



The Genesis of the Askartor Be-Mo Deposit in the North Xinjiang, Northwest China: Evidence From Geology, Geochemistry, U-Pb, and Re-Os Geochronology

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The Askartor Be-Mo deposit is located in the southeastern area of the Chinese Altay orogenic belt in Xinjiang, NW China. Zircon U-Pb data show that there are two periods of magmatic activities in the Askartor Be-Mo ore district, namely, the Devonian granodiorite (386.8 ± 2.6 Ma) and biotite granite (385.4 ± 4.4 Ma), and the Triassic two-mica granite (247.5 ± 2.2 Ma) and muscovite granite (231.4 ± 2.0 Ma). The zircon U-Pb age of pegmatoid orebody is 220.6 ± 1.6 Ma which coincides with the molybdenite Re-Os isochron age of 228.7 ± 7.1 Ma. The two-mica and muscovite granites belong to the high-K Calc-alkaline series with peraluminous features, and are characterized by high SiO_2 (71.92–75.41 wt%), and Al_2O_3 (13.43–15.98 wt%), and low TiO_2 (0.01–0.25 wt%), Fe_2O_3 (0.11–1.14 wt%) and CaO (0.07–0.76 wt%). The highly fractionated element ratios of Y/Ho, Zr/Hf and Nb/Ta, and the rare earth element tetrad effect occur in the muscovite granite, indicating the fluid exsolution occurs at the late stage of magma evolution, and the muscovite granite experienced the strong self-metasomatism. Rayleigh fractional calculations show that the Askartor Be-Mo deposit is the product of multistage fractional crystallization of initial Be-enriched magma.

Keywords: Askartor Be deposit, U-Pb age, tetrad effect, melt-fluid interaction, NW China

INTRODUCTION

Because of its unique physical and chemical properties, beryllium (Be) is widely used in many important industrial products used in the aerospace, computer, defense, medical, nuclear, and telecommunications industries. The two most important Be ores are bertrandite [$\text{Be}_2\text{Si}_2\text{O}_7(\text{OH})_2$] and beryl [$\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$]. At present, 90% of the source mineral of the world's beryllium produce comes from bertrandite, but industrial beryl is critical for the production of the very high purity beryllium metal needed for some strategic applications (Foley et al., 2017). At present, two distinct classes of deposits currently account for most beryllium ores (Barton and Young, 2002; London and Evensen, 2002): they are 1) volcanic and carbonated-hosted deposits that contain the mineral bertrandite, and 2) pegmatite-type deposits that have an abundance of the mineral beryl.

The Chinese Altay orogen, located in Northwest China, is the most important beryllium ore belt in China. Its deposit is mainly pegmatite type. The geological characteristics (Zou and Li, 2006; Qin et al., 2013; Yang et al., 2018; Zhang et al., 2019), geochronology (Wang et al., 2007; Chen, 2011; Ren

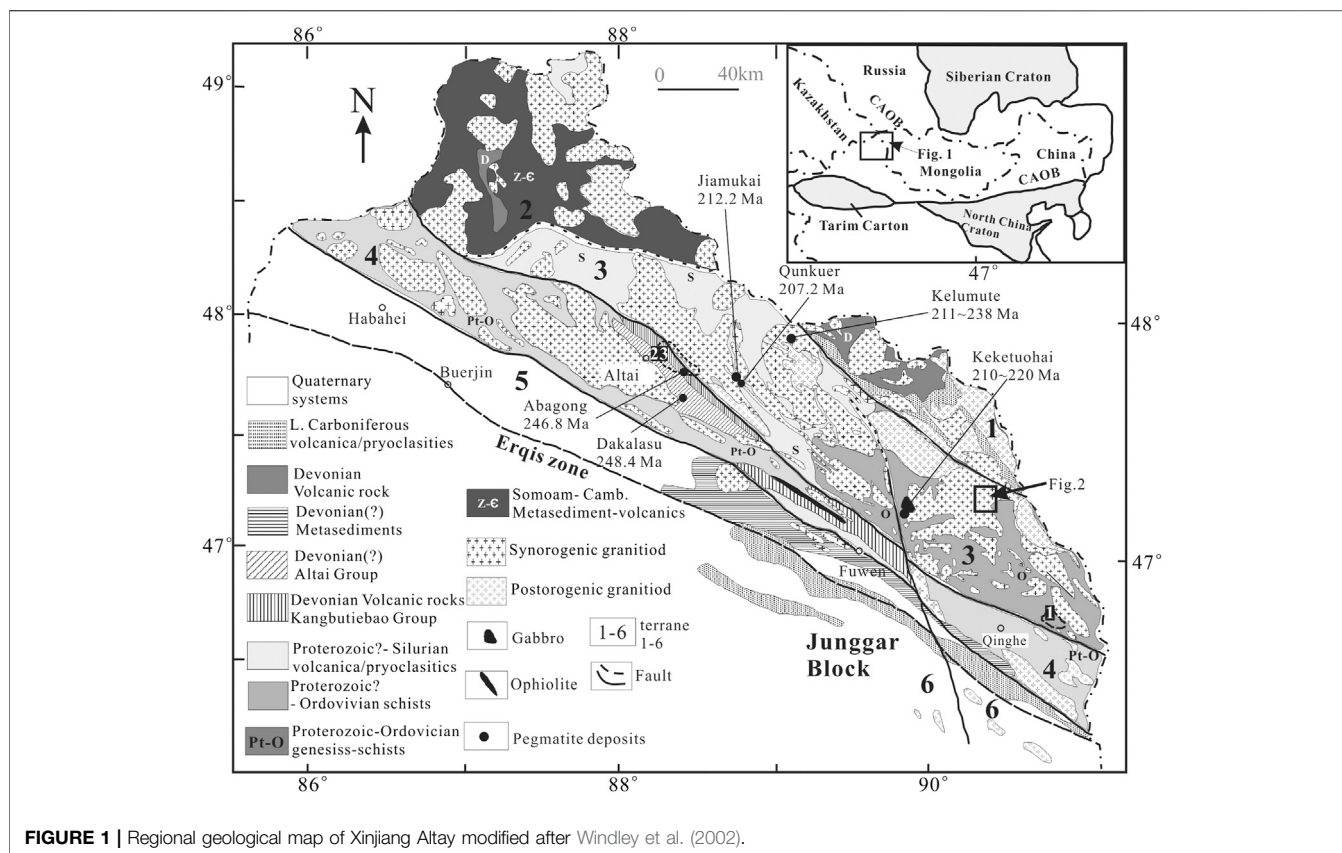


FIGURE 1 | Regional geological map of Xinjiang Altay modified after Windley et al. (2002).

et al., 2011; Lv et al., 2012) and internal evolution (Zhang et al., 2008; Lv et al., 2012; Stepanov and Hermann, 2013; Yin et al., 2013) of pegmatites in this area have been studied systematically. However, the mechanism of extraordinary enrichment of beryllium in pegmatites is not clear. Based on the solubility of beryl and the partition coefficient of Be, Evensen and London (2002) considered that extended fractionation beyond 90% total solidification by at least a three-step process is required to achieve beryl saturation in granitic magma systems, but there is a lack of factual evidence.

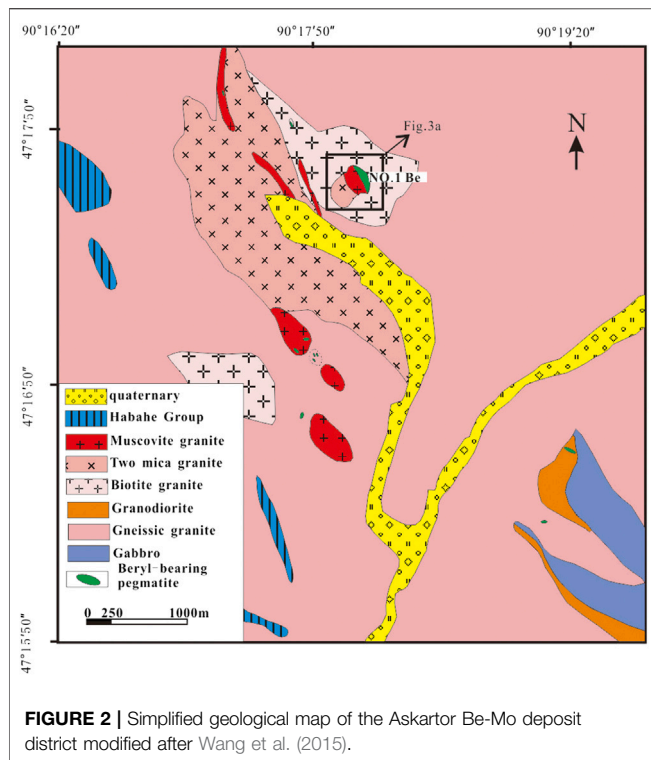
The Askartor deposit is the only granite-related Be-Mo deposit in the Chinese Altay orogen. The Askartor granite pluton is a composite rock body with obvious vertical zoning, from bottom to top, the rock types change from two-mica granite, through muscovite granite, to pegmatite. In addition, there are granodiorite and biotite granite in the ore district. Zou and Li (2006) presented the geological features, and ore body morphology. The ages of different rock types have been presented by Wang et al. (2015), Ding et al. (2016), Zhang et al. (2017). However, the processes that might have contributed to the genesis of this deposit have not been noticed. Therefore, in this study, we have carried out a systemic study of the geology, geochronology, and geochemistry, in order to establish the mineralization model of the Askartor Be-Mo deposit, and identify the key factors restricting the enrichment of Be.

GEOLOGICAL BACKGROUND

Regional Geology

The Altay orogen, which is the southernmost part of the Central Asian Orogenic Belt (CAOB), is situated between the south Siberian Craton to the north and the Junggar Block to the south. According to Windley et al. (2002), the Altay orogen in China is composed of the following six terranes, and details of the terranes can be found in Windley et al. (2002). The rare metal deposits are mainly distributed in Terrane 3 and Terrane 4 (Figure 1).

Recent studies have showed that the Chinese Altay orogen belt is a subduction-related accretionary orogen belt. The tectonic setting of the Chinese Altay varied from a passive continental margin to active continental margin during the Middle Cambrian, and then, it underwent a prolonged subduction process from Ordovician to Carboniferous, characterized by massive magma activities, and high-temperature metamorphism (e.g., Sun et al., 2008; Jiang et al., 2010; Cai et al., 2010; Cai et al., 2011a; Cai et al., 2012a; Cai et al., 2011b). During the Permian period, the Chinese Altai converged consecutively with the East and West Junggar arcs because of the closure of the Paleo-Asian Ocean (e.g., Cai et al., 2012b; Li et al., 2015; Cai et al., 2016; Broussolle et al., 2018). Since the Triassic period, the Chinese Altai has entered into a post-orogenic stage after the amalgamation of the Siberia and Tarim



cratons (e.g., Xiao et al., 2008, Xiao et al., 2009, Xiao et al., 2015; Cai et al., 2016; Xiao et al., 2018).

The granitoids occupy over ~40% of the Chinese Altay orogen (Zou et al., 1988). High precision U-Pb dating results of LA-ICPMS, SHRIMP, and SIMS shows that most of the granitoids were emplaced during the Early to Middle Paleozoic time, with minor ones in the Permian period (Zou et al., 1988; Chen and Jahn, 2002; Wang et al., 2006; Yuan et al., 2007; Sun et al., 2008). The Early Middle Paleozoic I and S-type granitoid, which is emplaced from 507 to 360 Ma, display arc-related geochemical characters (Yuan et al., 2007; Wang et al., 2009; Cai et al., 2011a, Cai et al., 2011b). They are usually deformed and partly metamorphosed to become foliated (Wang et al., 2009). In contrast, the A or I-type granitoids emplaced at ca. 290–250 Ma are mostly undeformed and possess within-plate geochemical characteristics (Tong et al., 2014).

The Chinese Altay orogen is an important rare metal metallogenic belt in China, and its deposit is mainly pegmatite. Approximately 100,000 pegmatite dykes exposed in the Chinese Altay (Zou and Li, 2006). These pegmatite dykes formed during the Devonian synorogenic to Jurassic post-orogenic to anorogenic stage, and mostly concentrated in Triassic (e.g., Ren et al., 2011; Lv et al., 2021 and references therein). The Askartor Be-Mo deposit is the only rare metal deposit related to granite.

Geology of the ore District

The Askartor Be deposit is located in the southeastern of the Central Altay, and about 80 km north of the Qinghe County (Figure 1). This deposit has mined since 1954, and a total of

11,200 tons of ore, which occupy only 2% of the total reserves, have been produced until 1996.

The Upper Ordovician Habahe subgroup sporadically crops out in the mining area, and is composed of biotite-quartz schist and biotite gneiss. Magmatic rocks develop well and make up 95% of the whole mining area, including granodiorites, biotite granites, two mica granites, and medium-fine grain muscovite granites (Figure 2). Granodiorites are the most voluminous of these intrusive rocks. These rocks are grey-black, fine to medium-grained, with a massive texture. They are composed of quartz (20–25 vol%), plagioclase (50 vol%), K-feldspar (± 10 vol%), and biotite (10–15 vol%). Accessory minerals include zircon, apatite, titanite, and magnetite. Biotite granites are the ore-hosting rock, with an outcrop area of about 0.9 km². These biotite granites are grey-white, and have an unequal-particle hypidiomorphic structure with a massive texture. Petrographic observation shows that the mineral compositions mainly involve quartz (30–35 vol%), plagioclase (± 40 vol%), K-feldspar (± 15 vol%), biotite (5–10 vol%), and muscovite (± 2 vol%). Biotite granites are intruded by two mica granites, and the boundary between those two intrusions is sharp and clear. The surface outcrop of the two mica granites is up to 5 km². They are grey-white, and have a medium-to coarse grain granitic structure with a massive texture. The two mica granites are mainly composed of quartz (35 vol%), plagioclase (~35 vol%), K-feldspar (20 vol%), biotite (± 5 vol%), and muscovite (± 5 vol%). Muscovite granites occur in the upper portion of the two mica granites, and the transition between both granite types is gradational. The Muscovite granites have a fine-to medium-grain granitic structure. These rocks are mainly composed of quartz (30–35 vol%), plagioclase (35 vol%), K-feldspar (± 20 vol%), and muscovite (5–10 vol%).

The Askartor Be-Mo deposit is composed of primary ore and placer. The primary ore consists of pegmatoid-type beryllium ore body in the upper part and granitite-type beryllium ore body in the lower part, and the two parts show a gradual transitional relationship. Detailed surface geological mapping, underground mining workings and drill holes demonstrate that the following six zones are successively encountered from bottom to top (Figure 3):

- (1) medium-to fine-grain muscovite granite. These rocks are mainly composed of quartz (30–35 vol%), plagioclase (35 vol%), K-feldspar (± 20 vol%), and muscovite (5–10 vol%).
- (2) beryl-bearing fine-grain albitized muscovite granite. They are grey-white, and have a fine-grain granitic structure with a massive texture. These rocks are mainly composed of quartz (30–35 vol%), albite (± 40 vol%), K-feldspar (± 20 vol%), and muscovite (± 10 vol%). Beryl sporadically occurs in these rocks.
- (3) banded muscovite-quartz-albite zone (Figures 4A,B). This zone is usually 4–5 m wide, 0.1–2 m long and spans 10 m at its widest place. Meanwhile, it has a strong Be-mineralization and a gradual transition relationship with fine-grained albitization muscovite granitite zone. Albite, microcline, quartz, muscovite, and beryl formed the zone's clear banded structure.

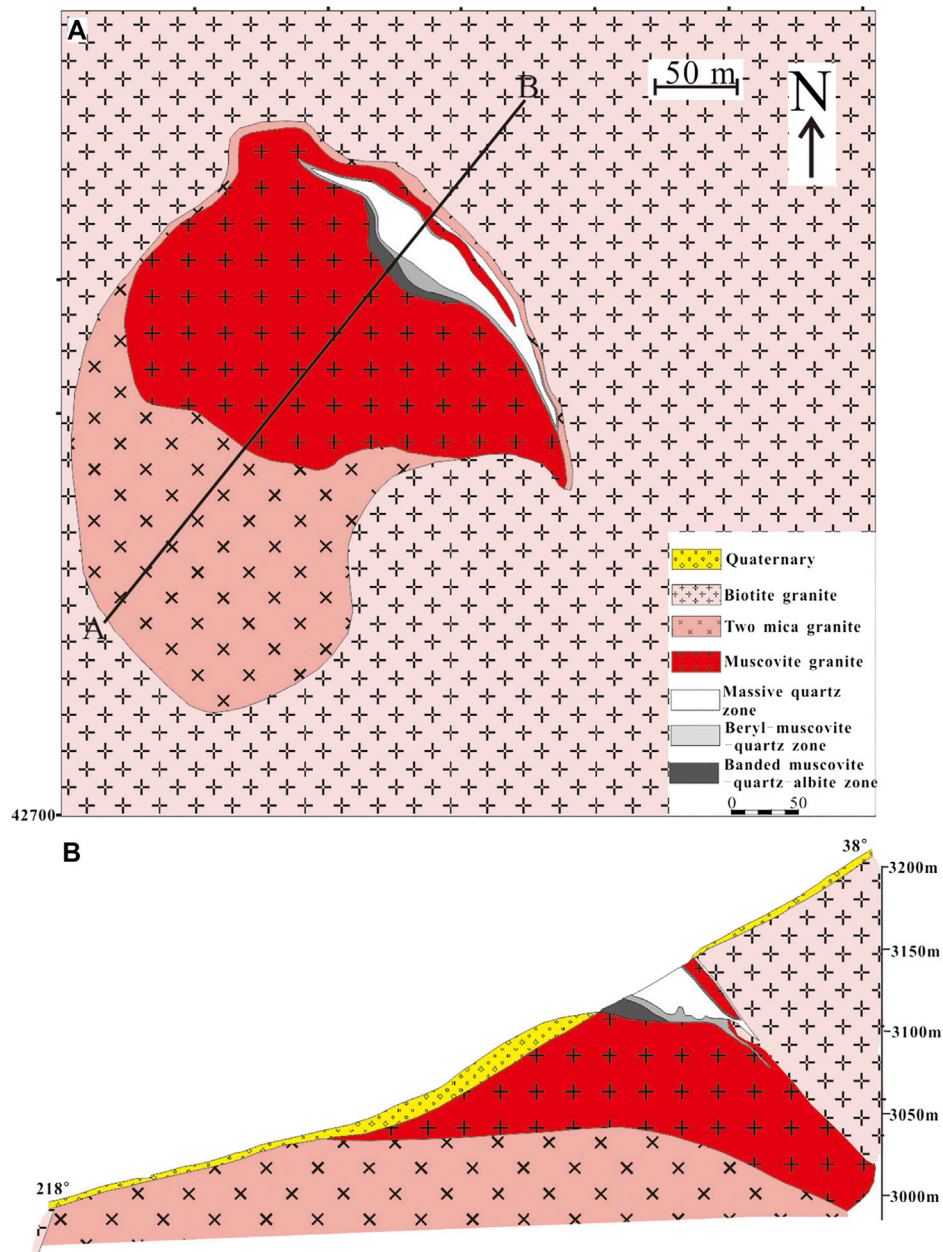


FIGURE 3 | Cross sections of the Askartor No.1 Be-Mo deposit.

- (4) Massive quartz zone (**Figure 4D**). This zone mainly consists of quartz, the colors of which are ivory, rosy, and transparency with dense block structure and the widest place of the core quartz reaches 32 m. Beryl only appears along the marginal areas, reflecting a weak Be-mineralization. There is pyrite, blende, bismuthinite, nesting of gypsum and barite vein in this zone, besides quartz, and the molybdenite appears in the inside of quartz vein's edge with little content.
- (5) Beryl-bearing muscovite-quartz zone (**Figure 4C**). This zone, showing circular distribution around the massive quartz with

- 0.1–5 m wide, is the primary Be-mineralization zone. The main mineral compositions are muscovite (20–30 vol%), quartz (10–20 vol%), beryl (3–5 vol%), and microcline (2–20 vol%). The molybdenite presents star-dotted lamellar and laminated shapes, coexisting with pyrite, bismuthinite, blende, spessartite, apatite, spodumene, and niobite.
- (6) muscovite-microcline-albite zone: This zone, which is 2–10 m thick with weak Be-mineralization, is in the top side of the deposit, contacting the biotite granite wall-rock directly. The main mineral compositions are quartz

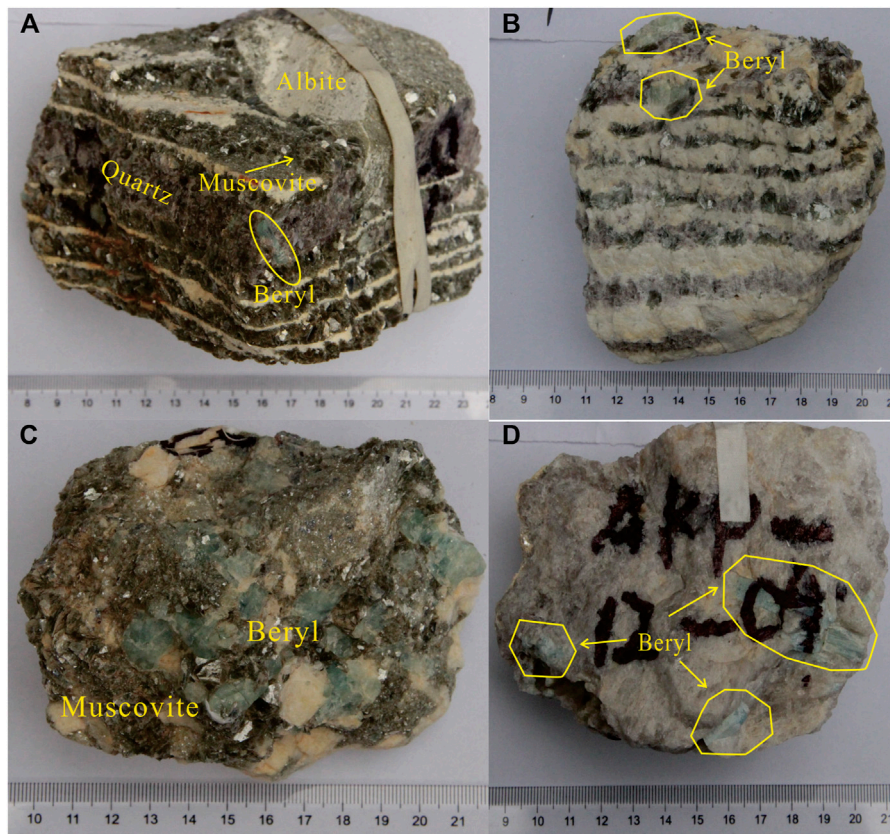


FIGURE 4 | Examples of beryl in different zones of the No.1 orebody.

(30 vol%), microcline (39 vol%), plagioclase (20 vol%), and muscovite (10 vol%), and the accessory minerals are spessartite, pyrite and molybdenite.

SAMPLES AND ANALYTICAL METHODS

Samples

Rock samples were examined by optical microscopy, and unaltered or least altered samples were selected for geochemical analysis. These samples were cleaned with deionized water, crushed, and powered with an agate mill. Five samples were selected for zircon U-Pb dating in this study. These samples are granodiorite (sample name: AKG01, Location: N47°17'32", E90°17'38"), biotite granite (sample name: AKG02, location: N47°18'21", E90°17'39"), two-mica granite (sample name: AKG04, N47°17'33", E90°17'34"), fine-grain muscovite (sample name: AKG05, location: N47°18'19", E90°17'43"), and the banded pegmatite (sample name: AKG06, N47°18'20", E90°17'45"), respectively. Seven molybdenite samples were collected from fine-grain muscovite granite and pegmatite.

Major and Trace Elements Analysis

Major and trace elements were determined at the State Key Laboratory of Ore Deposit Geochemistry, Chinese Academy of

Sciences (SKLOGD, CAS). Major elements were analyzed by standard X-ray fluorescence (XRF). Samples were prepared as glass discs, formed by mixing 0.70 g of rock powder (dried at 110°C) with 7.0 g of lithium tetraborate for 15 min at 1,100°C in 95%P-5%Au crucibles. Analyses were performed on a PANalytical Axios PW4400 X-ray fluorescence spectrometer. The analytical precision, as determined on the Chinese National Standards GSR-1 and GSR-3, was better than 5%. Loss on ignition (LOI) was obtained using 1 g power heated to 1,100°C for 1 h.

Trace elements were analyzed with a Finnigan MAT ELEMENT magnetic sector ICP-MS. 50 mg of powdered granite sample were dissolved in a high-pressure PolyTetraFluoroEthylene (PTFE) bomb for 48 h using HF + HNO₃. Rh was used as an internal standard to monitor signal drift during counting. The USGS and Chinese National Standards BCR-1, BHVO-1, and GSR-3 were chosen for calibrating element concentrations. The discrepancy between the triplicates is less than 5% for all the elements (Qi et al., 2000).

Zircon U-Pb Dating

The zircon U-Pb dating samples were crashed, and grinded, and then separated by heavy liquid and magnetic separation methods. Zircons were picked by hand under a binocular microscope and mounted in epoxy resin. Before U-Pb dating analysis, The

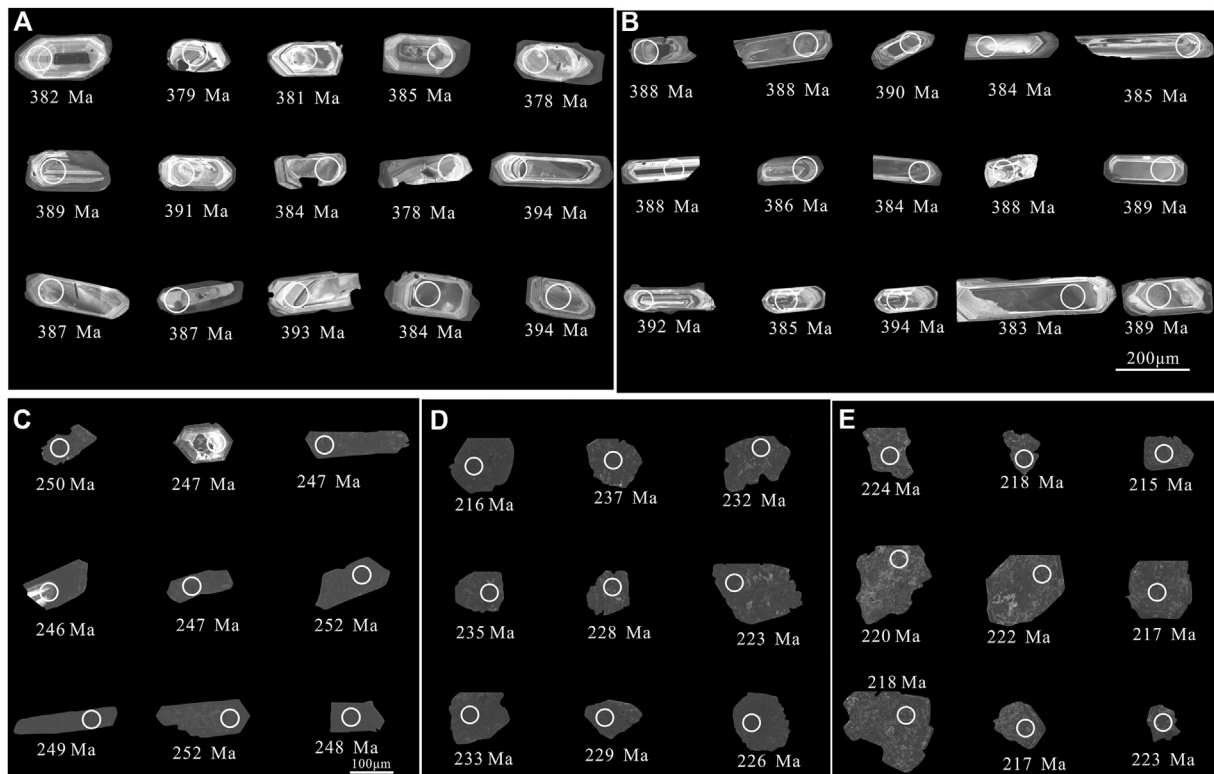


FIGURE 5 | Representative cathodoluminescence (CL) images of zircons from the different intrusions with analytical spots of the Askartor deposit. **(A)** granodiorite; **(B)** biotite granite; **(C)** two-mica granite; **(D)** muscovite granite; **(E)** pegmatite.

Cathodoluminescence (CL) images were used to assess the zircon at the Beijing zircon dating navigation technology limited company, and CL images performed at JSM6510 scanning electron microscope produced by JEOL Corporation (Japan).

Zircon U-Pb dating was done by an Elan DRC-e ICP-MS coupled with a GeoLasPro 193 nm Laser-Ablation System at SKLODG, CAS. The conditions were summarized as follows: the laser frequency was 8 Hz with an energy of 34–40 mJ; the beam diameter was 30 μm ; and the acquisition was 30 s for background and 60 s for signal. Helium was used as a carrier gas to transport the ablated materials from the laser-ablation cell to the ICP-MS torch. The external standard is Zircon 91,500, and the internal standard to calculate U, Th, and Pb concentrations of unknowns was NIST610. Glass was used as an internal standard to

Raw data were processed using the ICPMSDataCal program (Liu et al., 2008). Uncertainties of individual analyses and weighted mean ages are reported within 1σ errors; Common Pb correction used the ^{204}Pb methods of Andersen (2002). The weighted mean U-Pb ages and Concordia plots were processed using ISOPLOT software (Ludwig 2003).

Molybdenite Re-Os Dating

Seven molybdenite samples were collected from fine-grain granite and pegmatite. Molybdenite with a purity of >99% were carefully handpicked under a binocular microscope. Re-Os isotope

analyses were done at SKLODG, CAS. The analysis procedures are similar to that provided by Du et al. (2004). The ISOPLOT program (Ludwig, 2003) was used to calculate the Re-Os isochron age. The decay constant used in this calculation was $\lambda^{187}\text{Re} = 1.666 \times 10^{-11} \text{ year}^{-1}$ (Smoliar et al., 1996). Uncertainty in Re-Os model ages was 1.02% uncertainty. The uncertainty includes the ^{187}Re decay constant and uncertainty in Re and Os concentrations.

RESULTS

Zircon U-Pb Ages

Granodiorite (AKG01): the zircon grains from granodiorite are mostly light-yellow brown, transparent, and short prismatic. Their sizes are between 100 and $\sim 300 \mu\text{m}$. Almost all grains show clear oscillatory zoning (Figure 5A). The contents of Th and U are respectively 8–253 ppm and 172–326 ppm, and the Th/U ratios are between 0.41 and 0.85 (Table 1), indicating that these zircons are of magmatic origin. Twenty spots were selected for U-Pb analysis and these points were tightly grouped, yielding a $^{206}\text{Pb}/^{238}\text{U}$ age of $386.8 \pm 2.6 \text{ Ma}$ (MSWD = 0.54) (Figure 6A), representing the crystallization age of the pluton.

Biotite granite (AKG02): the feature of zircon grains from biotite granite is similar to that in granodiorite (Figure 5B). The contents of Th and U are 73–453 ppm and 102–646 ppm,

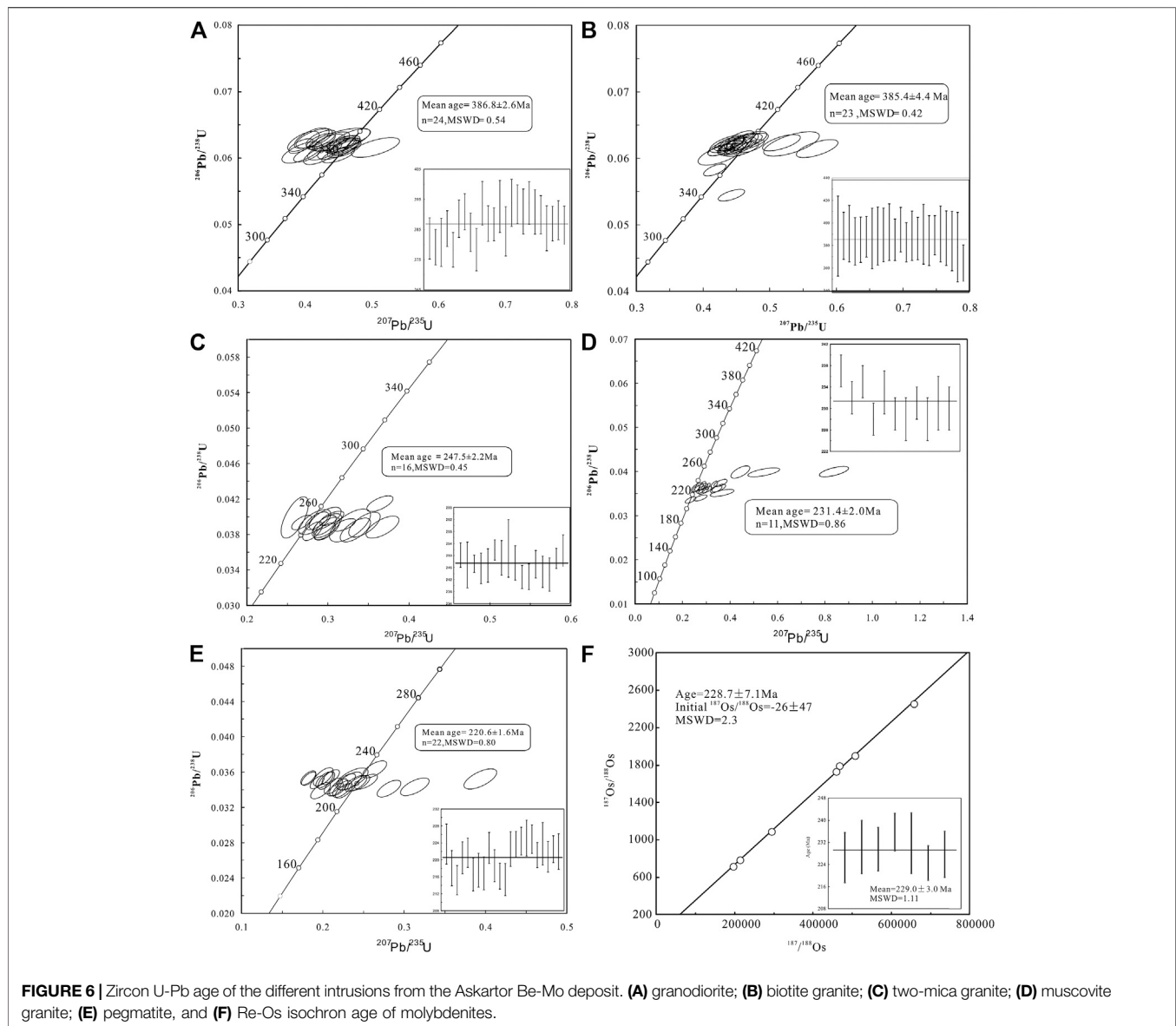
TABLE 1 | LA-ICPMS U-Pb data of zircons from the Askaetor Be deposit.

| Sample | Concentration (ppm) | | Th/U | Isotopic ratio | | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ | Ages (Ma) | | | |
|----------|---------------------|--------|------|--------------------------------------|---------|-------------------------------------|---------|-------------------------------------|---------|-------------------------------------|----|-------------------------------------|----|
| | Th | U | | ²⁰⁷ Pb/ ²⁰⁶ Pb | 1σ | | | | | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ |
| | | | | | | | | | | | | | |
| AKG01.01 | 114 | 189 | 0.60 | 0.05164 | 0.00273 | 0.43061 | 0.02071 | 0.06106 | 0.00112 | 364 | 15 | 382 | 7 |
| AKG01.02 | 116 | 233 | 0.50 | 0.04802 | 0.00216 | 0.40546 | 0.01694 | 0.06058 | 0.00096 | 346 | 12 | 379 | 6 |
| AKG01.03 | 123 | 241 | 0.51 | 0.04695 | 0.00319 | 0.39674 | 0.02423 | 0.06084 | 0.00132 | 339 | 18 | 381 | 8 |
| AKG01.04 | 120 | 222 | 0.54 | 0.05362 | 0.00220 | 0.46003 | 0.01773 | 0.06159 | 0.00098 | 384 | 12 | 385 | 6 |
| AKG01.05 | 146 | 212 | 0.69 | 0.05318 | 0.00242 | 0.45116 | 0.02016 | 0.06043 | 0.00094 | 378 | 14 | 378 | 6 |
| AKG01.06 | 160 | 277 | 0.58 | 0.05267 | 0.00247 | 0.45924 | 0.02003 | 0.06214 | 0.00102 | 384 | 14 | 389 | 6 |
| AKG01.07 | 153 | 287 | 0.53 | 0.04878 | 0.00217 | 0.42531 | 0.01754 | 0.06251 | 0.00099 | 360 | 12 | 391 | 6 |
| AKG01.08 | 130 | 222 | 0.58 | 0.05370 | 0.00250 | 0.46034 | 0.02064 | 0.06139 | 0.00105 | 384 | 14 | 384 | 6 |
| AKG01.09 | 210 | 263 | 0.80 | 0.05074 | 0.00258 | 0.42444 | 0.02039 | 0.06044 | 0.00116 | 359 | 15 | 378 | 7 |
| AKG01.10 | 112 | 185 | 0.60 | 0.04680 | 0.00249 | 0.41514 | 0.02213 | 0.06297 | 0.00120 | 353 | 16 | 394 | 7 |
| AKG01.11 | 176 | 219 | 0.80 | 0.05420 | 0.00233 | 0.46224 | 0.01759 | 0.06187 | 0.00097 | 386 | 12 | 387 | 6 |
| AKG01.12 | 149 | 326 | 0.46 | 0.04624 | 0.00185 | 0.39560 | 0.01460 | 0.06182 | 0.00090 | 338 | 11 | 387 | 5 |
| AKG01.13 | 129 | 215 | 0.60 | 0.05190 | 0.00443 | 0.45338 | 0.03755 | 0.06280 | 0.00142 | 380 | 26 | 393 | 9 |
| AKG01.14 | 112 | 219 | 0.51 | 0.05318 | 0.00301 | 0.45134 | 0.02534 | 0.06144 | 0.00135 | 378 | 18 | 384 | 8 |
| AKG01.15 | 108 | 172 | 0.62 | 0.04750 | 0.00261 | 0.41188 | 0.02123 | 0.06300 | 0.00129 | 350 | 15 | 394 | 8 |
| AKG01.16 | 127 | 308 | 0.41 | 0.04889 | 0.00225 | 0.42556 | 0.01818 | 0.06292 | 0.00106 | 360 | 13 | 393 | 6 |
| AKG01.17 | 185 | 281 | 0.66 | 0.04605 | 0.00232 | 0.39918 | 0.01924 | 0.06253 | 0.00123 | 341 | 14 | 391 | 7 |
| AKG01.18 | 124 | 188 | 0.66 | 0.05419 | 0.00273 | 0.47174 | 0.02214 | 0.06299 | 0.00116 | 392 | 15 | 394 | 7 |
| AKG01.19 | 102 | 206 | 0.50 | 0.05198 | 0.00273 | 0.44181 | 0.02155 | 0.06250 | 0.00121 | 372 | 15 | 391 | 7 |
| AKG01.20 | 157 | 249 | 0.63 | 0.05019 | 0.00234 | 0.43714 | 0.01953 | 0.06235 | 0.00104 | 368 | 14 | 390 | 6 |
| AKG01.21 | 91 | 196 | 0.46 | 0.05867 | 0.00322 | 0.50699 | 0.02966 | 0.06161 | 0.00122 | 416 | 20 | 385 | 7 |
| AKG01.22 | 184 | 282 | 0.65 | 0.05268 | 0.00212 | 0.45656 | 0.01764 | 0.06186 | 0.00095 | 382 | 12 | 387 | 6 |
| AKG01.23 | 232 | 311 | 0.75 | 0.05240 | 0.00225 | 0.45382 | 0.01851 | 0.06205 | 0.00106 | 380 | 13 | 388 | 6 |
| AKG01.24 | 253 | 297 | 0.85 | 0.05368 | 0.00227 | 0.46268 | 0.01870 | 0.06178 | 0.00105 | 386 | 13 | 386 | 6 |
| Sample | Concentration (ppm) | | Th/U | Isotopic ratio | | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ | Ages (Ma) | | | |
| | Th | U | | ²⁰⁷ Pb/ ²⁰⁶ Pb | 1σ | | | | | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ |
| | | | | | | | | | | | | | |
| AKG01.01 | 73 | 102 | 0.72 | 0.06418 | 0.00470 | 0.53331 | 0.03401 | 0.06208 | 0.00151 | 434 | 23 | 388 | 9 |
| AKG01.02 | 182 | 337 | 0.54 | 0.05139 | 0.00192 | 0.44326 | 0.01562 | 0.06212 | 0.00089 | 373 | 11 | 388 | 5 |
| AKG01.03 | 155 | 178 | 0.87 | 0.05423 | 0.00264 | 0.47109 | 0.02247 | 0.06244 | 0.00106 | 392 | 16 | 390 | 6 |
| AKG01.04 | 109 | 242 | 0.45 | 0.05391 | 0.00258 | 0.45821 | 0.02113 | 0.06130 | 0.00090 | 383 | 15 | 384 | 5 |
| AKG01.05 | 301 | 339 | 0.89 | 0.05167 | 0.00198 | 0.44134 | 0.01561 | 0.06155 | 0.00086 | 371 | 11 | 385 | 5 |
| AKG01.06 | 339 | 363 | 0.93 | 0.05158 | 0.00183 | 0.44679 | 0.01488 | 0.06199 | 0.00077 | 375 | 10 | 388 | 5 |
| AKG01.07 | 85 | 163 | 0.52 | 0.05297 | 0.00276 | 0.45214 | 0.02318 | 0.06173 | 0.00114 | 379 | 16 | 386 | 7 |
| AKG01.08 | 82 | 181 | 0.45 | 0.06687 | 0.00316 | 0.57185 | 0.02548 | 0.06135 | 0.00113 | 459 | 16 | 384 | 7 |
| AKG01.09 | 81 | 156 | 0.52 | 0.05182 | 0.00308 | 0.43671 | 0.02144 | 0.06210 | 0.00109 | 368 | 15 | 388 | 7 |
| AKG01.10 | 122 | 207 | 0.59 | 0.05923 | 0.00266 | 0.51857 | 0.02309 | 0.06226 | 0.00100 | 424 | 15 | 389 | 6 |
| AKG01.11 | 123 | 140 | 0.88 | 0.05480 | 0.00266 | 0.47020 | 0.02110 | 0.06266 | 0.00105 | 391 | 15 | 392 | 6 |
| AKG01.12 | 453 | 497 | 0.91 | 0.05195 | 0.00153 | 0.45040 | 0.01274 | 0.06154 | 0.00078 | 378 | 9 | 385 | 5 |
| AKG01.13 | 218 | 320 | 0.68 | 0.05196 | 0.00201 | 0.45766 | 0.01591 | 0.06303 | 0.00083 | 383 | 11 | 394 | 5 |
| AKG01.14 | 221 | 420 | 0.53 | 0.04953 | 0.00187 | 0.42675 | 0.01517 | 0.06117 | 0.00075 | 361 | 11 | 383 | 5 |
| AKG01.15 | 174 | 211 | 0.83 | 0.05082 | 0.00227 | 0.44076 | 0.01884 | 0.06214 | 0.00093 | 371 | 13 | 389 | 6 |
| AKG01.16 | 273 | 329 | 0.83 | 0.05443 | 0.00199 | 0.47273 | 0.01595 | 0.06174 | 0.00080 | 393 | 11 | 386 | 5 |
| AKG01.17 | 93 | 161 | 0.58 | 0.05384 | 0.00261 | 0.45893 | 0.01995 | 0.06235 | 0.00112 | 384 | 14 | 390 | 7 |
| AKG01.18 | 208 | 328 | 0.63 | 0.05005 | 0.00333 | 0.42699 | 0.02773 | 0.06047 | 0.00134 | 361 | 20 | 379 | 8 |
| AKG01.19 | 149 | 191 | 0.78 | 0.05056 | 0.00220 | 0.42830 | 0.01684 | 0.06143 | 0.00095 | 362 | 12 | 384 | 6 |
| AKG01.20 | 251 | 646 | 0.39 | 0.05066 | 0.00148 | 0.44541 | 0.01285 | 0.06221 | 0.00074 | 374 | 9 | 389 | 4 |
| AKG01.21 | 137 | 269 | 0.51 | 0.05317 | 0.00245 | 0.46259 | 0.02204 | 0.06240 | 0.00104 | 386 | 15 | 390 | 6 |
| AKG01.22 | 97 | 182 | 0.53 | 0.05282 | 0.00245 | 0.44924 | 0.02006 | 0.06178 | 0.00103 | 377 | 14 | 386 | 6 |
| AKG01.23 | 120 | 304 | 0.40 | 0.05901 | 0.00223 | 0.44341 | 0.01598 | 0.05430 | 0.00074 | 373 | 11 | 341 | 5 |
| AKG01.24 | 343 | 435 | 0.79 | 0.05139 | 0.00176 | 0.41835 | 0.01375 | 0.05813 | 0.00073 | 355 | 10 | 364 | 4 |
| Sample | Concentration (ppm) | | Th/U | Isotopic ratio | | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ | Ages (Ma) | | | |
| | Th | U | | ²⁰⁷ Pb/ ²⁰⁶ Pb | 1σ | | | | | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ |
| | | | | | | | | | | | | | |
| AKG04.01 | 1,592 | 11,768 | 0.14 | 0.04965 | 0.00161 | 0.28534 | 0.00956 | 0.03956 | 0.00066 | 255 | 8 | 250 | 4 |
| AKG04.02 | 1,680 | 12,157 | 0.14 | 0.05605 | 0.00187 | 0.32628 | 0.01686 | 0.03903 | 0.00123 | 287 | 13 | 247 | 8 |
| AKG04.03 | 1,160 | 8,796 | 0.13 | 0.05658 | 0.00171 | 0.31940 | 0.00928 | 0.03910 | 0.00047 | 281 | 7 | 247 | 3 |
| AKG04.04 | 60,118 | 15,458 | 3.89 | 0.06415 | 0.00178 | 0.36682 | 0.01357 | 0.03885 | 0.00082 | 317 | 10 | 246 | 5 |
| AKG04.05 | 1,486 | 10,054 | 0.15 | 0.05197 | 0.00164 | 0.29778 | 0.01214 | 0.03901 | 0.00089 | 265 | 9 | 247 | 6 |

(Continued on following page)

TABLE 1 | (Continued) LA-ICPMS U-Pb data of zircons from the Askartor Be deposit.

| Sample | Concentration (ppm) | | Th/U | Isotopic ratio | | $^{207}\text{Pb}/^{235}\text{U}$ | 1 σ | $^{206}\text{Pb}/^{238}\text{U}$ | 1 σ | Ages (Ma) | | | |
|----------|---------------------|--------|------|-----------------------------------|------------|----------------------------------|------------|----------------------------------|------------|----------------------------------|------------|----------------------------------|------------|
| | Th | U | | $^{207}\text{Pb}/^{206}\text{Pb}$ | 1 σ | | | | | $^{207}\text{Pb}/^{235}\text{U}$ | 1 σ | $^{206}\text{Pb}/^{238}\text{U}$ | 1 σ |
| | | | | | | | | | | | | | |
| AKG04.06 | 772 | 9,875 | 0.08 | 0.05248 | 0.00161 | 0.30379 | 0.00996 | 0.03984 | 0.00054 | 269 | 8 | 252 | 3 |
| AKG04.07 | 911 | 8,517 | 0.11 | 0.04810 | 0.00175 | 0.28231 | 0.01325 | 0.03942 | 0.00093 | 252 | 10 | 249 | 6 |
| AKG04.08 | 2066 | 15,936 | 0.13 | 0.04504 | 0.00167 | 0.25770 | 0.01127 | 0.03992 | 0.00154 | 233 | 9 | 252 | 10 |
| AKG04.09 | 1,507 | 10,554 | 0.14 | 0.05904 | 0.00163 | 0.34457 | 0.01288 | 0.03914 | 0.00092 | 301 | 10 | 248 | 6 |
| AKG04.10 | 1,040 | 9,661 | 0.11 | 0.05247 | 0.00162 | 0.29513 | 0.00845 | 0.03839 | 0.00062 | 263 | 7 | 243 | 4 |
| AKG04.11 | 617 | 9,999 | 0.06 | 0.04926 | 0.00144 | 0.27990 | 0.00824 | 0.03841 | 0.00068 | 251 | 7 | 243 | 4 |
| AKG04.12 | 772 | 11,048 | 0.07 | 0.05071 | 0.00159 | 0.29490 | 0.00942 | 0.03907 | 0.00074 | 262 | 7 | 247 | 5 |
| AKG04.13 | 1,561 | 8,696 | 0.18 | 0.05884 | 0.00191 | 0.36347 | 0.01064 | 0.04147 | 0.00058 | 315 | 8 | 262 | 4 |
| AKG04.14 | 1,187 | 11,746 | 0.10 | 0.05119 | 0.00172 | 0.29746 | 0.01073 | 0.03867 | 0.00084 | 264 | 8 | 245 | 5 |
| AKG04.15 | 482 | 10,083 | 0.05 | 0.05817 | 0.00180 | 0.33289 | 0.01242 | 0.03852 | 0.00089 | 292 | 9 | 244 | 6 |
| AKG04.16 | 455 | 7,250 | 0.06 | 0.04612 | 0.00146 | 0.26626 | 0.00815 | 0.03939 | 0.00054 | 240 | 7 | 249 | 3 |
| AKG04.17 | 1,080 | 7,121 | 0.15 | 0.05212 | 0.00227 | 0.29562 | 0.01312 | 0.03980 | 0.00085 | 263 | 10 | 252 | 5 |
| Sample | Concentration (ppm) | | Th/U | Isotopic ratio | | $^{207}\text{Pb}/^{235}\text{U}$ | 1 σ | $^{206}\text{Pb}/^{238}\text{U}$ | 1 σ | Ages (Ma) | | | |
| | Th | U | | $^{207}\text{Pb}/^{206}\text{Pb}$ | 1 σ | | | | | $^{207}\text{Pb}/^{235}\text{U}$ | 1 σ | $^{206}\text{Pb}/^{238}\text{U}$ | 1 σ |
| | | | | | | | | | | | | | |
| AKG05.01 | 466 | 8,360 | 0.06 | 0.05887 | 0.00396 | 0.27643 | 0.01825 | 0.03406 | 0.00046 | 248 | 15 | 216 | 3 |
| AKG05.02 | 1,539 | 9,060 | 0.17 | 0.07022 | 0.00370 | 0.36196 | 0.01832 | 0.03739 | 0.00055 | 314 | 14 | 237 | 3 |
| AKG05.03 | 1,385 | 32,709 | 0.04 | 0.05839 | 0.00128 | 0.30657 | 0.00648 | 0.03672 | 0.00050 | 272 | 5 | 232 | 3 |
| AKG05.04 | 2,175 | 9,735 | 0.22 | 0.06268 | 0.00175 | 0.33484 | 0.00922 | 0.03708 | 0.00051 | 293 | 7 | 235 | 3 |
| AKG05.05 | 1,244 | 7,222 | 0.17 | 0.06124 | 0.00281 | 0.30387 | 0.01322 | 0.03599 | 0.00053 | 269 | 10 | 228 | 3 |
| AKG05.06 | 4,544 | 24,671 | 0.18 | 0.07573 | 0.00706 | 0.36702 | 0.03374 | 0.03515 | 0.00053 | 317 | 25 | 223 | 3 |
| AKG05.07 | 1,453 | 6,478 | 0.22 | 0.05318 | 0.00213 | 0.28493 | 0.00935 | 0.03679 | 0.00068 | 255 | 7 | 233 | 4 |
| AKG05.08 | 515 | 10,428 | 0.05 | 0.04876 | 0.00215 | 0.25751 | 0.01019 | 0.03616 | 0.00056 | 233 | 8 | 229 | 3 |
| AKG05.09 | 1,048 | 6,806 | 0.15 | 0.05874 | 0.00285 | 0.28896 | 0.01335 | 0.03568 | 0.00052 | 258 | 11 | 226 | 3 |
| AKG05.10 | 12,226 | 6,492 | 1.88 | 0.14124 | 0.00673 | 0.84036 | 0.04060 | 0.04005 | 0.00079 | 619 | 22 | 253 | 5 |
| AKG05.11 | 4,420 | 8,378 | 0.53 | 0.09897 | 0.00833 | 0.54416 | 0.04485 | 0.03988 | 0.00069 | 441 | 29 | 252 | 4 |
| AKG05.12 | 2,713 | 9,038 | 0.30 | 0.06395 | 0.00301 | 0.34327 | 0.01609 | 0.03606 | 0.00060 | 300 | 12 | 228 | 4 |
| AKG05.13 | 1,671 | 18,199 | 0.09 | 0.05063 | 0.00322 | 0.23443 | 0.01453 | 0.03358 | 0.00047 | 214 | 12 | 213 | 3 |
| AKG05.14 | 971 | 6,915 | 0.14 | 0.05554 | 0.00366 | 0.27971 | 0.01792 | 0.03652 | 0.00055 | 250 | 14 | 231 | 3 |
| AKG05.15 | 1,130 | 25,526 | 0.04 | 0.05239 | 0.00243 | 0.28043 | 0.01268 | 0.03597 | 0.00060 | 251 | 10 | 228 | 4 |
| AKG05.16 | 858 | 7,029 | 0.12 | 0.05235 | 0.00356 | 0.26304 | 0.01704 | 0.03645 | 0.00074 | 237 | 14 | 231 | 5 |
| AKG05.17 | 2,947 | 5,148 | 0.57 | 0.07749 | 0.00518 | 0.44492 | 0.02590 | 0.03994 | 0.00093 | 374 | 18 | 252 | 6 |
| AKG05-18 | 1,217 | 7,419 | 0.16 | 0.07066 | 0.00401 | 0.35344 | 0.01911 | 0.03628 | 0.00062 | 307 | 14 | 230 | 4 |
| Sample | Concentration (ppm) | | Th/U | Isotopic ratio | | $^{207}\text{Pb}/^{235}\text{U}$ | 1 σ | $^{206}\text{Pb}/^{238}\text{U}$ | 1 σ | Ages (Ma) | | | |
| | Th | U | | $^{207}\text{Pb}/^{206}\text{Pb}$ | 1 σ | | | | | $^{207}\text{Pb}/^{235}\text{U}$ | 1 σ | $^{206}\text{Pb}/^{238}\text{U}$ | 1 σ |
| | | | | | | | | | | | | | |
| AKG06.01 | 3,936 | 6,450 | 0.61 | 0.0778 | 0.0030 | 0.3940 | 0.0135 | 0.0353 | 0.0008 | 337 | 10 | 224 | 5 |
| AKG06.02 | 3,533 | 6,229 | 0.57 | 0.0623 | 0.0024 | 0.3125 | 0.0117 | 0.0344 | 0.0007 | 276 | 9 | 218 | 4 |
| AKG06.03 | 1,124 | 5,935 | 0.19 | 0.0456 | 0.0015 | 0.2249 | 0.0070 | 0.0339 | 0.0006 | 206 | 6 | 215 | 3 |
| AKG06.04 | 2,150 | 4,780 | 0.45 | 0.0495 | 0.0019 | 0.2630 | 0.0098 | 0.0364 | 0.0006 | 237 | 8 | 230 | 4 |
| AKG06.05 | 952 | 4,751 | 0.20 | 0.0474 | 0.0019 | 0.2396 | 0.0091 | 0.0348 | 0.0006 | 218 | 7 | 220 | 4 |
| AKG06.06 | 1,603 | 4,578 | 0.35 | 0.0494 | 0.0019 | 0.2522 | 0.0093 | 0.0350 | 0.0006 | 228 | 8 | 222 | 3 |
| AKG06.07 | 2,383 | 5,664 | 0.42 | 0.0443 | 0.0016 | 0.2227 | 0.0078 | 0.0342 | 0.0006 | 204 | 7 | 217 | 4 |
| AKG06.08 | 796 | 6,841 | 0.12 | 0.0434 | 0.0016 | 0.2183 | 0.0076 | 0.0343 | 0.0006 | 201 | 6 | 218 | 4 |
| AKG06.09 | 1867 | 4,985 | 0.37 | 0.0557 | 0.0019 | 0.2807 | 0.0096 | 0.0342 | 0.0006 | 251 | 8 | 217 | 4 |
| AKG06.10 | 811 | 6,042 | 0.13 | 0.0391 | 0.0015 | 0.2009 | 0.0071 | 0.0352 | 0.0006 | 186 | 6 | 223 | 4 |
| AKG06.11 | 1,594 | 7,267 | 0.22 | 0.0419 | 0.0016 | 0.2116 | 0.0075 | 0.0345 | 0.0006 | 195 | 6 | 219 | 4 |
| AKG06.12 | 291 | 5,837 | 0.05 | 0.0432 | 0.0014 | 0.2148 | 0.0066 | 0.0341 | 0.0005 | 198 | 6 | 216 | 3 |
| AKG06.13 | 2075 | 7,608 | 0.27 | 0.0395 | 0.0016 | 0.1959 | 0.0081 | 0.0340 | 0.0006 | 182 | 7 | 215 | 4 |
| AKG06.14 | 890 | 5,567 | 0.16 | 0.0400 | 0.0015 | 0.2030 | 0.0068 | 0.0351 | 0.0007 | 188 | 6 | 223 | 4 |
| AKG06.15 | 576 | 4,896 | 0.12 | 0.0353 | 0.0012 | 0.1814 | 0.0059 | 0.0353 | 0.0005 | 169 | 5 | 224 | 3 |
| AKG06.16 | 372 | 4,870 | 0.08 | 0.0354 | 0.0013 | 0.1807 | 0.0063 | 0.0354 | 0.0005 | 169 | 5 | 224 | 3 |
| AKG06.17 | 2,609 | 5,378 | 0.49 | 0.0387 | 0.0016 | 0.1992 | 0.0082 | 0.0355 | 0.0007 | 184 | 7 | 225 | 4 |
| AKG06.18 | 1,122 | 5,172 | 0.22 | 0.0404 | 0.0014 | 0.2084 | 0.0071 | 0.0355 | 0.0005 | 192 | 6 | 225 | 3 |
| AKG06.19 | 1743 | 6,841 | 0.25 | 0.0375 | 0.0012 | 0.1916 | 0.0059 | 0.0349 | 0.0005 | 178 | 5 | 221 | 3 |
| AKG06.20 | 1953 | 4,277 | 0.46 | 0.0458 | 0.0026 | 0.2348 | 0.0131 | 0.0353 | 0.0008 | 214 | 11 | 224 | 5 |
| AKG06.21 | 2,160 | 4,034 | 0.54 | 0.0474 | 0.0017 | 0.2434 | 0.0090 | 0.0348 | 0.0006 | 221 | 7 | 221 | 4 |
| AKG06.22 | 538 | 4,539 | 0.12 | 0.0436 | 0.0015 | 0.2278 | 0.0076 | 0.0351 | 0.0005 | 208 | 6 | 223 | 3 |
| AKG06.23 | 459 | 4,607 | 0.10 | 0.0449 | 0.0020 | 0.2320 | 0.0099 | 0.0350 | 0.0007 | 212 | 8 | 222 | 4 |
| AKG06.24 | 3,936 | 6,450 | 0.61 | 0.0778 | 0.0030 | 0.3940 | 0.0135 | 0.0353 | 0.0008 | 337 | 10 | 224 | 5 |



respectively, and the Th/U ratios ranged from 0.39 to 0.93. Twenty-three yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages with a weighted mean age of 385.8 ± 4.4 Ma (MSWD = 0.42, $n = 23$) (**Figure 6B**), representing the crystallization age of this rock. One point showed a younger age of 341 ± 5 Ma (**Table 1**, AKG02.23), which may be affected by minor Pb loss.

Two-mica granite (AKG04): The zircon grains separated from two-mica granite are mostly brown and opaque, and varying in size of 80–220 μm , with euhedral habit featuring tetragonal dipyrmaid \pm prism. They show weak and intense luminescences in CL photos, with reservation of primary oscillatory zone in some zircons (**Figure 5C**). The CL features indicate that the zircons have suffered from low degree of recrystallization induced by metamictization due to high contents of U (7,121–15936 ppm) and Th (mostly fall in range of 455–2066 ppm) and fluid alteration after crystallization from

melting. The zircons mostly have low Th/U ratios of 0.1–0.2. Seventeen analytical points were conducted on the zircons with legible oscillatory zones, and sixteen of them yielded consistent and concordant $^{206}\text{Pb}/^{238}\text{U}$ ages with a weighted mean age of 247.5 ± 2.2 Ma (MSWD = 0.45) (**Figure 6C**), which represents the crystallization time of the muscovite granite. The rest one analytical point yielded an older $^{206}\text{Pb}/^{238}\text{U}$ age of 262 ± 3.6 Ma (**Table 1**, AKG04.16), which may reflect the incorporation of common lead after crystallization.

Fine-grain muscovite granite (AKG05): Zircons from fine-grain muscovite granite generally exhibit euhedral tetragonal-dipyramid or stubby tetragonal prism shapes and range from 80 to 180 μm in size. Most of them are opaque and brown to dark brown in color, with weak oscillatory zoning structure (**Figure 5D**). Th and U contents of the zircon grain are 466–4,544 ppm and 5,148–32,709 ppm, respectively, with Th/U

TABLE 2 | The whole-rock compositions of different intrusions from Askartor Be deposit.

| Rock type | Two-mica granite | | | | | | | | | | | | Muscovite granite | |
|---------------------------------|-------------------|--------------|--------------|------------|------------|------------|--------------|--------------|--------------|--------------|------------|------------|---------------------------------|--|
| | AKG-12-04K-A | AKG-12-03A-A | AKG-12-03B-D | AKG-12-03C | AKG-12-03D | AKG-12-03E | AKG-12-04D-A | AKG-12-04E-A | AKG-12-04F | AKG-12-04G-D | AKG-12-04C | AKG-12-04C | AKG-12-04C | |
| SiO ₂ | 74.77 | 73.87 | 73.37 | 73.10 | 73.05 | 74.25 | 75.06 | 74.58 | 74.21 | 73.70 | 74.40 | 74.40 | 74.40 | |
| TiO ₂ | 0.07 | 0.09 | 0.24 | 0.19 | 0.20 | 0.16 | 0.09 | 0.05 | 0.15 | 0.25 | 0.04 | 0.04 | 0.04 | |
| Al ₂ O ₃ | 14.47 | 14.38 | 13.43 | 14.86 | 14.04 | 14.16 | 14.06 | 14.16 | 14.40 | 13.61 | 14.71 | 14.71 | 14.71 | |
| TFe ₂ O ₃ | 0.76 | 0.83 | 0.92 | 1.11 | 1.14 | 0.97 | 0.71 | 0.49 | 0.90 | 0.97 | 0.35 | 0.35 | 0.35 | |
| MnO | 0.03 | 0.04 | 0.04 | 0.05 | 0.04 | 0.05 | 0.02 | 0.02 | 0.05 | 0.02 | 0.02 | 0.02 | 0.02 | |
| MgO | 0.17 | 0.20 | 2.37 | 0.27 | 0.29 | 0.22 | 0.17 | 0.12 | 0.19 | 0.04 | 0.05 | 0.05 | 0.05 | |
| CaO | 0.36 | 0.53 | 0.60 | 0.74 | 0.76 | 0.42 | 0.48 | 0.58 | 0.56 | 0.60 | 0.10 | 0.10 | 0.10 | |
| Na ₂ O | 4.28 | 4.21 | 3.47 | 3.72 | 3.06 | 3.41 | 4.06 | 4.58 | 3.64 | 3.31 | 4.85 | 4.85 | 4.85 | |
| K ₂ O | 3.89 | 4.11 | 3.99 | 4.39 | 4.12 | 4.01 | 4.13 | 3.83 | 4.46 | 4.12 | 3.81 | 3.81 | 3.81 | |
| P ₂ O ₅ | 0.17 | 0.19 | 0.16 | 0.18 | 0.19 | 0.18 | 0.17 | 0.14 | 0.18 | 0.18 | 0.07 | 0.07 | 0.07 | |
| LOI | 0.87 | 0.94 | 1.32 | 0.54 | 1.23 | 1.63 | 0.72 | 0.66 | 0.97 | 1.09 | 1.12 | 1.12 | 1.12 | |
| Total | 99.84 | 99.39 | 99.91 | 99.15 | 98.12 | 99.45 | 99.67 | 98.21 | 99.69 | 97.89 | 99.53 | 99.53 | 99.53 | |
| A/CNK | 1.22 | 1.17 | 1.21 | 1.22 | 1.29 | 1.32 | 1.17 | 1.11 | 1.22 | 1.24 | 1.20 | 1.20 | 1.20 | |
| Li | 107.0 | 148.0 | 148.0 | 183.0 | 211.0 | 236.0 | 100.0 | 75.1 | 151.0 | 97.8 | 59.7 | 59.7 | 59.7 | |
| Be | 12.6 | 12.8 | 19.5 | 12.6 | 21.7 | 15.3 | 9.1 | 9.0 | 12.7 | 13.8 | 13.9 | 13.9 | 13.9 | |
| Rb | 345.0 | 401.0 | 386.0 | 343.0 | 345.0 | 350.0 | 309.0 | 271.0 | 364.0 | 369.0 | 338.0 | 338.0 | 338.0 | |
| Sr | 21.7 | 32.8 | 48.4 | 52.8 | 47.8 | 43.2 | 19.2 | 14.7 | 24.1 | 25.7 | 18.3 | 18.3 | 18.3 | |
| Y | 6.8 | 5.9 | 8.0 | 8.6 | 9.1 | 5.6 | 4.0 | 3.4 | 5.8 | 3.2 | 2.4 | 2.4 | 2.4 | |
| Zr | 59.8 | 67.4 | 83.9 | 106.0 | 119.0 | 92.3 | 54.0 | 33.3 | 83.8 | 60.0 | 16.7 | 16.7 | 16.7 | |
| Nb | 19.7 | 20.3 | 17.6 | 18.9 | 21.2 | 21.2 | 14.4 | 15.1 | 17.2 | 13.1 | 16.0 | 16.0 | 16.0 | |
| Ba | 58.4 | 88.7 | 135.0 | 131.0 | 104.0 | 115.0 | 26.2 | 15.2 | 50.7 | 77.3 | 16.4 | 16.4 | 16.4 | |
| La | 4.86 | 11.60 | 13.70 | 23.50 | 19.90 | 12.90 | 8.57 | 5.76 | 10.90 | 8.07 | 0.67 | 0.67 | 0.67 | |
| Ce | 26.20 | 26.20 | 28.80 | 50.50 | 41.90 | 34.00 | 19.30 | 11.00 | 23.10 | 21.40 | 1.30 | 1.30 | 1.30 | |
| Pr | 3.08 | 3.08 | 3.52 | 6.23 | 5.27 | 3.39 | 2.22 | 1.49 | 2.97 | 2.10 | 0.16 | 0.16 | 0.16 | |
| Nd | 11.10 | 11.10 | 13.40 | 23.10 | 19.60 | 12.60 | 8.08 | 5.43 | 11.30 | 7.59 | 0.50 | 0.50 | 0.50 | |
| Sm | 1.09 | 1.89 | 2.28 | 3.89 | 3.61 | 2.14 | 1.43 | 1.04 | 2.05 | 1.34 | 0.16 | 0.16 | 0.16 | |
| Eu | 0.13 | 0.25 | 0.32 | 0.41 | 0.36 | 0.25 | 0.16 | 0.11 | 0.20 | 0.16 | 0.02 | 0.02 | 0.02 | |
| Gd | 0.89 | 1.19 | 1.55 | 2.35 | 2.20 | 1.41 | 0.98 | 0.58 | 1.30 | 0.77 | 0.14 | 0.14 | 0.14 | |
| Tb | 0.17 | 0.19 | 0.23 | 0.35 | 0.33 | 0.21 | 0.14 | 0.10 | 0.21 | 0.13 | 0.03 | 0.03 | 0.03 | |
| Dy | 1.04 | 0.95 | 1.20 | 1.53 | 1.54 | 1.00 | 0.64 | 0.52 | 0.98 | 0.55 | 0.24 | 0.24 | 0.24 | |
| Ho | 0.18 | 0.22 | 0.24 | 0.28 | 0.28 | 0.18 | 0.12 | 0.10 | 0.17 | 0.09 | 0.05 | 0.05 | 0.05 | |
| Er | 0.69 | 0.54 | 0.82 | 0.82 | 0.85 | 0.54 | 0.37 | 0.33 | 0.56 | 0.30 | 0.20 | 0.20 | 0.20 | |
| Tm | 0.12 | 0.09 | 0.15 | 0.12 | 0.12 | 0.08 | 0.05 | 0.05 | 0.08 | 0.05 | 0.04 | 0.04 | 0.04 | |
| Yb | 0.67 | 0.67 | 1.23 | 0.80 | 0.83 | 0.60 | 0.38 | 0.35 | 0.54 | 0.30 | 0.35 | 0.35 | 0.35 | |
| Lu | 0.13 | 0.10 | 0.19 | 0.11 | 0.12 | 0.10 | 0.05 | 0.05 | 0.08 | 0.04 | 0.05 | 0.05 | 0.05 | |
| Hf | 2.3 | 2.3 | 2.6 | 3.0 | 3.6 | 2.9 | 1.9 | 1.3 | 2.8 | 1.9 | 1.0 | 1.0 | 1.0 | |
| Ta | 3.3 | 2.1 | 2.6 | 2.6 | 3.1 | 2.1 | 1.7 | 1.5 | 3.0 | 2.6 | 2.1 | 2.1 | 2.1 | |
| Th | 11.1 | 11.1 | 12.2 | 21.1 | 19.8 | 13.6 | 8.5 | 4.8 | 15.3 | 9.6 | 1.4 | 1.4 | 1.4 | |
| U | 1.8 | 4.6 | 1.9 | 40.1 | 11.3 | 2.1 | 4.9 | 0.9 | 13.3 | 1.5 | 1.5 | 1.5 | 1.5 | |
| Nb/Ta | 6.0 | 9.8 | 6.8 | 7.2 | 6.3 | 9.9 | 8.2 | 8.0 | 5.7 | 5.1 | 7.7 | 7.7 | 7.7 | |
| Zr/Hf | 26.3 | 30.0 | 32.0 | 34.9 | 32.8 | 31.4 | 28.9 | 26.0 | 30.0 | 31.1 | 16.4 | 16.4 | 16.4 | |
| Y/Ho | 30.5 | 32.7 | 32.6 | 31.2 | 34.1 | 30.2 | 34.1 | 32.6 | 33.6 | 34.4 | 48.6 | 48.6 | 48.6 | |
| Sr/Eu | 172.8 | 131.7 | 143.8 | 129.2 | 131.4 | 170.8 | 123.7 | 128.1 | 121.5 | 158.0 | 87.8 | 87.8 | 87.8 | |
| ΣREE | 31.77 | 58.03 | 67.63 | 113.98 | 96.91 | 69.40 | 42.48 | 26.92 | 54.44 | 42.89 | 3.91 | 3.91 | 3.91 | |
| δEu | 0.39 | 0.50 | 0.52 | 0.41 | 0.39 | 0.44 | 0.40 | 0.45 | 0.37 | 0.49 | 0.42 | 0.42 | 0.42 | |
| δCe | 1.40 | 1.05 | 0.99 | 1.00 | 0.98 | 1.23 | 1.06 | 0.90 | 0.97 | 1.25 | 0.96 | 0.96 | 0.96 | |
| TE3.4 | 1.03 | 1.04 | 1.02 | 1.02 | 1.00 | 0.99 | 0.98 | 1.03 | 1.03 | 1.06 | 1.16 | 1.16 | 1.16 | |
| Rock type sample | Muscovite granite | | | | | | | | | | | | Beryl-bearing muscovite granite | |
| | AKG-12-04G | AKG-12-04J | AKG-12-04M | AKG-12-04N | AKG-12-04L | AKG-12-04O | AKG-12-04B | AKG-12-04H | AKG-12-04R-A | AKG-12-04S | AKG-12-04I | AKG-12-04I | AKG-12-04I | |
| SiO ₂ | 74.33 | 74.85 | 75.41 | 74.87 | 74.86 | 74.04 | 72.64 | 75.05 | 71.92 | 74.13 | 75.04 | 75.04 | 75.04 | |
| TiO ₂ | 0.06 | 0.05 | 0.04 | 0.03 | 0.04 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.03 | 0.03 | |
| Al ₂ O ₃ | 14.70 | 14.81 | 13.78 | 14.61 | 14.51 | 15.00 | 15.34 | 14.15 | 15.98 | 15.19 | 15.41 | 15.41 | 15.41 | |
| TFe ₂ O ₃ | 0.51 | 0.42 | 0.27 | 0.33 | 0.34 | 0.41 | 0.17 | 0.43 | 0.22 | 0.11 | 0.32 | 0.32 | 0.32 | |
| MnO | 0.02 | 0.02 | 0.01 | 0.02 | 0.02 | 0.08 | 0.02 | 0.04 | 0.01 | 0.04 | 0.08 | 0.08 | 0.08 | |
| MgO | 0.09 | 0.04 | 0.03 | 0.02 | 0.04 | 0.02 | 0.00 | 0.04 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | |

(Continued on following page)

TABLE 2 | (Continued) The whole-rock compositions of different intrusions from Askartor Be deposit.

| Sample | Two-mica granite | | | | | | | | | | Muscovite granite | |
|-------------------------------|------------------|--------------|--------------|------------|------------|------------|--------------|--------------|------------|--------------|-------------------|-------|
| | AKG-12-04K-A | AKG-12-03A-A | AKG-12-03B-D | AKG-12-03C | AKG-12-03D | AKG-12-03E | AKG-12-04D-A | AKG-12-04E-A | AKG-12-04F | AKG-12-04G-D | AKG-12-04C | |
| CaO | 0.19 | 0.26 | 0.25 | 0.16 | 0.25 | 0.22 | 0.07 | 0.33 | 0.15 | 0.09 | 0.09 | |
| Na ₂ O | 4.04 | 4.36 | 4.49 | 4.49 | 4.53 | 4.76 | 5.51 | 5.41 | 5.96 | 6.03 | 6.03 | 0.09 |
| K ₂ O | 4.47 | 4.14 | 3.87 | 3.87 | 3.77 | 3.96 | 3.90 | 2.92 | 4.39 | 3.07 | 3.07 | 3.98 |
| P ₂ O ₅ | 0.11 | 0.09 | 0.11 | 0.11 | 0.11 | 0.14 | 0.11 | 0.19 | 0.15 | 0.13 | 0.13 | 0.10 |
| LOI | 0.55 | 0.74 | 1.00 | 0.91 | 1.00 | 0.84 | 1.04 | 0.69 | 1.04 | 0.89 | 0.89 | 0.75 |
| Total | 99.08 | 99.77 | 99.46 | 99.42 | 99.47 | 99.51 | 98.80 | 99.26 | 99.31 | 99.69 | 99.69 | 99.72 |
| A/CNK | 1.24 | 1.22 | 1.16 | 1.23 | 1.21 | 1.20 | 1.14 | 1.12 | 1.08 | 1.13 | 1.13 | 1.37 |
| | | | | | | ppm | | | | | | |
| Li | 70.8 | 66.2 | 45.5 | 56.5 | 45.5 | 37.5 | 30.4 | 23.5 | 23.7 | 29.7 | 29.7 | 36.3 |
| Be | 10.0 | 10.5 | 9.7 | 10.3 | 11.0 | 8.0 | 200.6 | 311.9 | 300.8 | 355.9 | 355.9 | 175.2 |
| Rb | 359.0 | 323.0 | 349.0 | 344.0 | 317.0 | 431.0 | 448.0 | 587.0 | 454.0 | 318.0 | 318.0 | 385.0 |
| Sr | 34.6 | 6.8 | 7.7 | 5.0 | 15.0 | 8.3 | 14.6 | 21.0 | 21.1 | 12.4 | 12.4 | 5.9 |
| Y | 2.3 | 2.3 | 2.9 | 4.4 | 3.0 | 3.9 | 5.3 | 5.8 | 5.6 | 5.6 | 5.6 | 2.5 |
| Zr | 15.1 | 18.2 | 15.5 | 33.2 | 14.6 | 23.0 | 26.7 | 20.8 | 20.8 | 21.4 | 21.4 | 22.5 |
| Nb | 17.5 | 14.4 | 8.6 | 13.9 | 15.5 | 21.4 | 98.7 | 96.7 | 110.0 | 105.0 | 105.0 | 80.6 |
| Ba | 6.6 | 7.2 | 5.2 | 3.1 | 4.0 | 13.6 | 15.4 | 32.3 | 30.6 | 19.5 | 19.5 | 5.9 |
| La | 1.35 | 1.82 | 1.89 | 1.79 | 1.05 | 1.18 | 0.41 | 0.68 | 1.04 | 0.90 | 0.90 | 0.98 |
| Ce | 2.93 | 3.54 | 3.74 | 3.36 | 2.26 | 2.20 | 0.79 | 1.56 | 2.05 | 1.51 | 1.51 | 1.16 |
| Pr | 0.35 | 0.43 | 0.49 | 0.42 | 0.24 | 0.27 | 0.10 | 0.19 | 0.21 | 0.11 | 0.11 | 0.13 |
| Nd | 1.20 | 1.45 | 1.58 | 1.41 | 0.70 | 0.84 | 0.32 | 0.68 | 0.66 | 0.40 | 0.40 | 0.41 |
| Sm | 0.32 | 0.32 | 0.38 | 0.37 | 0.21 | 0.23 | 0.08 | 0.16 | 0.20 | 0.10 | 0.10 | 0.10 |
| Eu | 0.05 | 0.04 | 0.05 | 0.03 | 0.04 | 0.03 | 0.01 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 |
| Gd | 0.25 | 0.26 | 0.26 | 0.31 | 0.18 | 0.20 | 0.09 | 0.18 | 0.15 | 0.12 | 0.12 | 0.10 |
| Tb | 0.06 | 0.05 | 0.05 | 0.08 | 0.04 | 0.05 | 0.04 | 0.06 | 0.05 | 0.06 | 0.06 | 0.03 |
| Dy | 0.35 | 0.30 | 0.37 | 0.58 | 0.29 | 0.39 | 0.40 | 0.53 | 0.44 | 0.53 | 0.53 | 0.21 |
| Ho | 0.07 | 0.07 | 0.07 | 0.12 | 0.07 | 0.08 | 0.12 | 0.14 | 0.09 | 0.12 | 0.12 | 0.05 |
| Er | 0.22 | 0.21 | 0.26 | 0.45 | 0.26 | 0.32 | 0.35 | 0.39 | 0.38 | 0.47 | 0.47 | 0.22 |
| Tm | 0.04 | 0.04 | 0.04 | 0.09 | 0.06 | 0.07 | 0.09 | 0.12 | 0.08 | 0.08 | 0.08 | 0.06 |
| Yb | 0.27 | 0.30 | 0.33 | 0.66 | 0.46 | 0.59 | 0.77 | 0.88 | 0.70 | 0.81 | 0.81 | 0.59 |
| Lu | 0.04 | 0.04 | 0.05 | 0.11 | 0.07 | 0.09 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.10 |
| Hf | 0.8 | 0.9 | 0.7 | 1.7 | 0.8 | 1.5 | 4.3 | 4.1 | 3.5 | 4.0 | 4.0 | 1.6 |
| Ta | 3.2 | 2.2 | 1.3 | 2.0 | 2.4 | 3.4 | 61.4 | 116.0 | 98.2 | 78.8 | 78.8 | 51.2 |
| Th | 2.8 | 2.7 | 2.1 | 2.9 | 1.5 | 1.6 | 3.4 | 3.9 | 4.8 | 5.4 | 5.4 | 0.8 |
| U | 2.1 | 8.0 | 1.5 | 3.2 | 1.4 | 2.0 | 18.4 | 16.6 | 10.8 | 5.8 | 5.8 | 2.3 |
| Nb/Ta | 5.4 | 6.6 | 6.8 | 6.9 | 6.5 | 6.2 | 1.6 | 0.8 | 1.1 | 1.3 | 1.3 | 1.6 |
| Zr/Hf | 18.5 | 19.3 | 21.8 | 19.2 | 17.4 | 15.1 | 6.2 | 5.6 | 5.9 | 5.3 | 5.3 | 14.2 |
| Y/Ho | 38.6 | 34.7 | 40.0 | 35.8 | 42.9 | 48.9 | 45.4 | 42.6 | 60.3 | 45.5 | 45.5 | 54.2 |
| Sr/Eu | 666.7 | 165.9 | 144.4 | 167.9 | 419.4 | 261.3 | 1,440.6 | 900.2 | 841.5 | 563.1 | 563.1 | 370.7 |
| ΣREE | 7.50 | 8.87 | 9.56 | 8.76 | 5.93 | 6.52 | 3.66 | 5.70 | 6.20 | 5.33 | 5.33 | 3.75 |
| δEu | 0.56 | 0.43 | 0.52 | 0.27 | 0.56 | 0.44 | 0.37 | 0.42 | 0.43 | 0.61 | 0.61 | 0.48 |
| δCe | 1.03 | 0.96 | 1.04 | 0.93 | 1.08 | 0.94 | 0.94 | 1.04 | 1.06 | 1.16 | 1.16 | 1.00 |
| TE3.4 | 0.38 | 0.28 | 0.32 | 0.33 | 0.31 | 0.31 | 0.30 | 0.38 | 0.31 | 0.18 | 0.18 | 0.28 |

ratios in the range of 0.06–0.30 (Table 1). Seventeen spots were selected from domains of homogenous composition and clear oscillatory zoning for U-Pb analysis. Of these, eleven yield an age population with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 231.4 ± 2.0 Ma (Figure 6D), representing the crystallization age of zircons. Four spots yield younger ages (213–226), deviating from the concordia due to a small amount of Pb loss or inclusions. The remaining spot yields an older age of 252 Ma, most likely representing the formation age of xenocrysts.

Pegmatite (AKG06): The zircon grains from the banded pegmatite collected for U-Pb dating are similar to those from sample AKG05 in color, transparency, crystal habit, and grain size. Some zircons show metasomatic relict textures in CL photos, and are characterized by microtaxitic mantle-core with nonuniform luminescences and relict rim with uniform luminescence, indicating evident metasomatic alteration after crystallization. The primary zircon domains are featured by weak and uniform luminescences, embayed texture, and regular or irregular shapes, and are enclosed by spongy domains (Figure 5E). All these features suggest that the zircons have suffered from metamictization, metasomatism, and recrystallization to different extents. The zircons have Th and U contents of 291–3,936 ppm and 4,034–7,608 ppm, respectively, with varying Th/U ratios from 0.05 to 0.61. Twenty-four analytical points were conducted on the primary zircon domains and twenty-two of them yielded consistent and concordant $^{206}\text{Pb}/^{238}\text{U}$ ages with a weighted mean age of 220.6 ± 1.6 Ma (MSWD = 0.80) (Figure 6E), which represents the crystallization time of the pegmatite. The other two points yielded inconcordant ages, indicating the incorporation of common lead after crystallization or influence of mineral inclusion in zircon.

Molybdenite Re-Os Ages

The Re-Os isotope results of the 7 molybdenite samples are shown in Table 2. The Re content of molybdenite is between 38 and 56 ppm with an average of 47 ppm. The Re-Os model ages of 7 molybdenite samples range from 224.6 ± 3.1 to 235 ± 3.4 Ma, with a weighted mean age of 229.0 ± 3.0 Ma (Table 3). ISOPLOT software was used to calculate the isochron age for the seven data points, and derived an isochron age of 228.7 ± 7.1 Ma (Figure 6D). The isochron age represents the time of molybdenite crystallization.

Geochemical Characteristic

The two-mica granite, muscovite granite, and beryl-bearing muscovite granite are rich in SiO_2 (71.92–75.41 wt%), Al_2O_3 (13.43–15.98 wt%), and total alkali $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (7.18–10.35 wt %), poor in CaO (0.07–0.76 wt%), TFe_2O_3 (0.11–1.14 wt%), and TiO_2 (0.01–0.25 wt%) (Table 2). In the TAS diagram, all the samples fall in the granite area (Figure 7A); on the K_2O - SiO_2 diagram, most of the samples fall in the range of high-k calc alkaline series (Figure 7B); the A/CNK index varies from 1.1 to 1.3 (Figure 7C), with strong peraluminous characteristics. Compared with the former two, beryl-bearing muscovite granite has higher $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio ($\text{Na}_2\text{O}/\text{K}_2\text{O} = 1.2$ –2.0). The REE content decreases gradually from two mica granite

($\sum\text{REE} = 27$ –114.0 ppm), medium fine-grained muscovite granite ($\sum\text{REE} = 4$ –10 ppm) to beryl-bearing muscovite granite ($\sum\text{REE} = 4$ –6 ppm); The rock samples all have negative Eu anomalies ($\delta\text{Eu} = 0.27$ –0.61). The Lanthanide tetrad effects in the REE patterns are observed in muscovite granite. The degrees of the tetrad effects ($\text{TE}_{3,4}$) in the muscovite and beryl-bearing muscovite granite are in the range of 1.08–1.19 and 1.24–1.34, respectively, (Table 2; Figures 8A,B).

In the normalized spider web diagram of trace element primitive mantle, all of the rock samples show enrichment of large ion lithophile elements, and have obvious negative anomalies of Ba, Sr, and Ti (Figures 8C,D).

DISCUSSION

The Formation age of Be Deposit in Altay

The zircon U-Pb age of pegmatoid orebody is 220.6 ± 1.6 Ma which coincides with the molybdenite Re-Os isochron age of 228.7 ± 7.1 . This age is slightly younger than that of muscovite granite (231.4 ± 2.0 Ma). The zircon U-Pb age of the Askartor Be-Mo deposit obtained in this paper is consistent with that of the previous study (Wang et al., 2015) (Table 4).

Recent studies have revealed that the geodynamic change in the Triassic period played a key role in the formation of rare-metal deposits in Altay, NW China. These deposits include (see Table 4): Koktokay No.3 pegmatite-type Li-Be-Ta-Nb-Cs deposit (220–209 Ma, Chen, 2011; Wang et al., 2007); Koktokay No.1 and Koktokay No.11 pegmatite-type Li-Be-Ta-Nb (208 and 212 Ma, respectively, Ren et al., 2011); Kelumute No.112 pegmatite-type Li-Be-Nb-Ta deposit (238–211 Ma, Lv et al., 2012), and Fuhai No.11 pegmatite-type Li-Be-Nb-Ta deposit (203 Ma, Lv et al., 2012). Some medium-scale Be-Nb-Ta deposits and small-scale pegmatite-type Be in Altay, such as Kalaerqisi, Qiebielin-xiaokalasu, and Jiamanhaba pegmatites were dated at 250–209 Ma (Ren et al., 2011; Ma et al., 2015).

Thus, the formation of Askartor Be-Mo deposit is not an accidental metallogenic event, but is representative of the Triassic rare metal metallogenic event in Altay.

The Genesis of Askartor Be-Mo Deposit

The two-mica granite, muscovite granite, beryl-bearing muscovite granite, and pegmatoid shell have a close spatial and temporal relationship, with similar zircon Hf isotopic composition (Wang et al., 2015). These features indicate that these rocks may be the products of the same magmatic system at different evolution stages.

As shown in Figure 9, although the beryl-bearing muscovite granite has higher Na_2O content and $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio, the evolutionary relationship among the major elements of the three types of granites is not obvious. The proportion of rock-forming minerals (such as quartz and feldspars) of the three types of granites is basically the same, which is close to the proportion of the minimum composition, $\text{Ab}_{37}\text{Ms}_{10}\text{Or}_{20}\text{Qtz}$ (Icenhower and London, 1995). Therefore, these rocks can be the products of

TABLE 3 | Re-Os data of molybdenite from the Askartor Be deposit.

| Sample | Re (ppm) | | ¹⁸⁷ Re (ppm) | | ¹⁸⁷ Os (ppb) | | Ages (Ma) | |
|----------|----------|-----|-------------------------|-----|-------------------------|-----|-----------|-----|
| | Measured | 1σ | Measured | 1σ | Measured | 1σ | Measured | 1σ |
| QHA12-02 | 49.7 | 2.3 | 31.1 | 1.4 | 117.1 | 2.3 | 226.5 | 4.5 |
| QHA12-03 | 43.3 | 2.0 | 27.1 | 1.3 | 103.8 | 2.2 | 230.4 | 4.8 |
| QHA12-04 | 45.7 | 0.7 | 28.6 | 0.4 | 109.3 | 1.9 | 229.6 | 3.9 |
| QHA12-05 | 38.3 | 0.7 | 24.0 | 0.4 | 93.90 | 1.4 | 235.7 | 3.4 |
| QHA12-07 | 56.4 | 0.7 | 35.3 | 0.4 | 136.2 | 3.2 | 231.8 | 5.5 |
| QHA12-08 | 46.8 | 0.8 | 29.3 | 0.5 | 109.4 | 1.5 | 224.6 | 3.1 |
| QHA12-10 | 50.9 | 1.5 | 31.7 | 1.0 | 120.1 | 2.2 | 227.8 | 4.2 |

model continuous fractional crystallization in the same magmatic systems.

One consequence of Goldschmidt's Rule is that isovalent trace elements of equal or very similar ionic radii should remain tightly coupled in geological processes. If, however, in certain geological systems other properties become important, this coherency is likely to break down. In octahedral coordination, Y³⁺, Ho³⁺, Zr⁴⁺, Hf⁴⁺, Nb⁵⁺, and Ta⁵⁺ show effective ionic radii of 1.04, 1.04, 0.86, 0.85, 0.78, and 0.78, respectively, (Shannon, 1976). Hence, the element pairs Y-Ho, Zr-Hf, and Nb-Ta are geochemical twin pairs. The fractionation of these trace element pairs occurred in muscovite granites, with the increase degree of the tetrad effect (Figure 10). The fractionation of isovalent trace element and the lanthanide tetrad are known to indicate magmatic-hydrothermal transition environments (e.g., Bau, 1996; Irber, 1999; Monecke et al., 2002; Monecke et al., 2007; Ballouard et al., 2016). The characteristics of trace elements indicate that muscovite granites have undergone self-metasomatism. This self-metasomatism refers to the reaction between the fluid, excluding from the granitic magma, and incompletely crystallized granite.

Based on the partition coefficients of Be and the results of this study, we preliminarily established the mineralization model of Askartor Be-Mo deposit (Figure 11). The model is mainly established on the basis of the Rayleigh fractional crystallization equation:

$$C^{RL} = C^L f^{D^S-1} \quad (1)$$

$$\overline{C^S} = C^L \times \frac{(1-f^{D^S})}{1-f} \quad (2)$$

C^L : concentration of Be in initial magma.

C^{RL} : instant concentration of Be in residual magma.

C^S : average concentration of Be in crystalline solid.

D^S : The total partition coefficient of Be

f : ratio of residual magma to initial magma.

The inclusion data show that the emplacement pressure and temperature of the initial magma of the Askartor Be-Mo deposit are 500 MPa and 750 ± 50°C (Ding, 2016). At these temperature and pressure conditions, the minimum and maximum water contents in the initial magma are 4 wt% and 10 wt%, respectively, (Holtz et al., 2001). When we assume that the water content of the initial is 4%, according to the balance calculation: 4 wt% = (1-f) × 0 wt% + f × 10 wt

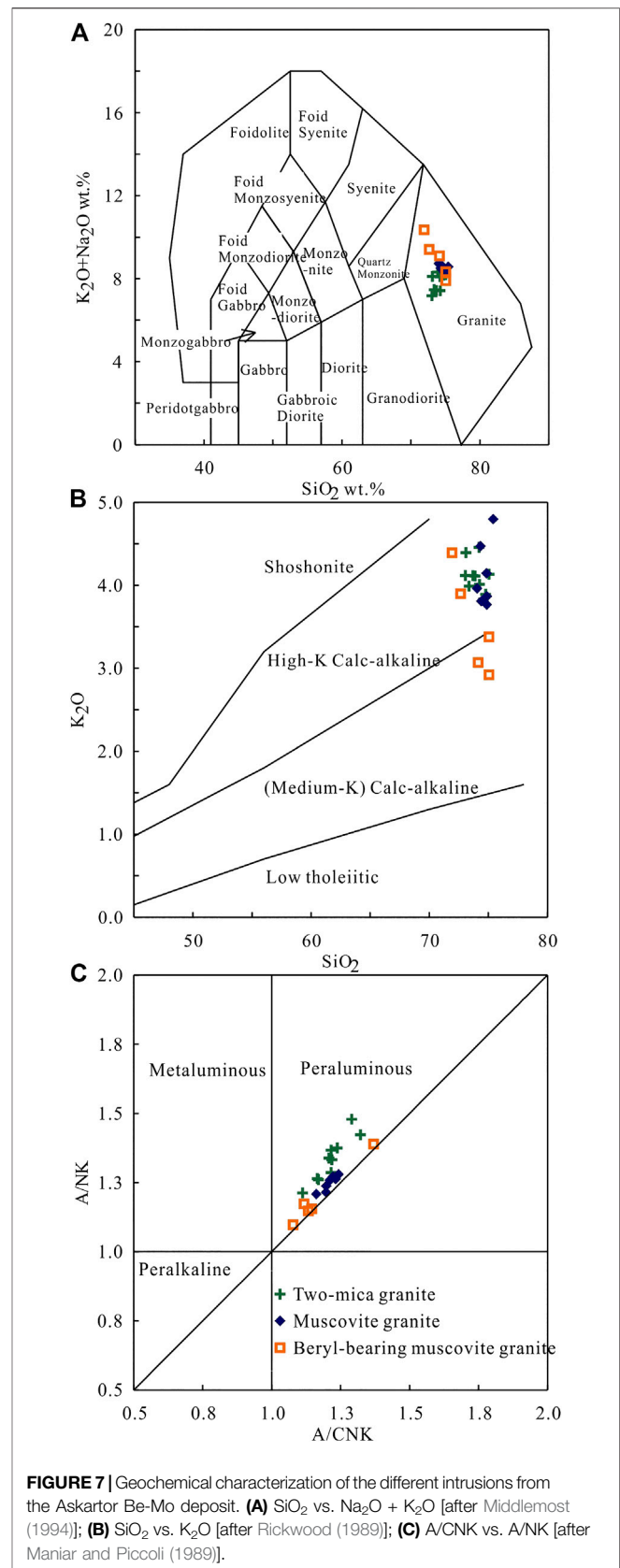


FIGURE 7 | Geochemical characterization of the different intrusions from the Askartor Be-Mo deposit. (A) SiO₂ vs. Na₂O + K₂O [after Middlemost (1994)]; (B) SiO₂ vs. K₂O [after Rickwood (1989)]; (C) A/NK vs. A/CNK [after Maniar and Piccoli (1989)].

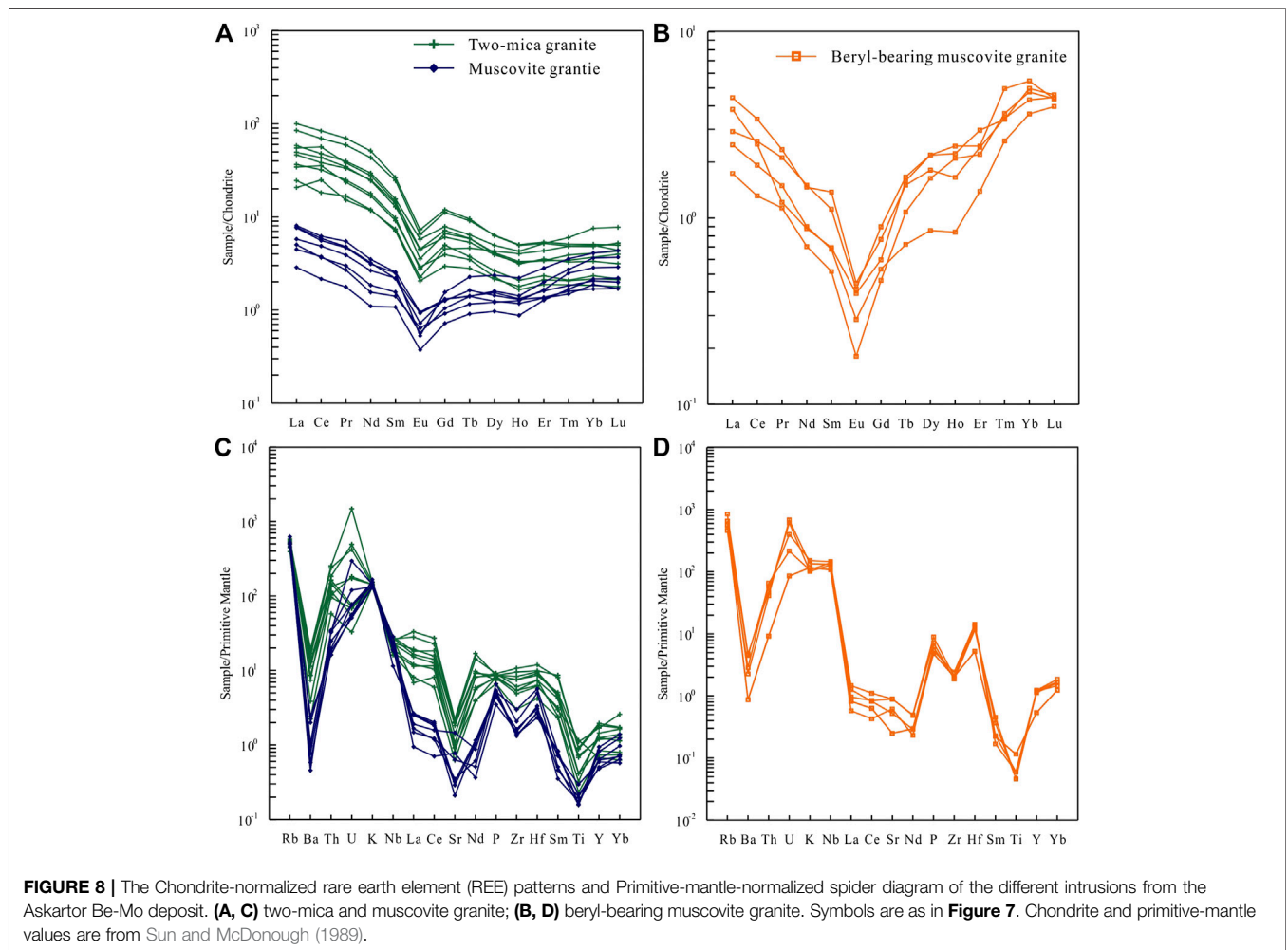
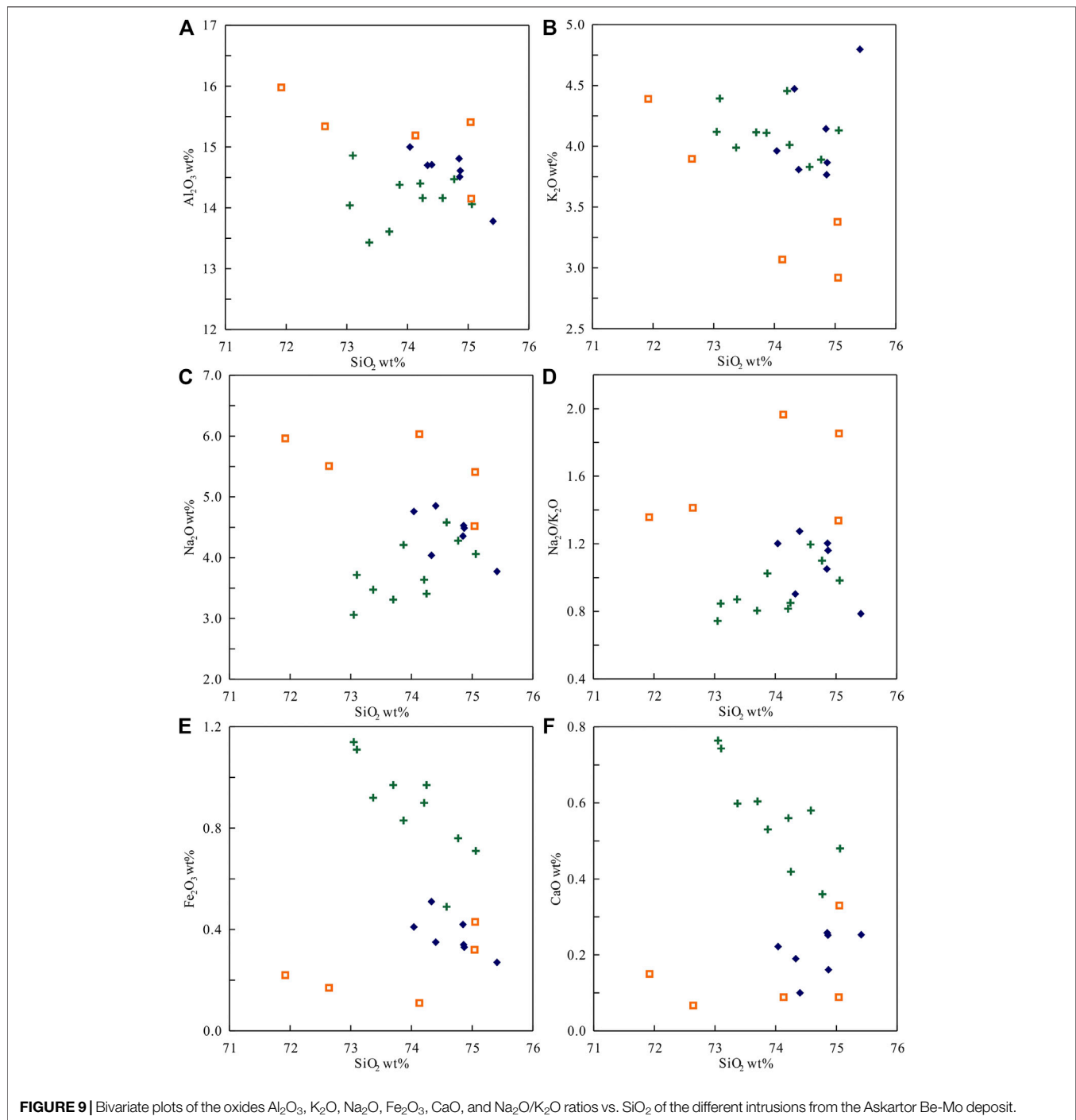


TABLE 4 | Age of rare metal deposit in the Chinese Altay orogenic belt.

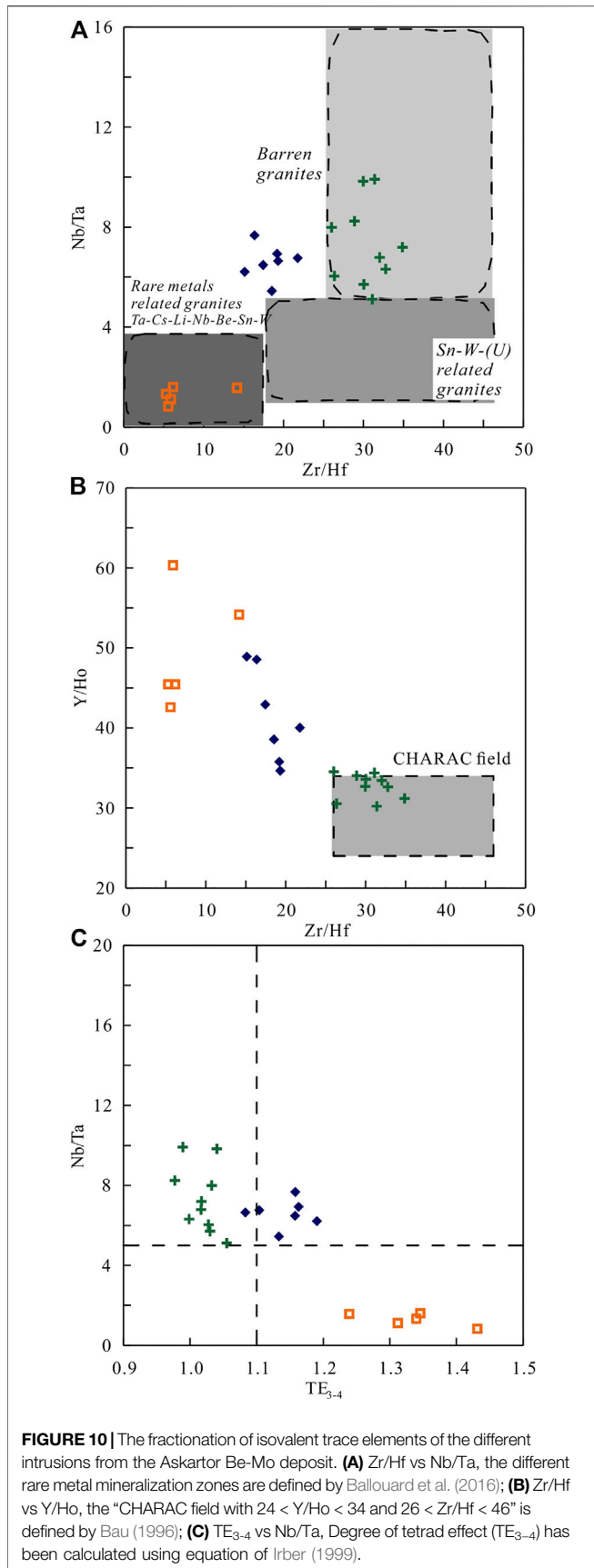
| Location | Deposit type | Deposit name | Mineralization type | Age (Ma) | Dating method | Reference |
|----------------------|---------------------|--------------|---------------------|-------------|---------------|--------------------|
| Koktokay | Pegmatite | KKT03 | Li-Be-Ta-Nb-Cs | 220–209 | U-Pb | Chen (2011) |
| | Pegmatite | KKT01 | Li-Be-Ta-Nb | 208.1 ± 0.8 | U-Pb | Wang et al. (2007) |
| | Pegmatite | KKT11 | Li-Be-Ta-Nb | 212.7 ± 2.5 | U-Pb | Ren et al. (2011) |
| Kelumute-jideke | Pegmatite | FH11 | Be-Ta-Nb | 202.9 ± 0.8 | U-Pb | Ren et al. (2011) |
| | Pegmatite | KLMT112 | Li-Be-Ta-Nb | 238–211 | U-Pb | Lv et al. (2012) |
| Kalaerqisi | Pegmatite | KKLG650 | Li-Be-Ta-Nb | 228–211 | U-Pb | Ren et al. (2011) |
| | Pegmatite | JMK02 | Li-Be-Ta-Nb | 212.2 ± 1.7 | U-Pb | Ma et al. (2015) |
| | Pegmatite | QK02 | Be-Ta-Nb | 206.8 ± 1.6 | U-Pb | Ren et al. (2011) |
| | Pegmatite | FH08 | Be-Ta-Nb | 244.3 ± 1.1 | U-Pb | Ren et al. (2011) |
| Qiebielin-xiaokalasu | Pegmatite | ALT01 | Be-Ta-Nb | 246.8 ± 1.2 | U-Pb | Ren et al. (2011) |
| | Pegmatite | BRJ10 | Be | 249.7 ± 0.7 | U-Pb | Ren et al. (2011) |
| | Pegmatite | BRJ07 | Be | 240.5 ± 1.4 | U-Pb | Ren et al. (2011) |
| Jiamanhaba | Pegmatite | HB07 | Be | 237.5 ± 2.6 | U-Pb | Ren et al. (2011) |
| Askartor | Granite ± pegmatite | Askartor | Be-Mo | 220.6 ± 1.6 | U-Pb | This study |
| | | | | 218.2 ± 3.9 | U-Pb | Wang et al. (2015) |
| | | | | 228.7 ± 7.1 | Re-Os | This study |
| | | | | 218.6 ± 1.3 | Re-Os | Wang et al. (2015) |



%, when the water content in magma will reach 10 wt%, the f equals to 0.4. Even if we consider hydrous minerals like mica, because the content of mica is low, it has little effect on the results. Trace element data show that the two-mica granite should be the product of pure magmatic crystallization, so at this stage, the fractional degree of initial magma will not exceed 0.6. The Be content in two-mica granite is ~ 13 ppm. If $f = 0.4$, from Eq. 2, we can calculate that the Be content in the initial magma is ~ 30 ppm, and then we can work out that the Be content in residual magma is ~ 60 ppm based on Eq. 1. Then we can

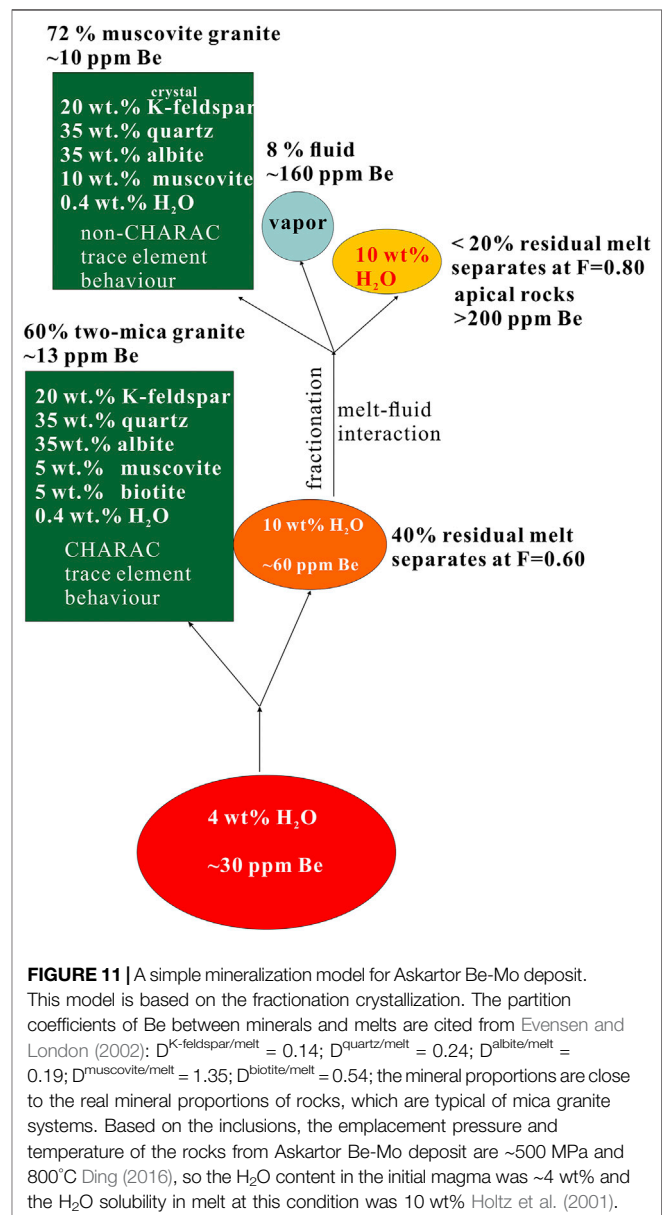
use the Be content in the beryl-bearing muscovite granite to calculate the fractional degree in the second stage. The mass of the fluid and the Be content in fluid are gained via the mass balance. Rayleigh fractional calculations show that:

- the content of Be in the initial magma forming the Askartor deposit is as high as 30 ppm, which is 10 times of the average Be content in the upper crust (Be = ~ 3 ppm in upper crust, Taylor and McLennan, 1995). This value is similar to the Be



content of the less-altered tuffs and pumices from the Macusani Province, Peru (28 ± 9 ppm, with a high of 37 ppm, Noble et al., 1984). These rhyolites are S-type in overall chemical character with high $^{87}Sr/^{86}Sr$, strongly peraluminous composition, and trace element patters that follow from an abundance of argillic or micaceous material at the source (Pichavant et al., 1988). Partial melting of a typical pelitic mica schist with 3 ppm Be, which is composed of muscovite, biotite, plagioclase, and quartz, will yield a content of 4~6 ppm Be in melt (Evensen and London, 2002), so, the pre-enrichment of Be in the source will restrict the mineralization of Be.

b. The initial magma is fluid saturated after the crystallization of 60%, and the residual magma contains ~60 ppm Be. After that, the system changed from pure magma (+crystal) stage to magma-hydrothermal transition stage.



- c. When this smaller volume of magma has reached ~80% solidification, then the residual magma could achieve beryl saturation (Be > 200 ppm), assuming that it could be efficiently extracted to produce beryl-bearing muscovite granite and its overlying pegmatoid shell.
- d. The Be content of the exsolution fluid is as high as 160 ppm. The partition coefficient of Be in coexisting fluid and melt is 0.8, which is consistent with that obtained from the inclusion data (e.g., 0.37 ± 0.43 , Zajacz et al., 2008).

- (3) Rayleigh fractional calculations show that the Askartor Be-Mo deposit is the product of multistage fractional crystallization of initial Be-enriched magma.

CONCLUSION

- (1) the zircon U-Pb ages of the granodiorite, biotite granite, two-mica granite, muscovite granite and pegmatoid are 386.8 ± 2.6 , 385.4 ± 4.4 , 247.5 ± 2.2 , 231.4 ± 2.0 , and 220.6 ± 1.6 Ma, respectively. The molybdenite Re-Os isochron age is 228.7 ± 7.1 , which coincides with the zircon U-Pb age of 220.6 ± 1.6 Ma of the pegmatoid orebody. The two-mica granite, muscovite granite, beryl-bearing muscovite granite and pegmatoid shell have close spatial and temporal relationships.
- (2) The highly fractionated element ratios of Y/Ho, Zr/Hf and Nb/Ta, plus the REE tetrad effect indicate the fluid exsolution occurs at the late stage of magma evolution and the muscovite granite experienced strong self-metasomatism.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

TY, ZH, and LZ-H designed the study and Participated in field work, TY and LZ-H analyze the sample and acquired the data, All authors contributed to the writing of the manuscript, and read and approved the final version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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