Nb_2O_5 , and Ta_2O_5 has partially reached industrial grade. At present, two new rare metal prospecting target areas of Bieyikebale and Aya-kekalsu have been recognized, and the new Bieyesamas North beryllium ore point and Bieyesamas West beryllium-rubidium ore point have been discovered. The beryllium ore resource of Bieyesamas North beryllium ore point is 6.235 million tons (334 level), BeO resource is 6985.3 tons, and the predicted resource of beryllium ore can reach the medium-scale deposit. The beryllium ore resource of Bieyesamas West beryllium-rubidium ore point is 7.372 million tons (334 level), BeO resource is 7298.4 tons, and the rubidium ore resource is 7.372 million tons (334 level); Rb_2O resource is 3885.1 tons, the predicted resources of beryllium ore at this site can reach medium-scale deposit, and the predicted resources of rubidium ore can reach large-scale deposit [18]. The above analyses show that regional rare metal mineral resources have great potential.

8. Conclusions

The conclusions of this study are listed as follows:

- (1) LA-ICP-MS zircon U-Pb dating indicates the $^{206}\text{Pb}/^{238}\text{U}$ weighted average age of the Bieyesamas monzogranite is 451.1 ± 5.1 Ma (MSWD = 6.0), representing the formation timing is Late Ordovician
- (2) The Bieyesamas monzogranite has high Si-Al, potassium and alkaline, and A/CNK values (1.16 to 1.28), which is high-K calcic-alkaline peraluminous series
- (3) The rocks show obvious fractionation of light and heavy rare earth elements, enriched in high field strength elements such as Nb, Ta, Hf, and U and large ionic lithophile elements such as K and Rb, and depletion in Ba, Sr, Ti, Zr, etc. The mineral assemblage, geochemical characteristics, and zircon Hf isotope analysis indicate that the pluton belongs to the highly fractionated S-type granite, which is a product of partial melting of the Meso- to Neoproterozoic crustal material
- (4) The newly discovered rare metal ore sites in the Bieyesamas area of the Altay Mountain are characterized by large-scale mineralization, high grade and industrial utilization value, etc. The Bieyesamas pluton is one of the key areas for rare metal prospecting breakthroughs in the future

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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