Early Cretaceous adakitic granites and mineralization of the Yili porphyry Mo deposit in the Great Xing’an Range: implications for the geodynamic evolution of northeastern China

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The Yili porphyry-type molybdenum deposit is located in the Northeastern Inner Mongolia Autonomous Region in China. Mineralization occurs mainly as veins, lenses, and layers within the host porphyry. In order to better understand the link between mineralization and host igneous rocks, we studied samples from underground workings. We report new Sensitive High Resolution Ion Microprobe II (SHRIMP II) zircon U–Pb and Re–Os molybdenite ages and geochemical data from the Yili granitoids. Five molybdenite samples yield a Re–Os isochron weighted mean age of 131.1 ± 3.4 Ma, while two Early Cretaceous adakitic porphyry granite samples yielded crystallization ages of 128.1 ± 1.6 Ma and 129.0 ± 3.5 Ma. The U–Pb and Re–Os ages are analytically indistinguishable, suggesting that mineralization was genetically related to Early Cretaceous magmatism in northeastern China. δ34S values of the sulphide vary from 0.3‰ to 3.8‰. We obtained two weighted mean U–Pb zircon ages of 287.7 ± 1.8 Ma for early Permian fine-grained granite and 349.8 ± 2.3 Ma for Early Carboniferous monzogranite in Yili area, respectively. A synthesis of geochronological and geological data reveals that porphyry emplacement and Mo mineralization in the Yili deposit occurred at the same time as Early Cretaceous lithospheric thinning, which was caused by the delamination and subsequent upwelling of the asthenosphere under the intra-continental extension in northeastern China.

Keywords: porphyry-type deposit; zircon U–Pb dating; molybdenite Re–Os ages; Early Cretaceous adakitic granites

1. Introduction

Economic molybdenum deposits in the world include porphyry, skarn, and hydrothermal vein types (Luo et al. 1991). Porphyry-type Mo deposits are the most important source of Mo in China (Chen et al. 2000; Mao et al. 2005, 2014). The Great Xing’an Range in the eastern section of the Central Asian Orogenic Belt between the Siberian Craton and North China Craton and its geology reflect superposition of the Palaeozoic Palaeoasian and Mesozoic Western Pacific marginal tectonic-metallocenic magmat-tectonic styles. The Great Xing’an Range (also referred to as the Da Hinggan Mountains in the literature) is an important polymetallic metallic province in northern China and is well known for its variety of ore systems (Chen et al. 2000; Mao et al. 2005; Liu et al. 2014). This area is also well known for its widespread distribution of Mesozoic igneous rocks, commonly known as the Great Xing’an Range Mesozoic Igneous Province (Sengör and Natal’ in 1996). Most deposits found in this area are closely associated with Mesozoic magmatic hydrothermal activity, together with porphyry, skarn, hydrothermal veins, and epithermal-type deposits (Zhao and Zhang 1997; Chen et al. 2007; Zeng et al. 2012). The degree of exploration is relatively high in the southern segment of the Great Xing’an Range, with Pb–Zn, Ag, Cu, Mo, Sn, and rare earth element (REE) deposits (Qin et al. 1999; Chu et al. 2002; Li et al. 2007; Niu et al. 2008; Zhou et al. 2010; Zhai et al. 2010; Wu et al. 2010; Liu et al. 2010). A few large and medium deposits have been discovered in the northern segment (Liu et al. 2010, 2014), but the size and number of deposits in the north are far less than those in the south. However, the discovery of the Chalukou giant Mo deposit (Liu et al. 2014) and Yili porphyry Mo deposit indicate that the northern area has a strong potential for porphyry molybdenum mineralization. However, few studies have been conducted to ascertain the sources of hydrothermal components and the geochronology of host granite intrusion and Mo mineralization. The lack of accurate geochronological data has increased the difficulty of establishing a genetic model for the Yili deposit and regional metallogensis in the northern segment of the Great Xing’an Range. The Yili porphyry Mo deposit was discovered in 2009, and the explored industrial Mo resource is about 21,500 t with an average grade of 0.085%; the resource of marginal Mo ore is about 13,000 t with an average grade of 0.05%.

Adakite, named for volcanic rocks on the Adak island in the Aleutian island arc (Defant and Drummond 1990), refers to intermediate and silicic igneous rocks that are
characterized by high SiO₂ (>56 wt.%), Al₂O₃ (>15 wt.%), Na₂O (>3.5 wt.%), Sr/Y and La/Yb (>40 and >20, respectively), low high-field-strength elements (HFSEs), low Y and heavy rare earth elements (HREEs) relative to normal andesite–dacite–rhyolite series (e.g. Y and Yb ≤ 18 and 1.9 ppm, respectively), high Sr relative to island arc andesite–dacite–rhyolite series (rarely <400 ppm), like in most island arc andesite–dacite–rhyolite series. These rocks usually contain abundant plagioclase and amphibole phenocrysts. Defant and Drummond (1990) suggested that these chemical features were consistent with an origin of partial melting of subducted oceanic crust under eclogite facies or garnet-bearing amphibolite conditions. Identification of adakite has enhanced our understanding of the fate of the subducted slab and the issue of crustal recycling and crust–mantle interactions at convergent plate margins. Due to its geodynamic significance, adakite and adakitic or adakite-like rocks have been widely studied to reveal their source characteristics, petrogenesis, and tectonic settings (Xu et al. 2002; Gao et al. 2004; Martin et al. 2005; Wang et al. 2005).

The current research of the Yili deposit is only limited to descriptions of the geological features. The mineralization of the Yili Mo deposit is proposed to be related to an intermediate-acid intrusive complex in the area. Based on observation and analysis of the relationship between the orebodies of the Yili deposit and the related porphyry and all types of wall-rocks, this study selected intrusive rocks of the Yili Mo deposit for Sensitive High Resolution Ion Microprobe II (SHRIMP II) zircon U–Pb dating and geochemistry, and dated the related ores with the molybdenite Re–Os method so as to eliminate the rock and ore-forming age and integrate the mineralization with its corresponding tectonic setting. We also present new S isotopic compositions of the main sulphides in the Yili Mo deposit.

2. Regional geology

The Great Xing’an Range is located in the eastern section of the Central Asian Orogenic Belt between the Siberian Craton and North China Craton (Jahn et al. 2000; Jahn 2004; Li 2006; Wu et al. 2012). The Great Xing’an Range area was mainly affected by NS-trending compression between the Siberia Craton and the North China Craton prior to the Early Jurassic. After the Middle/Late Jurassic, the main tectonic influence was the oblique subduction to the northwest of the Pacific Plate towards the east of the Eurasian continent (Liu et al. 2014). New Sr–Nd–Pb isotope mapping results obtained from this area suggest that during the Mesozoic era crustal growth mainly occurred around the collisional sutures and along the major lithosphere-scale faults (Guo et al. 2010). The regional stratigraphy of the Great Xing’an Range can be divided into four units as follows: (1) Precambrian metamorphic basement; (2) early Palaeozoic metamorphosed volcanic and sedimentary rocks; (3) late Palaeozoic lower metamorphic grades and more extensive exposures; and (4) Jurassic and Cretaceous intermediate-felsic volcanic and sedimentary rocks (Lin et al. 1998; Zhou et al. 2012). The strata outcropped in the northern area of the Great Xing’an Range are mainly metamorphic rocks in the Precambrian crystalline basement, clastic and carbonate rocks of the Palaeozoic cover sequence, Jurassic and Cretaceous volcaniclastic rocks, and a coal-bearing seam. Widespread magmatism occurred across the Great Xing’an Range region (Figure 1), including multi-phase plutonic and volcanic activity. The Great Xing’an Range area is known for large outcropping Mesozoic granite and volcanic rocks (Wang et al. 2006; Ge et al. 2007; Zhang et al. 2008) (Figure 1). Magmatic activity during the Yanshanian period shows a close temporal–spatial relationship with mineralization, and the Mesozoic era was the most important period for magmatic activity in northern China, with some of these granites being associated with Cu, Mo, Fe, Sn, Pb–Zn, and Ag mineralization (e.g. Wu et al. 2005; Mao et al. 2005; Zhang et al. 2010). On the basis of isotopic dating, the granites have been divided into two magmatic stages: early and late Yanshanian, which are separated at 135 Ma (Xiao et al. 2004). The early Yanshanian stage can be divided into two sub-stages, early and late, which are separated at 160 Ma (Xiao et al. 2004; Mao et al. 2005; Liu et al. 2014). A small amount of Variscan magmatic activity occurred mainly to the northwest of the Great Xing’an Range. The intrusive rocks in the northern area of the Great Xing’an Range were mainly formed in the late Palaeozoic and Mesozoic with a small amount in the early Palaeozoic (Figure 1), and massive intermediate-acid intrusive rocks were mainly developed in the Mesozoic (Wu et al. 2005; Liu et al. 2014). Most of the typical porphyry Cu–Mo or Mo–Cu deposits in the Great Xing’an Range area have been studied (Qin et al. 1999).

3. Ore deposit geology

The Yili porphyry Mo deposit is located in Dayangshu city, 30 km southwest of Elunchunqi in the Great Xing’an Range area at geographic coordinates 124°12’00″ E to 124°17’30″ E and 49°23’00″ N to 49°25’00″ N (Figure 2). Although the degree of exploration in the Western River area is low, it still shows good potential for Mo mineralization. The rocks outcropped in the mining area are mainly sedimentary rocks of the Silurian Wuduhe Formation and Cretaceous volcano-sedimentary rocks. The sedimentary rocks of the Wuduhe Formation are mainly composed of metamorphic sandstone, slate, feldspathic lithic sandstone, and metavolcanic rocks. The Cretaceous volcano-sedimentary rocks are mainly basalt, rhyolite, rhyolitic tuff lava, dacite, trachyte, and andesite, which are important ore-bearing wall-rocks. The
Cretaceous volcanic rocks cut the porphyry rocks and Mo orebodies. The intermediate-acidic intrusive rocks are relatively well developed, and the main rock types are monzogranite, granite porphyry, and fine-grained granite rocks. The tectonics mainly exhibit as two NNE-, NE-, and SN-trending faults. The centre of volcanic-magmatic activity was localized at the intersection of these faults. Breccia is relatively well developed and is mainly distributed as tubular or lenticular bodies, or as pipes. The diameter of the breccia clastics is mostly less than 10 cm, with individual clasts reaching tens of centimetres. Most breccias are angular–subangular-shaped, and few are sub-rounded. The compositions of the breccias are mainly granite porphyry and monzogranite. The cements are mainly composed of rock fragments, hydrothermal siliceous cement and metallic sulphides, which contain molybdenite, pyrite, chalcopyrite, and bornite. The Yili deposit mainly developed porphyry Mo mineralization style. The overall Mo orebody is stratoid, as produced in granite porphyry, quartz veins, fine-grained granite, and Cretaceous volcano-sedimentary rocks. The Mo orebodies, mainly hidden with small parts, are exposed at the surface. The currently dominant Mo orebody extends over 800 m with a width of 700 m and a vertical thickness generally of 280–720 m. The geometry of the Mo orebodies is divided into two types: thin-layered orebody and thicker-layered orebody. The ore-bearing wall-rocks are mainly Permian granitoids and Jurassic granitoids.
with a small amount of Silurian sediments and an average Mo grade of 0.07–0.12%. The thin-layered orebodies appear as thin layers with small-scale continuity and an average thickness of 27 m. The ore-bearing wall-rocks are mainly Permian granitoids and Jurassic granitoids with a small amount of Silurian sediments and an average Mo grade of 0.08–0.09%. The thicker-layered orebodies appear as thick layers of large scale and good continuity with an average thickness of 120 m. The ore-bearing wall-rocks are Permian granitoids and Jurassic granitoids with a small amount of Silurian sediments with an average Mo grade of 0.07–0.12%. The metallic minerals are mainly molybdenite, covellite, pyrite, sphalerite, and galena, accompanied by minor chalcopyrite, pyrrhotite, magnetite, and haematite. The gangue minerals are mainly quartz, K-feldspar, and plagioclase and minor fluorite, sericite, calcite, kaolinite, biotite, chlorite, and epidote. The molybdenite occurs as two main types: (1) as filling in cracks of granite porphyry, monzogranite, Cretaceous volcano-sedimentary rocks, and Silurian sediments as scales or films; (2) distributed within quartz veins as disseminations or films in association with metallic sulphides, such as pyrite, chalcopyrite, and galena.
Figure 3. Simplified cross sections along exploration line 17 (A) and line 06 (B) in the Yili deposit. YL1 and YL3, the Early Cretaceous Yili granite porphyry; YL2, the Early Permian Yili fine-grained granite; YL4, the Early Carboniferous Yili monzogranite; YL01–YL05: the Yili molybdenite samples. The red and black stars show the location of granitoids and molybdenites, respectively.
The alteration of wall-rocks is strong and zoning from the centre of the porphyry body outward with potassic, sericitic, argillic, and propylitization zones. There are no clear boundaries between mineralization zones, they frequently show a grading relationship. Potassic, sericitization, kaolinization, montmorillonitization, chloritization, and epidotization are absent, but there are silification, fluoritization, and carbonatization. The potassic, silification, and fluoritizations are closely related to the Mo mineralization. According to the mineral assemblages and ore fabrics, as well as the cross-cutting relationships of veins, the mineralization process can be preliminarily divided into five stages. The first stage is a pyrite + quartz stage, and the minerals were produced as pyrite + quartz veins and magnetite + pyrite + quartz veins. The second stage is a quartz + molybdenite stage including molybdenite + quartz veins, pyrite + molybdenite + quartz veins, magnetite + pyrite + molybdenite + quartz veins, pyrite + chalcopyrite + molybdenite + quartz veins. The molybdenite is distributed as disseminations or films in quartz veins. The third stage is a molybdenite + K-feldspar + quartz stage with molybdenite + K-feldspar + quartz veins, pyrite + molybdenite + K-feldspar + quartz veins, and pyrite + chalcopyrite + molybdenite + K-feldspar + quartz veins. The fourth stage is a fluorite + K-feldspar + quartz stage with pyrite + fluorite + quartz veins and pyrite + fluorite + K-feldspar + quartz veins. The last stage is a carbonate stage with calcite and chlorite veins.

4. Sample characteristics and methods

4.1. Sample description

Ore minerals are molybdenite and bornite, with minor pyrite, chalcopyrite, magnetite, galena, sphalerite, scheelite, and native silver. The ores are euhedral to subhedral, and with massive structure. The five molybdenite samples used for Re–Os dating were collected from quartz-K-feldspar-molybdenite veins (Figure 4) and Mo mineralized granite porphyry (Table 1). Four samples of fine-grained plutonic rock were analysed using SHRIMP II. In this region, the Permian intrusive rocks (fine-grained granite) are well developed, mainly in the central area, with nearly NNE-trending zonal distribution; the intrusive rocks have an E–W elongated shape about 95 km long and more than 15 km across at its broadest point and cover an area of approximately 150 km². The Jurassic intrusive rocks are only distributed in the western part of the Yili Mo deposit between Naiman river and Zhangdaqi river, showing E–W distribution with two stocks output, with a total area of 27 km². The Early Carboniferous monzogranite and the Early Cretaceous granites porphyry are just scattered.

The Early Cretaceous granite porphyry (YL1 and YL3). (The rocks have a porphyritic texture with approximately 10% phenocrysts that are mainly composed of plagioclase (2%), K-feldspar (5%), and quartz (3%). The plagioclase appears as hypidiomorphic boards, polysynthetic twins with sizes of 0.3–2 mm that partly show sericitization. The K-feldspar appears as hypidiomorphic boards or xenomorphic granular, perthitic texture with sizes of 0.4–3.5 mm and is partly replaced by kaolinite. The quartz appears as xenomorphic with sizes of 0.3–2 mm. The groundmass has a micro-granular texture and consists of K-feldspar, plagioclase, and quartz with sizes of <0.2 mm. The accessory minerals are zircon and titanite.

The early Permian fine-grained granite (YL2): The rock has a porphyry-like texture and is mainly composed of quartz (45%), K-feldspar (35%), and plagioclase (20%). The quartz appears as hypidiomorphic-xenomorphic granular wave extinction with size of 0.4–1.6 mm. The K-feldspar appears as hypidiomorphic-idiomorphic boards, clathrate twins, and perthitic texture with sizes of 0.3–1.8 mm. A few of K-feldspars are replaced by kaolinite. The plagioclase appears as hypidiomorphic boards and polysynthetic twins with sizes of 0.4–1 mm. Biotite appears as brown hypidiomorphic flakes with sizes of 0.2–0.5 mm. The accessory minerals are zircon and titanite.

The early Carboniferous monzogranite (YL4): The rock has a granitic texture and medium-grained texture, and is mainly composed of plagioclase (40%), K-feldspar (30%), quartz (25%), and biotite (5%). The plagioclase appears as hypidiomorphic-idiomorphic boards, polysynthetic twins, and simple double-crystal growth with sizes of 0.6–4.7 mm and partly shows sericitization and epidotization. The K-feldspar appears as hypidiomorphic boards or xenomorphic granular, clathrate twins, and perthitic texture with sizes of 0.8–3.2 mm and is replaced by kaolinite. The quartz appears as hypidiomorphic–xenomorphic granular, wavy extinction, and myrmekitic texture with sizes of 0.6–3.2 mm. Biotite appears as brown flakes with sizes of 0.5–2 mm and is partly replaced by chlorite with iron separated. The accessory minerals are zircon and titanite.

4.2. SHRIMP II U–Pb analytical method

Zircon grains obtained from three samples of fine-grained plutonic rock were analysed using SHRIMP II. The granitoid samples were sent to the Institute of Hebei Regional Geology and Mineral Survey in Langfang, Hebei Province, China, for mineral separation. Sample preparation included standard crushing, heavy liquid, and paramagnetic techniques for picking out zircon grains. Representative zircon from the sample was selected using a binocular microscope. The zircon grains were mounted in epoxy with standard zircon (TEMORA), sectioned in half, and polished. Reflected and transmitted light photomicrographs and cathode luminescence (CL) scanning electron micrographs were prepared to determine
Figure 4. Photographs of selected features of ore vein mineralization from the Yili deposit. (A, B, C, and D) Disseminated and massive orebody occurring in the contact zone between granite porphyry and quartz veins. (E and F) Vein- and lens-type orebody in granitoid porphyry. Mo, molybdenite. Py, pyrite; Cv, covelline; Ccp, chalcopyrite. (G and H) Molybdenite and quartz veins in the K-feldspar granitic porphyry. (I and J) Photomicrographs of selected related mineralization granites porphyry. Q, Quartz; Kf, K-feldspar; Pl, plagioclase; Bi, biotite.
the internal structures of the grains and to target areas within the zoned zircon grains. U–Pb isotopes were analysed on the SHRIMP II at the Ion Probe Center of the Institute of Geology, CAGS, Beijing, following the procedures described in Song et al. (2002). All data were processed using the SQUID and ISOPLOT/Ex macro of Ludwig (2004). Measured $^{206}$Pb was corrected by common Pb. The analytical precision for the U/Pb ratio was 1σ and the weighted mean age was 2σ. The zircon grains collected from the Jiazishan fine-grained plutonic rocks are irregular or tabular in shape and range from 50 to 120 μm in size. The CL images show that these zircon grains have been weak and broken, and display clear zoning or core–mantle–rim structures. Reflected and transmitted light show that a few zircon grains developed cracks or voids, which might be influenced by thermal evolution during late metamorphism.

4.3. Re–Os analytical method

Five molybdenite samples were collected from drilling cores for Re–Os dating. Gravitational and magnetic separation was carried out and then handpicked under a binocular microscope (purity > 99%). The molybdenite in the samples was fine-grained (<0.1 mm), to avoid the decoupling of Re and Os within large molybdenite grains (Stein et al. 2003; Selby and Creaser 2004). Re–Os isotope analysis was performed in the Re–Os Laboratory, Institute Of Geology and Mineral Resources in Tianjin, China. An ICP-MS (TJA X-series; Thermo Electron Corporation, Waltham, MA, USA) was used. The analytical procedures followed are those of Shirey and Walker (1995). The model ages were calculated following the equation: $t = \ln \left( 1 + \frac{\lambda}{\text{Re}} \right) / \lambda$, where $\lambda$ is the decay constant of $^{187}$Re, 1.666 × 10$^{-11}$ year$^{-1}$ (Smoliar et al. 1996). The data are presented in Table 3.

4.4. Major and trace elemental analyses

Major and trace elemental analyses were carried out in the Institute of Geology and Mineral Resources in Tianjin, China. Major oxide concentrations were determined by wavelength-dispersive X-ray fluorescence spectrometry (XRF) on fused glass beads using a Philips PW 2400 spectrometer with matrix correction following the procedure described by Norrish and Hutton (1969). Chinese national rock standard GSR-1 (granite) was used as reference material. The accuracies of the XRF analyses are estimated to be approximately 1% (relative) for SiO$_2$ and approximately 2% (relative) for the other oxides. Trace-element compositions were analysed by inductively coupled plasma mass spectrometry (ICP-MS) of nebulized solutions using a VG Plasma-Quad Excell ICP-MS at the Institute Of Geology and Mineral Resources in Tianjin, China. The detailed analytical procedures are described by Liang et al. (2000). About 50 ± 1 mg of powdered sample was digested in Teflon bombs using mixed HF and HNO$_3$. An internal standard solution of 103Rh was used to monitor drift (Liang et al. 2000). Two multi-element standard solutions, one containing Li, Ba, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Cs, Ba, Pb, Th, U, Sc, Y, and 14 REEs and the other containing W, Mo, Nb, Ta, Zr, and Hf, were employed for external calibration. The reference standards were the same as those used for the XRF analyses. The accuracies for most of the trace elements are estimated to be better than approximately 5% (relative). Geochemical data are presented in Table 2 for major oxides and trace elements.

4.5. Sulphur isotopic compositions analyses

For S isotope determinations, powdered samples were mixed with the single mineral of sulphide and Cu$_2$O in oxidizing conditions. Isotopic ratios were obtained on the Finnigan MAT-262 TIMS at Beijing Institute of Nuclear Geological Research with VCDT standard, and the analytical precision was better than ±0.01‰.

5. Analytical results

5.1. SHRIMP II U–Pb ages

A total of 100 zircons were analysed and the SHRIMP II analytical data are presented in the online Supplemental Material at http://dx.doi.org/10.1080/00206814.2014.934746. Most zircon grains of the granitoid samples were transparent and colourless under the optical microscope. Concentric zoning was common, and no inherited cores were observed. These zircons have highly variable Th and U, but their Th/U ratios indicated a magmatic origin (Th/ U > 0.4). Four samples were analysed, and all analyses were concordant or nearly concordant and cluster as a single population with a weighted mean $^{206}$Pb/$^{238}$U age of

| Sample No. | Rock type       | Drill core no. | Location of samples (m) |
|------------|-----------------|----------------|-------------------------|
| YL1        | Granite porphyry| ZK1718         | 159                     |
| YL2        | Fine grained granite | ZK1306     | 28                      |
| YL3        | Granite porphyry| ZK1718         | 347                     |
| YL4        | Monzogranite    | ZK1306         | 363                     |

Table 1. Location of the granitoids to date and geochemistry test from the Yili deposit.
Table 2. Whole-rock major, trace, and rare earth element concentrations of the Yili granitoids.

|          | YL1   | YL2   | YL3   | YL4   |
|----------|-------|-------|-------|-------|
| XRF – major element (wt.%) |       |       |       |       |
| SiO₂     | 72.77 | 74.14 | 68.49 | 69.56 |
| TiO₂     | 0.27  | 0.27  | 0.57  | 0.61  |
| Al₂O₃    | 15.07 | 12.98 | 16.73 | 15.55 |
| TFe₂O₃   | 1.61  | 2.45  | 2.68  | 2.93  |
| MnO      | 0.03  | 0.04  | 0.04  | 0.10  |
| MgO      | 0.58  | 0.03  | 0.92  | 0.88  |
| CaO      | 1.43  | 0.00  | 2.37  | 1.29  |
| Na₂O     | 3.98  | 2.49  | 4.47  | 4.03  |
| K₂O      | 3.22  | 5.77  | 2.76  | 3.85  |
| P₂O₅     | 0.09  | 0.02  | 0.22  | 0.16  |
| LOI      | 0.78  | 1.57  | 0.63  | 0.92  |
| Total    | 99.74 | 99.70 | 99.72 | 99.76 |
| Mg#      | 41.98 | 2.15  | 40.81 | 37.49 |
| K₂O/Na₂O | 0.81  | 2.31  | 0.62  | 0.96  |
| A/CNK    | 1.19  | 1.25  | 1.14  | 1.18  |
| A/NK     | 1.50  | 1.25  | 1.62  | 1.44  |
| DI       | 86.72 | 94.10 | 80.18 | 85.02 |
| Normative CIPW (%) |       |       |       |       |
| Quartz   | 33.52 | 37.78 | 25.62 | 27.47 |
| Anorthite| 6.89  | 0.00  | 10.95 | 5.72  |
| Albite   | 34.00 | 21.54 | 38.13 | 23.04 |
| Orthoclase| 19.20 | 34.78 | 16.43 | 1.14  |
| Corundum | 2.57  | 2.69  | 2.43  | 1.17  |
| Diopside | 0.00  | 0.00  | 0.00  | 1.80  |
| Hypersthene| 2.12 | 1.05  | 3.27  | 2.11  |
| Ilmenite | 0.52  | 0.52  | 1.10  | 1.17  |
| Magnetite| 0.95  | 1.58  | 1.53  | 0.90  |
| Apatite  | 0.21  | 0.04  | 0.52  | 0.37  |
| Zircon   | 0.02  | 0.07  | 0.04  | 0.06  |
| Total    | 100.00| 100.05| 100.02| 100.05|
| ICP-MS – trace element (ppm) |       |       |       |       |
| Rb       | 84.40 | 125.00| 44.00 | 92.90 |
| Sr       | 510.20| 24.80 | 964.80| 302.40|
| Y        | 13.28 | 25.74 | 6.80  | 33.51 |
| Zr       | 118.51| 338.27| 188.12| 285.72|
| Nb       | 9.18  | 9.06  | 4.81  | 20.30 |
| Ba       | 623.10| 135.00| 1143.10| 880.50|
| La       | 16.60 | 27.80 | 22.10 | 36.40 |
| Ce       | 36.00 | 65.30 | 51.00 | 86.80 |
| Pr       | 4.38  | 7.99  | 6.24  | 10.60 |
| Nd       | 17.02 | 32.50 | 25.05 | 43.59 |
| Sm       | 3.26  | 6.22  | 4.05  | 5.83  |
| Eu       | 0.63  | 0.50  | 1.18  | 1.98  |
| Gd       | 2.66  | 5.26  | 2.77  | 7.41  |
| Tb       | 0.42  | 0.86  | 0.32  | 1.17  |
| Dy       | 2.37  | 4.86  | 1.49  | 6.28  |
| Ho       | 0.42  | 0.94  | 0.23  | 1.18  |
| Er       | 1.18  | 2.62  | 0.57  | 3.29  |
| Tm       | 0.20  | 0.46  | 0.08  | 0.54  |
| Yb       | 1.26  | 3.23  | 0.45  | 3.54  |
| Lu       | 0.17  | 0.50  | 0.06  | 0.50  |
| Hf       | 4.04  | 11.42 | 8.97  | 15.06 |
| Ta       | 0.74  | 0.51  | 0.28  | 1.20  |
| Pb       | 20.80 | 18.06 | 15.96 | 15.63 |
| Th       | 5.03  | 5.70  | 2.19  | 8.22  |
| U        | 1.01  | 1.01  | 0.31  | 2.00  |
| Eu/Eu*   | 0.65  | 0.27  | 1.08  | 0.76  |
| Sr/Y     | 38.42 | 0.96  | 141.88| 8.93  |
| (La/Yb)₅₀ | 19.44 | 6.17  | 35.31 | 7.39  |

Note: LOI, loss on ignition; m, measured values; A/CNK, molecular Al₂O₃/(CaO + Na₂O + K₂O); A/NK, molecular Al₂O₃/(Na₂O + K₂O) total iron as TFe₂O₃; Mg# = 100 mol Mg²⁺/(Mg²⁺ + total Fe²⁺); Eu/Eu* = EuN/([SmN GdN]¹/₂); N is chondrite-normalized (Sun and McDonough 1989).
128.1 ± 1.6 Ma (MSWD = 2.2, granitoid sample YL1), 287.7 ± 1.8 Ma (MSWD = 1.6, granitoid sample YL2), 129.0 ± 3.5 Ma (MSWD = 8.8, granitoid sample YL3), and 349.8 ± 2.3 Ma (MSWD = 1.7, granitoid sample YL4), which represents the crystallization age of the pluton and was used for the calculation of initial isotopic ratios of the other isotopic systems (Figure 5).

5.2. Molybdenite Re–Os ages

Results of molybdenite Re–Os dating are listed in Table 3. The concentrations of Re and $^{187}$Os range from 20.80 to 34.89 ppm and 28.27 to 47.74 ppb, respectively. Five samples give a Re–Os model age of 129.5–130.5 Ma. The Yili Molybdenite Re–Os data, processed using the ISOPLOT/Ex program (Ludwig 2004), yielded an

Table 3. Results of Re–Os isotopic analyses of molybdenite from the Yili Mo deposit.

| Sample No. | Drill No. | Location of sample | Weight (g) | Re ug/g | Re$^{187}$ ug/g | Os$^{187}$ ng/g | Model age (Ma) |
|------------|-----------|--------------------|------------|---------|----------------|----------------|----------------|
| YL01       | ZK1702    | ZK1702 drill core 127m | 0.03041    | 34.89   | 0.26           | 21.93          | 0.16           | 47.74          | 0.38           | 130.5          | 1.8             |
| YL02       | ZK906     | ZK906 drill core 372m | 0.04046    | 20.80   | 0.20           | 13.08          | 0.13           | 28.27          | 0.24           | 129.6          | 2.0             |
| YL03       | ZK1306    | ZK1306 drill core 407m | 0.04038    | 30.89   | 0.25           | 19.41          | 0.16           | 42.13          | 0.36           | 130.1          | 1.9             |
| YL04       | ZK1702    | ZK1702 drill core 29m | 0.04036    | 21.17   | 0.16           | 13.31          | 0.10           | 28.91          | 0.25           | 130.3          | 1.8             |
| YL05       | ZK2106    | ZK2106 drill core 427m | 0.04036    | 23.76   | 0.22           | 14.94          | 0.14           | 32.27          | 0.33           | 129.5          | 2.1             |

Note: Uncertainty for the calculated ages is 1.02% at 95% confidence level.
isochron age of 131.1 ± 3.4 Ma (MSWD = 0.25) and an initial $^{187}$Os of $-0.27 \pm 0.89$ ppb (Figure 6). The nearly identical model age and isochron age suggest that the analytical results are reliable. The isochron age represents the time of molybdenite crystallization; the mineralization age of the Yili Mo deposit is 131.1 ± 3.4 Ma.

5.3. Major and trace-element geochemistry and Sulphur isotopic compositions

A total of four granitic samples (Figure 7) were analysed for major and trace element compositions. The loss on ignition (LOI) for most samples is about 1 wt.%.

The Early Cretaceous granite porphyry (YL1 and YL3) are characterized by 68.49–72.77 wt.% SiO$_2$, 15.07–16.73 wt.% Al$_2$O$_3$, 0.58–0.92 wt.% MgO, 1.43–2.37 wt.% CaO, 3.98–4.47 wt.% Na$_2$O, 2.76–3.22 wt.% K$_2$O, (Na$_2$O + K$_2$O): 7.19–7.23 wt. %, 0.62–0.81 K$_2$O/Na$_2$O and 0.27–0.57 wt.% TiO$_2$ (Table 2). The A/CNK values were 1.14–1.19, with differential index (DI = 80.18 ~ 86.72) and presence of normative corundum (2.43% ~ 2.57%), and these rocks are peraluminous (molar A/CNK = 1.10–1.40 and A/NK = 1.24–1.85; Figure 7B). According to the K$_2$O versus SiO$_2$ diagram (Le Maitre 1984; Rickwood 1989) (Figure 7A), all samples fall in the field of the high K calc-alkaline series, which reflects a relatively oxydic magmatic evolution environment. All the studied Early Cretaceous rocks are characterized by low Y (6.8–13.28 ppm), Yb (0.45–1.26 ppm) and HFSEs, and high Sr (510–965 ppm), Ba (623–1143 ppm), and La (16.6–22.1 ppm) contents (Tables 2). Their primitive mantle normalized trace element concentrations display relative enrichment of large ion lithophile elements (LILEs) and depletion of HFSEs, with negative Nb, Ta, Zr, Hf, Ti, and positive Pb, and Sr anomalies, consistent with a subduction-related setting (Figure 7C). The chondrite-normalized REE patterns of the YL3 rocks show a steep decrease from light rare earth elements (LREEs) to HREEs, with $(\text{La}/\text{Yb})_N$ ratios of 35.31 (where N denotes normalized to chondrite values of Sun and McDonough (1989)) (Figure 7D and Table 2), and the rock does not exhibit conspicuous Eu anomalies ($\delta$Eu =1.08). The chondrite-normalized REE patterns of the YL1 rocks show relative enrichment of LREEs, with the $(\text{La}/\text{Yb})_N$ ratios of 19.44 (where N denotes normalized to chondrite values of Sun and McDonough (1989)), and significant negative Eu anomalies are evident ($\delta$Eu = 0.65).

The Early Permian fine-grained granite (YL2) is characterized by 74.14 wt.% SiO$_2$, 12.98 wt.% Al$_2$O$_3$, 0.03 wt.% MgO, 2.49 wt.% Na$_2$O, 5.77 wt.% K$_2$O, (Na$_2$O + K$_2$O): 8.26 wt.%, 2.31 K$_2$O/Na$_2$O and 0.27 wt.% TiO$_2$ (Table 2). The A/CNK value was 1.25, with differential index (DI = 94.1) and presence of normative corundum (2.69%), and these rocks are peraluminous (molar A/CNK = 1.25 and A/NK = 1.25; Figure 7B). According to the K$_2$O versus SiO$_2$ diagram (Le Maitre 1984; Rickwood 1989) (Figure 7A), the sample is falling in the field of the calc-alkaline series. The studied early Permian fine-grained granite is characterized by low Ba

Figure 6. Re–Os isochron age of molybdenites from the Yili Mo deposit. The ISOPLOT software of Ludwig (2004) was used to calculate the isochron age, decay constant: $\lambda(\text{Re}) = 1.666 \times 10^{-11}$/year (Smoliar et al. 1996), uncertainties are absolute at 2$\sigma$ with error of 1.01% at 95% confidence level.
Their primitive-mantle-normalized trace element concentrations display relative enrichment of LILEs (such as Rb, Th, U, K) and Pb, depletion of HFSEs (such as Nb, Ta, P, and Ti). The chondrite-normalized REE patterns of the YL2 rocks show relative enrichment of LREEs, with \((\text{La}/\text{Yb})_\text{N}\) ratio of 6.17 (where N denotes normalized to chondrite values of Sun and McDonough 1989) (Figure 7D and Table 2), significant negative Eu anomalies are evident (δEu = 0.27).

The early Carboniferous monzogranite (YL4) is characterized by 69.56 wt.% SiO₂, 15.55 wt.% Al₂O₃, 0.88 wt. % MgO, 4.03 wt.% Na₂O, 3.85 wt.% K₂O, (Na₂O+K₂O): 7.88 wt.% 0.96 K₂O/Na₂O and 0.61 wt.% TiO₂ (Table 4). The A/CNK value was 1.18, with differential index (DI = 85.02) and presence of normative corundum (2.71%), and these rocks are peraluminous (molar A/CNK = 1.18 and A/NK = 1.44; Figure 7B). According to the K₂O versus SiO₂ diagram (Le Maitre 1984; Rickwood 1989) (Figure 7A), the sample is falling in the field of high K calc-alkaline series. The chondrite-normalized REE patterns of the studied early Permian fine-grained granite are relatively uniform. Their primitive-mantle-normalized trace element concentrations display relative enrichment of LILEs (such as Rb, Th, U, K) and Pb, depletion of HFSEs (such as Nb, Ta, P, and Ti).
Table 4. Result of S isotopic compositions of ore sulphides samples.

| Sample Number   | Depth of sample (m) | Mineral         | $\delta^{34}$S $\%_{\text{VCDT}}$ | Sample description                          | Data source |
|-----------------|---------------------|-----------------|-----------------------------------|---------------------------------------------|-------------|
| ZK1203-Py1      | 320.2               | Pyrite          | 0.6                               | From quartz-pyrite-molybdenite veins, massive pyrite | This study  |
| ZK1706-Py3      | 239                 | Pyrite          | 0.7                               | From pluton, disseminated pyrite            | This study  |
| ZK1706-Py2      | 158                 | Pyrite          | 0.9                               | From quartz-pyrite veins, massive pyrite    | This study  |
| ZK801-Py1       | 138.9               | Pyrite          | 3.1                               | From quartz-pyrite-molybdenite veins, massive pyrite | This study  |
| ZK2106-Py1      | 81                  | Pyrite          | 1.7                               | From pluton, coarse pyrite vein.            | This study  |
| ZK1700-Py1      | 51.5                | Pyrite          | 3.8                               | From quartz-pyrite veins, massive pyrite    | This study  |
| ZK1603-240      | 240                 | Pyrite          | 2.7                               | From quartz-pyrite-molybdenite veins, massive pyrite | This study  |
| ZK1302-240      | 240                 | Pyrite          | 1                                 | From quartz-pyrite-molybdenite veins, massive pyrite | This study  |
| ZK1706-Mot1     | 220.7               | Pyrite          | 0.3                               | From quartz-pyrite-molybdenite veins, massive pyrite | This study  |

and K) and Pb, and depletion of HFSEs (such as Nb, Ta, P, and Ti) and Sr (Figure 7C). The chondrite-normalized REE patterns of the YL4 rocks show relative enrichment of LREEs, with $(\text{La/Yb})_N$ ratio of 6.17 (where N denotes normalized to chondrite values of Sun and Mcdonough 1989) (Figure 7D and Table 2), with or without a weak Eu anomaly ($\Delta$Eu $\approx 0.76$). Various discrimination diagrams are also used to constrain the tectonic environment of the Yili granitoids. Samples in this study plot in the field of ‘volcanic arc granite’ with a few in the field of ‘syn-collision granite’ in the diagrams of Pearce et al. (1984) (Figure 7E and F).

A total of nine ore sulphides samples (Table 4) were analysed for sulphur isotopic compositions. Their $\delta^{34}$S values vary between 0.3‰ and 3.8‰, which overlaps with, and is slightly higher than, mantle sulphur, reflecting their deep sources.

6. Discussion

6.1. Ore-forming material source, ages of magmatism and mineralization

For the evolutionary sequence of magmatic rocks in the Yili deposit, the first concern is the intrusive age and order of magmatic rocks. The area of outcropping of early Permian fine-grained granites and of Middle Jurassic monzogranites is relatively large around the Yili deposit. In contrast, outcrops of Early Cretaceous granite porphyry and Early Carboniferous monzogranites are sporadic. The Re–Os isochron age of the molybdenite from the Yili deposit is 131.1 ± 3.4 Ma, which is consistent with the intrusion time of the Early Cretaceous granite porphyry. The order of magmatic activity in the Yili deposit is early Carboniferous monzogranite $\rightarrow$ early Permian fine-grained granite $\rightarrow$ Middle Jurassic monzogranite $\rightarrow$ Early Cretaceous granite porphyry. According to the LA-ICP-MS zircon U–Pb dating results, the ages of the intrusive rocks in the Yili deposit range between 349.8 ± 2.3 Ma and 128.1 ± 1.6 Ma, while magma-hydrothermal activity at 129.0 ± 3.5 and 128.1 ± 1.6 Ma is closely related to the large-scale Mo mineralization of the Yili deposit. The intrusive rocks were developed in at least four periods and include early Carboniferous monzogranite, the early Permian fine-grained granites, the Middle Jurassic monzogranites, and the Early Cretaceous granites porphyry. The Early Cretaceous magmatic-hydrothermal activity is temporally associated with large-scale Mo mineralization. The early Carboniferous monzogranite, the early Permian fine-grained granites, and the Middle Jurassic monzogranites are widely exposed as products of the early magmatic activities. At present, the degree of exploration is high in the Yili deposit, which contains the majority of total Mo resources, but only a small amount of shallow drilling was carried out in this. Therefore, we cannot exclude the possibility that more Mo resource will be discovered by further exploration. Field observations indicate that the granite porphyry contains Mo mineralization even cutting through the Mo orebodies and porphyry rocks.

Liu et al. (2014) proposed that the porphyry (Cu)–Mo deposits in NE China are distributed in the overlapping region of the Central Asian Palaeozoic metallogenic and the West Pacific Mesozoic metallogenic domain. This mineralization was concentrated in three parts: (1) early Palaeozoic Cu–Mo mineralization, including the Duobaoshan and Tongshan porphyry Cu–Mo deposits (Wu et al. 2009; Liu et al. 2010b, 2012); (2) Early–Middle Jurassic porphyry deposits, comprising Wunugetushan Cu–Mo, Daheishan Mo, and Lanjiagou Mo deposits (Li et al. 2007; Dai et al. 2008; Wang et al. 2009); (3) the Late Jurassic–Early Cretaceous Chalukou giant porphyry Mo deposit (148 Ma) (Liu et al. 2014), Taipinggou medium-sized porphyry Mo deposit (129 Ma) (Zhai et al. 2008b), Jiazhishan porphyry Mo deposit (140 Ma), Taolaituo porphyry Mo deposit (133 Ma), and Yili porphyry Mo deposit (131 Ma).

We collected nine pyrite samples from the Yili deposit. The $\delta^{34}$S values of pyrite samples are similar to the $\delta^{34}$S values of magma hydrothermalism (Ohmoto and Goldhaber 1997). Their $\delta^{34}$S values vary between 0.3‰ and 3.8‰ (Table 4) and are slightly higher than mantle S, indicating that S sources should be in the deep.
contents of the molybdenite range from 20.80 ppm to 34.89 ppm (with an average of 26.30 ppm), which is similar to those found in deposits associated with juvenile mantle-derived materials. This conclusion is supported by $\delta^{34} \text{S}_{\text{CDT}}$ of sulphides, and these values are interpreted to reflect a deep magmatic source of the sulphur contained within the ore minerals of the deposit.

6.2. Early Cretaceous adakite-like rocks

The petrology, geochemistry, and geotectonic settings of adakitic rocks provide important constraints on magmatic processes at convergent margins. Defant and Drummond (1990) suggested that adakitic magmas are produced by the partial melting of hot and young (<25 Ma) subducted oceanic crust. However, subsequent investigations revealed that adakitic magmas in other geodynamic settings do not always correlate with the subduction of young oceanic lithosphere. Partial melting of thickened lower crust (Chung et al. 2003; Wang et al. 2005), partial melting of delaminated lower crust (Xu et al. 2002; Gao et al. 2004; Guo et al. 2007), assimilation and fractional crystallization processes involving basaltic magma (Castillo et al. 1999; Macpherson et al. 2006), and slab window processes related to ridge subduction (Zhang et al. 2010) are among the various alternate models proposed to explain the origin of adakites.

The petrologic and geochemical data presented in our study clearly suggest that the two Early Cretaceous intrusions of the Yili Mo deposit have an adakitic composition, such as high SiO$_2$ (69.49–72.77 wt.%), Al$_2$O$_3$ (15.07–16.73 wt.%), Na$_2$O (3.98–4.47 wt.%), Sr (510–965 ppm), and La (16.60–22.10 ppm), moderate K$_2$O (2.76–3.22 wt.%), and low Y (6.8–13.28 ppm) and Yb (0.45–1.26 ppm). Their REE patterns lack Eu anomalies (suggesting that plagioclase was not a major phase controlling the fractional crystallization and/or accumulation for the Yili adakitic rocks), and the rocks contain abundant plagioclase, amphibole, and biotite phenocrysts. On the Y versus Sr/Y and Yb$_N$ versus (La/Yb)$_N$ diagrams (Defant and Drummond 1990; Figure 8a and b), the rocks plot in the compositional field of adakitic rocks with high Sr/Y (38.4–141.9), chondrite-normalized (La/Yb)$_N$ (19.4–35.3) ratios, and low Y (6.8–13.3 ppm) contents and low chondrite-normalized Yb (0.45–1.26) values. Martin et al. (2005) classified adakitic rocks into two groups as high-silica adakites and low-silica adakites. The high-silica adakites are slab-derived melts, which interacted with the mantle wedge, whereas the low-silica adakites represent metasomatized mantle. The Early Cretaceous intrusions in

![Figure 8](image-url)

Figure 8. Y versus Sr/Y (A), Yb$_N$ versus La$_N$/Yb$_N$ (B), SiO$_2$ versus MgO (C), and SiO$_2$ versus Mg# and (D) geochemical classification diagrams for the Yili granitoids ((A) and (B) after Defant and Drummond (1990); (C) after Martin et al. (2005); (D) subducting oceanic crust-derived adakites, Wang et al. 2006; delaminated lower crust-derived adakites, Gao et al. 2004; Wang et al. 2004; 2006; Xu et al. 2002; pure slab melt, Stern and Kilian 1996; metabasaltic and eclogite experimental melts, Rapp et al. 1999; 2002).
the Yili Mo deposit have compositional similarities to high-silica adakites, suggesting the involvement of slab-derived melts (Figure 8C). In addition, their Yb concentrations are always lower than 1.3 ppm, which is very unusual for subduction-related rocks produced at mantle depths (Bourdon et al. 2002). Low magnesium adakites may be related to derivation by direct partial melting of subducted basaltic crust. On the other hand, high-Mg adakites may represent melt contamination with the ultramafic rocks of the overlying mantle wedge. The studied adakitic rocks are characterized by moderate to high Mg# (40.8–42.0) and plot within the same range of value for rocks previously interpreted as subducted oceanic crust-derived melts on a Mg# versus SiO₂ discrimination diagram (Figure 8D). Generally, high SiO₂ contents and Mg# of the Yili adakitic rocks indicate various degrees of interaction between mantle rocks and the adakitic melts during their petrogenesis. Two Early Cretaceous samples from the Yili Mo deposit display a fractionated REE pattern, similar to those of adakitic rocks in general, with HREE depletion. The low HREE content in the Yili adakitic rocks is consistent with the melting of a depleted source that also contains residual garnet (Figure 7D).

Considering all the available information, we suggested that the Early Cretaceous adakitic rocks were formed by partial melting of thickened lower crust following NNW subduction of the Palaeo-Pacific Plate (Figure 9), with high SiO₂, alkalis comprising K₂O, Na₂O, and Al₂O₃, and low MgO, FeO, and CaO. In addition, Huang et al. (2014) also suggested that these Yili Cretaceous adakitic rocks were produced by partial melting of thickened lower crust, and that the trigger mechanism for Mo mineralization was associated with the delamination of thickened lower crust after melting. The change in the subduction direction of the Palaeo-Pacific Plate (Zhang et al. 2010) or the break-off of subducted slabs (Wu et al. 2011) may have caused the tectonic regime transition from compression to extension in northeastern China, causing large-scale delamination of the

![Figure 9](image-url)
thickened continental crust and upwelling of the asthenosphere (Figure 9). The thinning of the lithosphere and the upwelling of asthenospheric material during this process caused strong crust–mantle interaction. Underplating of the mantle-derived magma and the direct heating effect of the asthenosphere on the crust mixed with part of the overlying pre-existing crustal material to form Mo-rich granitic magma (Liu et al. 2014). When the magma invaded the shallow crust along weak tectonic zones, the rapid cooling and crystallization formed ore-bearing porphyry and large-scale Mo mineralization in the Yili area.

6.3 Relationship between mineralization and geodynamic evolution

Wu et al. (2011) suggested that northeastern China – where the Yili deposit is located – can be considered to have been one of the most active areas of the eastern Asian active continental margin during the Mesozoic era. The dynamic setting of the geological processes may be linked to the subduction of the Palaeo-Pacific plate beneath the Eurasian plate during 140–120 Ma (Mao et al. 2005; Zhang et al. 2010). Based on the abundance of zircon U–Pb age analyses, two stages of magmatism (i.e. Jurassic and Early Cretaceous) could be identified in northeastern China (Zhang et al. 2010). The granitic rocks in the Great Xing’ an Range mainly formed in the Early Cretaceous, with a small amount in the Jurassic (Wu et al. 2002, 2003; Lin et al. 2004; Ge et al. 2007; Sui et al. 2007; Wu et al. 2011). In the Jurassic, the subduction of the Palaeo-Pacific Plate beneath the Eurasian Plate caused the crust to shorten and thicken. The subduction of the Palaeo-Pacific plate changed its direction from W to N or NW, which caused a transition in the tectonic regime from compression to extension in the Cretaceous period and subsequently induced large-scale delamination, and the consequent upwelling of the asthenosphere promoted the emplacement of Yanshanian granites (Wu et al. 2005; Zhang et al. 2010). Many studies have demonstrated that the Palaeo-Pacific plate subduction in the Mesozoic era caused most of the magmatism-mineralization occurrences in eastern China (Mao et al. 2003, 2005; Zhang et al. 2009; Wu et al. 2011). The Palaeo-Pacific plate subduction also triggered intensive magmatism and mineralization events in the Great Xing’an Range in northeastern China (e.g. the Xilamulun Mo–Cu metallogenic belt) during the Mesozoic era (Zhang et al. 2009), making this district an important Cu–Mo–Sn–Fe–Ag–Pb–Zn polymetallic metallogenic province in northern China. Hydrothermal deposits in those ore belts are related to subduction during the Late Jurassic to Early Cretaceous period and also share a tectonic setting of lithospheric thinning and magmatic underplating (Zhang et al. 2009). Wu et al. (2011) proposed that the Late Jurassic to Early Cretaceous granites were formed and significantly affected by the subduction process, which resulted in regional lithospheric thickening, and subsequent delamination of the thickened lithosphere due to its gravitational instability during the Early Cretaceous. The Early Cretaceous magmatic activity in the Great Xing’an Range area occurred in an extension setting (Ge et al. 2001; Fan et al. 2003; Gao et al. 2004; Zhang et al. 2008, 2010). This process has also been evidenced by the Sr–Nd isotope modelling results (Fu et al. 2012), Sr–Nd–Pb and Hf isotopic compositions of granites (Zhou et al. 2012), and our geochemistry data from the Yili deposit.

The mineralization age of the Yili deposit is Early Cretaceous, which corresponds to the formation of large-scale Mo mineralization in eastern China. The formation of the Yili deposit coincides with lithospheric thinning, which was caused by delamination and subsequent upwelling of the asthenosphere under extensional tectonics in northeastern China. The thinning of the lithosphere and the upwelling of asthenospheric material during this process caused strong crust–mantle interaction. Underplating of the mantle-derived magma and the direct heating effect of the asthenosphere on the crust mixed with part of the overlying pre-existing crustal material to form Mo-rich granitic magma (Liu et al. 2014). When the magma invaded the shallow crust along weak tectonic zones, the rapid cooling and crystallization formed ore-bearing porphyry and large-scale Mo mineralization in the Yili area. The dynamic settings for the geological processes were linked to the NNW subduction of the Palaeo-Pacific Plate beneath the Eurasian plate during the Mesozoic era.

Conclusions

The zircon SHRIMP II U–Pb, Re–Os molybdenite dating, and whole-rock geochemistry of the Yili deposit in northeastern Inner Mongolia, enables us to draw the following conclusions:

(1) Zircon SHRIMP II U–Pb ages indicate that the fine-grained porphyry granitoids were intruded in the Early Cretaceous, at 128.1 ± 1.6 Ma and 129.0 ± 3.5 Ma. Re–Os dating of five molybdenite samples give an isochron age of 131.1 ± 3.4 Ma. The analytically indistinguishable U–Pb and Re–Os ages suggest that the mineralization and porphyry alteration accompanied intrusive activity. In addition, we obtained two weighted mean 206Pb/238U ages of 287.7 ± 1.8 Ma and 349.8 ± 2.3 Ma for early Permian fine-grained granite and early Carboniferous monzogranite in Yili area, respectively.

(2) Re contents of the molybdenite range from 20.80 ppm to 34.89 ppm (with an average of 26.30 ppm), which is similar to that found in deposits associated with deep materials. This conclusion is
supported by δ³⁴S_CDT of sulphides, and these values are interpreted to reflect a deep magmatic source of the sulphur contained within the ore minerals of the deposit.

(3) The two Early Cretaceous porphyry granitoids are adakitic granites, which are characterized by moderate to high Mg# and high-silica, interpreted as a result of partial melting of thickened lower crust following NNW subduction of the Palaeo-Pacific Plate.

(4) Yili intrusive activity and Mo mineralization occurred contemporaneously with the tectonic and magmatic events during the Early Cretaceous tectonothermal event that affected this region during an extensional regime. The formation of this deposit coincides with lithospheric thinning, which was caused by delamination and subsequent upwelling of the asthenosphere under extensional tectonics in northeastern China. The geodynamic setting for the geological processes should be linked to the NNW subduction of the Palaeo-Pacific oceanic plate beneath the Eurasian plate during the Mesozoic era.

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