Early Cretaceous A-type granites and Mo mineralization, Aershan area, eastern Inner Mongolia, Northeast China: geochemical and isotopic constraints

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The Jiazishan porphyry-type molybdenum deposit is located in the eastern Inner Mongolia Autonomous Region in China. Mineralization occurs mainly as veins, lenses, and layers within the host porphyry. To better understand the link between mineralization and host igneous rocks, we studied samples from underground workings and report new SHRIMP II zircon U–Pb and Re–Os molybdenite ages, and geochemical data from both the molybdenites and the porphyry granites. Seven molybdenite samples yield a Re–Os isochron weighted mean age of 135.4 ± 2.1 Ma, whereas the porphyry granite samples yield crystallization ages of 139 ± 1.5 Ma (Jiazishan deposit) and 133 ± 1 Ma (Taoaltuuo deposit). The U–Pb and Re–Os ages are similar, suggesting that the mineralization is genetically related to Early Cretaceous porphyry emplacement. Re contents of the molybdenite range from 21.74 ppm to 52.08 ppm, with an average of 35.92 ppm, whereas δ 18 O values of the sulphide vary from 1.3‰ to 4.2‰. The ores have 206 Pb/204 Pb, 207 Pb/204 Pb, and 208 Pb/204 Pb ratios of 18.178–18.385, 15.503–15.613, and 37.979–38.382, respectively. We also obtained a weighted mean U–Pb zircon age of 294.2 ± 2.1 Ma for the oldest granite in Jiazishan area. All granites are A-type granites. These observations indicate that the molybdenites and the porphyry granites were derived from a mixed source involving young accretionary materials and enriched subcontinental lithospheric mantle. A synthesis of geochronological and geological data reveals that porphyry emplacement and Mo mineralization in the Jiazishan deposit occurred contemporaneously with Early Cretaceous tectonothermal events associated with lithospheric thinning, which was caused by delamination and subsequent upwelling of the asthenosphere associated with intra-continental extension in Northeast China.

Keywords: Aershan area; porphyry-type deposit; zircon U–Pb dating; molybdenite Re–Os ages; S–Pb isotopic geochemistry; A-type granites

1. Introduction

Economic molybdenum deposits include porphyry-, skarn-, and hydrothermal vein types (Luo et al. 1991). Porphyry-type Mo deposits are the most important metal source in China (Chen et al. 2000; Mao et al. 2005, 2014). The Great Hinggan Range in northern China is well known for its variety of ore systems (Chen et al. 2011; Li et al. 2012; Zhai et al. 2013, 2014; Mao et al. 2014). The Great Hinggan Range hosts a number of skarn, porphyry, and epithermal ore deposits, which are believed to be related to Mesozoic magmatism (Mao et al. 2003, 2005; Chen et al. 2007; Zhai et al. 2013, 2014). This area is also well known for the widespread distribution of Mesozoic igneous rocks, commonly known as the Great Hinggan Mesozoic Igneous Province (Sengör and Natal’ in 1996). The Jiazishan area is located in the Gobi-Mount Aershan-Mount–Duobaoshan molybdenum polymetallic mineralization belt in the China–Mongolia border region. Although this region has good prospecting potential, few breakthroughs have been made for years because little work has been carried out (Berzina and Sotnikov 2005). The region is located on the southeastern margin of the Siberian block, in a region that was affected by the Palaeo-Asiatic tectonomagmatic and circum-Pacific tectonomagmatic domains (Wu et al. 2002, 2005a, 2005b). Some evidence indicates that eastern China was in an extensional regime during the Early Cretaceous (Wu et al. 2005a, 2005b). The study area is characterized by extensive magmatic activity in the Mesozoic, when large-scale volcanic eruptions, granitoid intrusions, and emplacement of porphyry molybdenum ore bodies occurred. The REE and trace-element characteristics of the granite-porphyry are very similar to the Mesozoic volcanic rocks (Wu et al. 2002, 2005a, 2005b), indicating similar magma sources and formation under similar regional geological-tectonic evolution processes.

In the Xing’an-Mongolian Orogenic Belt of Northeast China, several Early Cretaceous A-type granitic plutons are reported, such as the Nianzishan (125 ± 8 Ma, Rb–Sr whole rock isochron) (Li and Yu 1993), Baerzhe (122 ± 5 Ma, Rb–Sr whole rock isochron), (Jahn et al. 2001), Woduhe (129 ± 5 Ma, Rb–Sr whole rock isochron) (Jahn et al. 2001), Shangmachang (106 ± 2 Ma, zircon U–Pb) (Wu et al. 2002), and Hulunhu (alkali rhyolite, 127 ± 5 Ma,
Rb–Sr whole rock isochron) (Ge 2001) in the Great Hinggan Range. Since A-type granite and alkaline rocks form in either post-orogenic or anorogenic settings, this suggests that the Early Cretaceous giant igneous event accompanied regional extension.

Some studies have been carried out on this deposit, generally focusing on geological characteristics (Wu et al. 2002, 2005a, 2005b). However, the timing of magma emplacement, ore genesis, and physico-chemical conditions of the ore fluids and Mo mineralization are poorly constrained. Accurate dating of ore deposits is critical for properly evaluating their relationship to tectonic evolutions and magmatic events (Stein et al. 1997; Mao et al. 2008). Molybdenite Re–Os dating is a powerful tool for precise age determination of ore deposits (cf. Jingwen et al. 1999; Mathur et al. 2000, 2005; Creaser et al. 2002; Gilmer et al. 2003; Selby and Creaser 2003; Mao et al. 2006a, 2008). In this contribution, we present new S and Pb isotopic compositions of the main sulfides along with U–Pb ages of magmatic zircon and the Re–Os isochron age of molybdenite from the Jiaziishan deposit to constrain the sources of ores and the relationships between Mo mineralization and regional geodynamic evolution. This work contributes to a better understanding of ore genesis, timing of the ore system, and the Mesozoic geodynamic evolution of the central-southern segment of the Great Hinggan Range in Northeast China.

2. Regional geological setting

The Great Hinggan Range is located in the eastern section of the Central Asian Orogenic Belt (CAOB) between the Siberian Craton and North China Craton (NCC) (Zhai et al. 2014; Mao et al. 2014) (Figure 1). The CAOB is a giant accretionary orogen bounded by the Siberian, Tarim, and North China Cratons (Figure 1) and is believed to have been the world’s largest site of juvenile crust formation in the Phanerozoic aeon (Shi et al. 2010). The CAOB is an important region for Cu, Fe, Sn, Ag, Au, and polymetallic and rare metal (Li, Be, Nb, Ta, REE) mineralization in the world (Dawei et al. 2003). 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/or along the major lithosphere-scale faults (Guo et al. 2010). The northern margin of North China experienced an intra-continental orogeny in Mesozoic time, known as the Yanshanian tectonothermal event, which resulted in uplift and erosion, volcanic eruptions, and magmatic intrusion, as well as large-scale folds and thrusts. After the Early Cretaceous, deformation becomes quite different from the Yanshan movements (Zhao et al. 2004). Early Cretaceous regional deformation was dominated by extension, with successive volcanic eruptions and associated weak
tectonic deformation. Widespread magmatism occurred across the Great Hinggan Range region (Figure 1), including multiphase plutonic and volcanic activity. Magmatic activity during the late Mesozoic (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 granites associated with Cu, Mo, Fe, Sn, Pb–Zn, and Ag mineralization (e.g. the Hashitu Mo deposit, the Xiaodonggou Mo deposit, and the Aolunhua Cu deposit, Zhang et al. 2009; Zhai et al. 2014).

Magmatic activity in this region began in the early Permian, with most granitic plutons being Late Jurassic–Early Cretaceous in age (Wu et al. 2005a, 2005b; Mao et al. 2014). Mesozoic magmatic activity is represented by both volcanic and intrusive rocks. Volcanic rocks include basalt, andesite, dacite, rhyolite, and volcanic breccia, whereas the intrusive rocks consist of gabbro, diabase, quartz diorite, porphyry granite, and intermediate-felsic granitoids. From the Early Jurassic to Late Cretaceous, the evolutionary trend of magma was from mafic to felsic. Most granitoid-porphry plutons occur as stocks or dikes, with outcrops covering less than 10 km², with a few being much larger.

3. Geology of the Jiazishan Mo deposit

The Jiazishan Mo deposit is situated in the city of Aershan in the eastern Inner Mongolia Autonomous Region in China (Figures 1 and 2). Paralic rocks of the early Permian Dashizhai Formation, comprising green metamorphic tuffaceous sandstone, quartz sandstone, silty slate, and acidic lava, are scattered in the ore district. The rocks of the Lower Triassic Hada Tolgoi Formation are exposed in the northeast, comprising andesite, variegated siltstone, shale, coarse sandstone, and intermediate lavas and tuff, covering about 16 km². The Jurassic Manketouebo Formation, Munito Formation, and Baiyingaolao Formation are widely exposed and are composed of an intermediate-acidic volcanic series. Intermediate lava of the Lower Cretaceous Meiletu Formation is also scattered in the study area. Faults are well developed in the ore district and mainly trend NE and NNE (Figure 1). The Jiazishan igneous complex was emplaced at the intersection of NE- and NNE-trending faults and, as mentioned above, has a close spatial relationship with the Mo ore body. The Manketouebo Formation and Munito Formation volcanic strata are folded, making up the Jiazishan anticlinorium. The Jiazishan igneous complex can be divided into Permian biotite granite and Jurassic diorite, alkaline-granite, and granite-porphry. The granite-porphry is spatially and temporally associated with the volcanic rocks, and they formed under a unified regional geological-tectonic evolution process and
Tectonic-magmatic activity. The porphyry molybdenum deposits are controlled by NE–NNE-trending structures. According to the comprehensive comparative study of porphyry-type molybdenum polymetallic deposits of south Gobi Mount–Aershan Mount–Duobaoshan in the China–Mongolia border region (Table 1; Figure 1), there is a chance to find large porphyry-type molybdenum polymetallic deposits in this area.

There are approximately 95 ore bodies in the Jiazishan ore district, which are principally hosted in four ore belts, labelled Nos. I–IV. Among these, Nos. I and IV ore belts have larger resources and are mined. The Mo mineralization mainly occurs within the fine granitic porphyry. All of the ore bodies mainly occur in porphyry zones formed at the contact between the granite intrusion and the andesitic porphyry and tuff. Mo mineralization has a clear spatial and temporal relationship with the porphyry. Ore bodies in No. I ore belt are generally NE–SW-striking and the Mo mineralization and ore-bearing porphyry extend continuously for ~3 km. The ore bodies include veinlets and disseminated sparse mineralization. Near the contact areas between the granitoid intrusion and the andesitic porphyry, the ore bodies are normally thick, continuous, and high grade. Ore bodies that occur away...
from the granitic porphyry–andesitic porphyry contact zones normally are thinner, discontinuous, and low grade. More than 20 minerals have been identified in the Jiazishan Mo deposit. The main ore minerals are molybdenite, bornite, magnetite, sphalerite, chalcopyrite, galena, scheelite, chalcocite, covellite, malachite, bis-muthinite, pyrrhotite, arsenopyrite, and pyrite. The main gangue mineral is quartz. The boundaries between ore
Table 1. Comprehensive comparative study of porphyry-type molybdenum polymetallic deposits of south Gobi Mount – Aershan Mount – Duobaoshan in the China–Mongolia border region.

| Deposit name                  | Ore-forming element | Ore-hosting structure | Ore-controlling element | Ore-mineral | Gangue mineral | Average grade |
|-------------------------------|---------------------|-----------------------|-------------------------|-------------|---------------|---------------|
| Tsagaan Suvarga of Mongolia  | Mo, Cu, Ag          | NE faults             | Potassic, sericite      | K-feldspar, quartz, calcite | Potassic, quartz, sericite, calcite | Mo, 0.05–0.8% |
| Gerel Mongolia (Hercynian, 1998) | Mo, Cu              | NNE faults            | Potassic, greisenization | K-feldspar, biotite, quartz | Potassic, greisenization, biotite, quartz | Mo, 0.049–0.104% |
| Huagangshan of Aershan area (early Yanshanian) | Mo, Cu              | NW faults             | Potassic, propylitization | K-feldspar, biotite, quartz | Potassic, propylitization, biotite, quartz | Mo, 0.03–0.041% |
| Du (1988)                     | Mo, Cu, Ag          | faults                | Potassic, silicification | K-feldspar, biotite, quartz | Potassic, silicification, biotite, quartz | Mo, 0.03–0.041% |
| Jiazishan, Taolaituo and Jiaozishan of Aershan area (early Yanshanian) | Mo, Cu              | NNE, NE faults        | Potassic, silicification | K-feldspar, biotite, quartz | Potassic, silicification, biotite, quartz | Mo, 0.03–0.041% |
| Xie (2010)                    | Mo, Cu, Ag          | NNE faults            | Potassic, silicification | K-feldspar, biotite, quartz | Potassic, silicification, biotite, quartz | Mo, 0.03–0.041% |
| This study                    | Mo, Cu, Ag          | NNE faults            | Potassic, silicification | K-feldspar, biotite, quartz | Potassic, silicification, biotite, quartz | Mo, 0.03–0.041% |

The rock has a porphyritic texture with approximately 10% phenocrysts that are mainly composed of plagioclase (2%), K-feldspar (5%), and quartz (3%) with accessory zircon, apatite, molybdenite, magnetite, and pyrite. The quartz orthogranitoid sample (Figure 3g) also with weak alteration, was collected from underground workings at drilling No. zk0001 (374 m level) (Supplementary Document 1), well away from ore bodies. The rock has a porphyritic texture with approximately

The rock has a porphyritic texture with approximately bodies and wallrocks are gradational. Sulphide films and very thin veins coat or crosscut quartz veinlets, forming disseminated stockworks that are typical of porphyry ore systems. The alteration of wallrocks is laterally zoned, comprising K-feldspar (potassic alteration), quartz sericite, silica, kaolinite (argillic alteration), epidote, pyrite, zeolite, and propylitization (albitized) minerals. There are no clear boundaries between mineralization zones frequently showing a grading relationship. The Mo mineralization is closely related to quartz sericitized and potassic zones of alteration. Mineralization increases with silicification. According to the mineral assemblages and ore fabrics, as well as the cross-cutting relationships of veins, the mineralization process can be divided into four stages. The first stage is a pyrite + quartz stage, and the minerals were produced as pyrite + quartz veins, 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, and 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 last stage is a fluorite + K-feldspar + quartz stage with pyrite + fluorite + quartz veins and pyrite + fluorite + K-feldspar + quartz veins.

4. Sample description and analytical methods

4.1. Sample description

The locations of all samples from this study are shown in online Supplementary Documents 1 and 2 at http://dx.doi.org/10.1080/00206814.2014.935965. Zircons from three samples of fine-grained plutonic rock were dated. The Jiazishan porphyry granitoid sample (Figure 3e and f), with weak alteration, was collected from underground workings at drilling No. zk0001 (374 m level) (Supplementary Document 1), well away from ore bodies. The rock has a porphyritic texture with approximately 10% phenocrysts that are mainly composed of plagioclase (2%), K-feldspar (5%), and quartz (3%) with accessory zircon, apatite, molybdenite, magnetite, and pyrite. The quartz orthogranitoid sample (Figure 3g), also with weak alteration, was collected from underground workings at zk0002 (339.7 m level) (Supplementary Document 1), and is composed of K-feldspar (70–75%), plagioclase (10–15%), calcite (5–10%), and quartz (~15%) with accessory zircon, apatite, magnetite, and pyrite. The Taolaiwto porphyry granitoid sample (Figure 3h) was collected from underground workings at drilling No. zk427 (370 m level). The rock has a porphyritic texture with approximately
Figure 3. (a–h) Photomicrographs of selected ore mineral assemblages and related mineralization granites porphyry from the Jiazishan, Taolaituo, and Xiaopaodangou deposits: (a) Taolaituo molybdenite (Mo); (b) Xiaopaodangou molybdenite (Mo) and pyrite (Py); (c, d) Jiazishan molybdenite (Mo), pyrite (Py), chalcopyrite (Clp), and sphalerite (Sp); (e, f) sample JZSG1, the phenocrysts are quartz and K-feldspar, the opaque minerals are molybdenite (Mo), pyrite (Py), and sphalerite (Sp); (g) sample TLTG, the phenocrysts are quartz and K-feldspar, the opaque mineral is pyrite (Py); (h) sample JZSG2, the main minerals are quartz, K-feldspar, and euhedral to subhedral plagioclase, the opaque mineral is pyrite (Py). (i, j) Photographs of selected features of ore vein mineralizations from the Jiazishan deposit.
10% phenocrysts that are mainly composed of plagioclase (5%), K-feldspar (2%), and quartz (3%), with accessory zircon, apatite, magnetite, and molybdenite.

4.2. SHRIMP II U–Pb analytical method

Zircon grains obtained from three samples of fine-grained plutonic rock were analysed using the Sensitive High Resolution Ion Microprobe II (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 isolating zircons. Representative zircons were 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 cathodoluminescence (CL) scanning electron microscope images were prepared to determine the internal structures of the grains and to target areas within the zoned zircon grains for analysis. U–Pb isotopes were analysed on the SHRIMP II at the Ion Probe Centre 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 macros of Ludwig (2004). Measured 206Pb was used to correct for common Pb. The reported analytical precision for the U/Pb ratio is 1σ and the weighted mean age is reported as 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 zircons are broken and display clear zoning or core-mantle-rim structure. Reflected and transmitted light show that a few zircon grains developed cracks or voids, which might have been influenced by thermal evolution during late metamorphism.

4.3. Re–Os analytical method

Seven molybdenite samples were collected from drilling cores for Re–Os dating. Gravitational and magnetic separation was applied and then handpicked under a binocular microscope (purity >99%). The molybdenite in the samples is fine-grained (<0.1 mm), thus avoiding 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), made by 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: 

\[ t = \left( \frac{\ln(1 + 187\text{Os}/187\text{Re})}{\lambda} \right) \]

is the decay constant of 187Re, \( 1.666 \times 10^{-11}/\text{yr}^{-1} \) (Smoliar et al. 1996). The data are presented in Table 5.

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 a procedure described by Norrish and Hutton (1969). Chinese national rock standard GSR-1 (granite) was used as reference material. Accuracies of the XRF analyses are estimated to be approximately 1% (relative) for SiO₂ 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 HNO₃. ¹⁰³Rb was used as an internal standard solution 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 fourteen 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 is presented in Table 6 for major oxides and in Table 7 for trace elements.

4.5. Sulphur and Lead isotopic compositions analyses

For S isotope determinations, a mixture of sample powders and Cu₂O was heated under oxidizing conditions to produce SO₂ for analysis. Isotopic ratios were obtained on a Finnigan MAT-251 at Beijing Institute of Nuclear Geological Research with VCDT standard, and the analytical precision was better than ±0.01‰. For Pb isotope determinations, sample powders were attacked with mixed HF and HNO₃ in a Savillex Teflon screwcap beaker on a 100 °C hotplate for 7 days. Pb was separated and purified with anion resin exchange technique with an HBr as the eluant. Isotopic ratios were obtained on the Finnigan MAT-262 TIMS at Beijing Institute of Nuclear Geological Research. Repeated analyses of NBS981 gave \( ^{204}\text{Pb}/^{206}\text{Pb} = 0.5895 \pm 15 \), \( ^{207}\text{Pb}/^{206}\text{Pb} = 0.91445 \pm 80 \), and \( ^{208}\text{Pb}/^{206}\text{Pb} = 2.16170 \pm 180 \).
5. Analytical results

5.1. SHRIMP II U–Pb ages

A total of 85 zircons were analysed and the SHRIMP II analytical data are presented in Tables 2–4. Most zircon grains of the porphyry granitoid sample are transparent and colourless under the optical microscope. Concentric zoning is common and no inherited cores were observed. These zircons have highly variable Th and U contents (79–2750 ppm), but their Th/U ratios range from 0.48 to 2.23, indicating a magmatic origin (Th/U > 0.4). Zircon grains of the quartz orthogranitoid sample have uniform U concentrations ranging from 47 to 248 ppm and variable Th concentrations, with Th/U between 0.46 and 1.42, suggesting a magmatic origin. Three samples were analysed, and all analyses are concordant or nearly concordant and cluster as a single population with a weighted mean 206Pb/238U age of 139 ± 1.5 Ma (MSWD = 4.9, the porphyry granitoid sample, is related to Jiazishan Mo mineralization), 133 ± 1 Ma (MSWD = 2.9, the porphyry granitoid sample, is related to TaoLaiTuo Mo mineralization), and 294.2 ± 2.1 Ma (MSWD = 3.6, the quartz orthogranitoid sample, is the oldest pluton of this region), which represents the crystallization age of the pluton and was used for the calculation of initial isotopic ratios of the other isotopic systems (Figure 4).

5.2. Re–Os ages

Results of molybdenite Re–Os dating are listed in Table 5. The concentrations of Re and 187Os range from 21.74 to 154.91 ppm and 30.31 to 227.96 ppb, respectively. Seven samples give a Re–Os model age of 132.2–142.6 Ma and a weighted mean age of 135.4 ± 2.1 Ma (MSWD = 0.47). Five Taolaituo molybdenite samples have a narrow range of Re–Os ages varying from 132.2 to 133.9 Ma. The Taolaituo Mo (Figure 1) Re–Os data, processed using the ISOPLOT/Ex program (Ludwig 2004), yielded an isochron age of 133.0 ± 0.82 Ma (MSWD = 0.37) and an initial 187Os of 0.11 ±0.72 ppb (Figure 5). The nearly identical model age and isochron age suggest that the analytical results are reliable.
5.3. Major and trace-element geochemistry

A total of 10 granitic samples (Figure 6A) were analysed for major and trace-element compositions. The loss on ignition (LOI) for most samples is about 1 wt.%. In general, the granitic samples are characterized by high SiO\(_2\) contents (71.2–78.2 wt.%) and have low Al\(_2\)O\(_3\) contents (11.2–14.1 wt.%). Total iron oxides (in the form of Fe\(_2\)O\(_3\)) vary from 1.46 to 5.10 wt.%. The contents of CaO and Na\(_2\)O vary from 0.90 to 1.79 wt.% and 2.76 to 4.63 wt.%, respectively. The K\(_2\)O content ranges from 4.19 to 4.98 wt.%. Other oxides are less than 1 wt.% (i.e. MgO = 0.08–0.71 wt.%, MnO = bd to 0.10 wt.%, TiO\(_2\) = 0.12–0.34 wt.%, and P\(_2\)O\(_5\) = 0.01–0.12 wt.%).

According to the K\(_2\)O versus SiO\(_2\) diagram (Le Maitre 1984; Rickwood 1989) (Figure 6B), almost all samples fall in the field of the high K calc-alkaline series. According to the modal abundances (QAPF classification), the Permian Aershan granitoid rock is an alkali feldspar granite, whereas the Early Cretaceous Aershan group falls into the quartz syenite field (Figure 7d).

Chondrite-normalized REE patterns invariably show relative enrichment of light rare earth elements (LREEs) with high (La/Yb)\(_N\) ratios (Figure 6D). Significant negative Eu anomalies are evident. However, some samples show distinctive, rather different REE patterns. The Permian A-type granitoid (JZSG2) shows a slight depletion of La. The REE patterns of these plutons seem to reflect the tetrad effect during the melt–fluid interaction at a late stage of magmatic evolution (Jahn et al. 2001). The granitoids share all the features common to A-type granitoids in terms of trace element geochemistry. They are typically high in Ga, Zn, Zr, Nb, and Y, and low in Ba and Sr, with some variation in the Ba/Sr ratio (Collins et al. 1982; Whalen et al. 1987). In the spider diagrams (Figure 6C), all the granitic rocks show the characteristic negative anomalies in Ba, Nb, Ta, Sr, P, Eu, and Ti.

5.4. Sulphur and Lead isotopic compositions

A total of seven ore sulphide samples (Table 5) were analysed for lead isotopic and sulphur isotopic compositions. Their \(\delta^{34}\)S values vary between 1.3‰ and 4.2‰, which is typical of mantle sulphur. The \(^{206}\)Pb/\(^{204}\)Pb, \(^{207}\)Pb/\(^{204}\)Pb,
Table 4. Zircon SHRIMP II dating results of the Early Cretaceous porphyry granite sample (TLTG) from the Taolaituo Mo deposit.

| Spot  | Pb(*10^-6) | U(*10^-6) | ^232Th/ 238U | ^207Pb/^206Pb | ±%   | ^206Pb/ 238U | ±% | ^207Pb/ 235U | ±% | Ages |
|-------|------------|-----------|--------------|---------------|------|--------------|----|--------------|----|------|
| TLTG-01 | 12 | 464 | 1.0601 | 0.0527 | 4.75 | 0.0209 | 0.92 | 0.1518 | 4.80 | 133 | 1 |
| TLTG-02 | 24 | 991 | 0.8687 | 0.0488 | 2.14 | 0.0208 | 0.80 | 0.1402 | 2.23 | 133 | 1 |
| TLTG-03 | 15 | 433 | 2.4395 | 0.0530 | 5.38 | 0.0201 | 1.31 | 0.1469 | 5.57 | 128 | 2 |
| TLTG-04 | 6 | 236 | 0.8244 | 0.0506 | 4.32 | 0.0210 | 1.20 | 0.1469 | 4.48 | 134 | 2 |
| TLTG-05 | 102 | 4510 | 0.7298 | 0.0494 | 1.17 | 0.0199 | 0.89 | 0.1319 | 1.47 | 127 | 1 |
| TLTG-06 | 6 | 219 | 1.2093 | 0.0506 | 5.45 | 0.0210 | 1.05 | 0.1464 | 5.67 | 134 | 1 |
| TLTG-07 | 4 | 151 | 0.7916 | 0.0494 | 4.09 | 0.0209 | 1.29 | 0.1424 | 4.17 | 133 | 2 |
| TLTG-08 | 17 | 662 | 0.9538 | 0.0482 | 4.07 | 0.0211 | 1.14 | 0.1400 | 4.33 | 134 | 2 |
| TLTG-09 | 85 | 3744 | 0.6276 | 0.0501 | 1.15 | 0.0203 | 1.00 | 0.1337 | 1.53 | 130 | 1 |
| TLTG-10 | 7 | 256 | 1.5723 | 0.0492 | 4.54 | 0.0211 | 1.05 | 0.1429 | 4.58 | 134 | 1 |
| TLTG-11 | 6 | 223 | 1.1806 | 0.0483 | 2.43 | 0.0210 | 1.18 | 0.1400 | 2.49 | 134 | 2 |
| TLTG-12 | 61 | 3017 | 0.2374 | 0.0512 | 0.90 | 0.0205 | 1.07 | 0.1452 | 1.61 | 131 | 1 |
| TLTG-13 | 9 | 361 | 0.8749 | 0.0478 | 2.67 | 0.0212 | 1.01 | 0.1398 | 2.86 | 135 | 1 |
| TLTG-14 | 130 | 6176 | 0.2780 | 0.0468 | 1.42 | 0.0215 | 1.15 | 0.1386 | 1.64 | 137 | 2 |
| TLTG-15 | 7 | 298 | 0.9117 | 0.0468 | 4.04 | 0.0211 | 1.27 | 0.1362 | 4.04 | 135 | 2 |
| TLTG-16 | 15 | 594 | 0.9294 | 0.0513 | 3.89 | 0.0210 | 0.86 | 0.1483 | 3.97 | 134 | 1 |
| TLTG-17 | 7 | 298 | 0.8718 | 0.0508 | 3.71 | 0.0214 | 1.21 | 0.1498 | 3.75 | 136 | 2 |
| TLTG-18 | 7 | 304 | 0.8238 | 0.0517 | 3.52 | 0.0214 | 1.10 | 0.1322 | 3.52 | 136 | 1 |
| TLTG-19 | 23 | 889 | 1.0913 | 0.0511 | 2.52 | 0.0207 | 0.94 | 0.1462 | 2.69 | 132 | 1 |
| TLTG-20 | 9 | 361 | 0.7872 | 0.0511 | 4.23 | 0.0210 | 1.02 | 0.1477 | 4.28 | 134 | 1 |
| TLTG-21 | 11 | 387 | 1.4318 | 0.0481 | 3.71 | 0.0210 | 1.06 | 0.1390 | 3.71 | 134 | 1 |
| TLTG-22 | 7 | 285 | 0.9920 | 0.0531 | 4.08 | 0.0203 | 1.27 | 0.1489 | 4.08 | 130 | 2 |
| TLTG-23 | 6 | 252 | 0.7086 | 0.0508 | 4.11 | 0.0206 | 1.01 | 0.1438 | 4.14 | 131 | 1 |
| TLTG-24 | 13 | 596 | 0.8325 | 0.0476 | 4.89 | 0.0201 | 0.95 | 0.1320 | 4.99 | 128 | 1 |
| TLTG-25 | 22 | 924 | 0.8246 | 0.0461 | 2.85 | 0.0203 | 1.00 | 0.1287 | 2.91 | 129 | 1 |

Note: Errors are 1-sigma.

^204Pb, and ^208Pb/^204Pb vary in the ranges of 18.178–18.385, 15.503–15.613, and 37.979–38.382, respectively.

6. Discussion

6.1. The Aershan pluton: an A-type affinity

The term ‘A-type granite’ was introduced by Loiselle and Wones (1979) to distinguish a group of granitic rocks that occur in extensional tectonic environments (i.e. rift zones or anorogenic settings) but there is no clear consensus on their origin (e.g. Loiselle and Wones 1979; Collins et al. 1982; Clemens et al. 1986; Whalen et al. 1987; Turner et al. 1992; Smith et al. 1999; Anderson et al. 2003; Franco Pirajno et al. 2008). The Aershan pluton has all the geochemical characteristics of A-type granitoids. The pluton contains moderate to high total alkalis (K2O + Na2O = 7.06–9.13 wt.%). The ACNK (Al/Ca + Na + K > 1) is higher than that of typical I-type granitoids, showing a metaluminous-peraluminous nature (i.e. Loiselle and Wones 1979; Douce 1997). The extremely low P2O5 abundances and absence of phosphate minerals also suggest that the Aershan pluton is an A-type granitoid rather than an S-type leucogranitoid (King et al. 1997; Bonin 2007). The trace-element compositions of the Aershan granitoid also show characteristics of A-type granites, including enrichment in HFSEs (e.g. Zr, Nb, Y) and REEs, and extreme depletion in Ba, Sr, P, Ti, and Eu. Other trace-element ratios such as Nb/Ta (11.38–17.91) and Zr/Hf (19.87–31.61) are also consistent with those in typical A-type granites (e.g. Eby 1992; Charvet et al. 1994; Martin et al. 1994; King et al. 1997). The extremely low Sr content is important in discriminating A-type granites from calc-alkaline granites, as Sr contents in A-type granites are only about 33–50% of those in the calc-alkaline varieties at the same SiO2 level (Douce 1997). Various discrimination diagrams are also used to constrain the tectonic environment of the Aershan 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 6E and F). Following the discrimination diagrams of Whalen et al. (1987), samples fall into the field of ‘A-type granites’ (Figure 7).

6.2. Petrogenesis of the granites

Many researchers consider that granitoids from the Great Hinggan Mountains were derived from young accretionary materials extracted from the mantle (Collins et al. 1982; Whalen et al. 1987; Jung et al.
Granitoid samples from the study area feature enrichment and positive anomalies of the large-ion lithophile element (LIL) group (Rb, Th, U, K) and light REE (LREE) with flat and negative anomalies of the high field strength (HFS) elements (Ba, Nb, Ta, Sr, P, and Ti) and heavy REEs (HREEs). These characteristics had a similar magma source to that of coeval volcanic rocks. The source of the late Mesozoic volcanic rocks is thought to have

Figure 4. SHRIMP II zircon U-Pb concordia diagrams of granitoids from the Jiazishan and Taolaituo Mo deposits. (A) Jiazishan porphyry granitoid; (B) Jiazishan quartz orthogranitoid; (C) Taolaituo porphyry granitoid.

Table 5. Result of Re–Os isotopic analyses of molybdenite from the Jiazishan Mo and Taolaituo Mo deposits.

| Drill No. | Sample No. | Weight(g) | Measured Re μg/g | 2σ Re | Measured Re<sup>187</sup> μg/g | 2σ Re<sup>187</sup> | Measured Os<sup>187</sup> ng/g | 2σ Os<sup>187</sup> | Model age (Ma) | 2σ |
|-----------|------------|-----------|-------------------|-------|-----------------------------|----------------|--------------------------|----------------|---------------|-----|
| ZK0001    | JZS1       | 0.05021   | 52.08             | 0.53  | 32.73                       | 0.33           | 77.85                    | 0.62           | 142.6         | 2.2 |
| ZK2321    | JZS2       | 0.03050   | 154.91            | 2.15  | 97.36                       | 1.35           | 227.96                   | 1.93           | 140.4         | 2.6 |
| ZK17-03   | TL1        | 0.05422   | 42.45             | 0.36  | 26.68                       | 0.23           | 58.83                    | 0.47           | 132.2         | 1.9 |
| ZK17-04   | TL2        | 0.05150   | 39.54             | 0.48  | 24.85                       | 0.30           | 55.50                    | 0.45           | 133.9         | 1.9 |
| ZK27-02   | TL3        | 0.03057   | 21.74             | 0.17  | 13.66                       | 0.10           | 30.31                    | 0.27           | 133.0         | 1.9 |
| ZK27-03   | TL4        | 0.03099   | 35.57             | 0.27  | 22.36                       | 0.17           | 49.45                    | 0.44           | 132.6         | 1.9 |
| ZK27-04   | TL5        | 0.03049   | 24.15             | 0.18  | 15.18                       | 0.11           | 33.66                    | 0.30           | 133.0         | 1.9 |

Note: Uncertainty for the calculated ages is 1.01% at the 95% confidence level.
been from enriched lithospheric mantle. When the magma travelled to the surface, it was slightly contaminated by crust and had some fractional crystallization. These high-K calc-alkaline series rocks were one result of postorogenic magmatism. Late Mesozoic upwelling supplied heat to melt the enriched lithospheric mantle, which resulted from the subduction of the Palaeo-Asian Ocean and/or Mongol–Okhotsk Ocean. These late Mesozoic volcanics and the contemporary emplacement of granitoids and the basaltic underplating in combination completed the late Mesozoic crust accretion history in Da’Hinggan Mountain (Lassiter et al. 1996; Lassiter and Hauri 1998; Lassiter 2003; Zhang 2007).

Re-melting of these residues cannot produce granitic liquids with high (Na2O + K2O)/Al2O3 and TiO2/MgO ratios that are characteristic of A-type granitoids (e.g. Eby 1990, 1992; Bonin and Giret 1990; Creaser et al. 1991; Turner et al. 1992; Douce 1997; Wei et al. 2002; Bonin 2007). Mantle–crust interaction in the Aershan pluton is manifested by both its trace-element and isotopic compositions.

Sr–Nd–Pb and Hf isotopic compositions of granites show that the Late Jurassic to Early Cretaceous granites were derived from the partial melting of juvenile lower crust that originated from a depleted mantle, which should be linked to the NNW subduction of the Izanagi plate at the time (Zhou et al. 2012). Wu et al. (2011) proposed that those 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. This process has also been evidenced by the Sr–Nd isotope modelling results and the relatively young Nd model ages of granites in this region (Fu et al. 2012).

As discussed above, trace-element geochemistry of the Aershan granitoid suggests that the magma was enriched in mantle materials and that crustal assimilation was minor, but some crustal contamination occurred. We conclude that young accretionary materials and enriched continental lithospheric mantle were the melt source of the Aershan pluton. We propose that the Early Cretaceous Aershan A-type granites were the product of extension in eastern Inner Mongolia after the delamination of thickened lithospheric mantle resulting from subduction of the Pacific plate (Figure 8).

6.3. Ore-forming material source, timing of magma emplacement and Mo mineralization

Through field investigation and geochemical study, combined with S and Pb isotopic tracing and Re–Os isotopic dating, we have demonstrated that ore sulphides of the porphyry copper belt have the same S and Pb isotopic compositions (Table 8) as that of ore-bearing porphyries. We collected seven pyrite and molybdenite samples from Jiazishan deposit and the adjacent region. The δ34S values of pyrite samples are similar to the δ34S values of magma hydrothermalism (Ohmoto and Rye...
Their $\delta^{34}$S values vary between 1.3‰ and 4.2‰ (Table 5) and are typical of mantle S. The $^{206}$Pb/$^{204}$Pb, $^{207}$Pb/$^{204}$Pb, and $^{208}$Pb/$^{204}$Pb ratios are broadly consistent with this interpretation.

In this study, we obtained a zircon SHRIMP II U–Pb weighted mean age of 139 ± 1.5 Ma and Re–Os isochron age for nine molybdenite samples of 132.6 ± 3.4 Ma (Re–Os isochron age for Jiazishan deposit two molybdenite samples is 141.7 ± 3.2 Ma). Both U–Pb age and Re–Os isochron age are identical within analytical error, indicating that the porphyry granitoid emplacement and the Mo mineralization occurred approximately at the same time (i.e. Early Cretaceous).

6.4. Regional mineralization and geodynamic evolution

The E–W-trending CAOB in China covers areas in Xinjiang Province and Inner Mongolia (Li et al. 2012). Mineral systems in the central part of Inner Mongolia, located in the eastern CAOB, including skarn, porphyry, and epithermal mineral deposits, formed during the Palaeozoic and Mesozoic eras (Chen et al. 2009). Mesozoic ore deposits (Yanshanian period) are related to
lithospheric thinning, caused by the upwelling of the asthenosphere under continental extension in eastern China (Zhang et al. 2010a). The dynamic setting of these geological processes may be linked to the subduction of the Izanagi plate beneath the Eurasian plate during the Early Cretaceous (Mao et al. 2005; Zhang et al. 2010b). The subduction of the Izanagi plate may have changed direction from west to north or northwest, which caused a transition in the tectonic regime from compression to extension and subsequently induced large-scale delamination of the thickened lower crust and lithospheric mantle (Zhang et al. 2010b).

The shortening and thickening of the crust delamination and consequent upwelling of the asthenosphere promoted the emplacement of Yanshanian granitoids (Wu et al. 2005a, 2005b; Zhang et al. 2010b). The magmatic fluids originated from granitic magmas or the deep magma chambers during the Mesozoic era (indicated by the U–Pb and Re–Os isotopic ages) supplied significant amounts of sulphur and other base metals to form large-scale hydrothermal deposits in NE China. Izanagi plate subduction also triggered intensive magmatism and mineralization events in the Great Hinggan Range in NE China. Other metallogenetic belts in the CAOB (e.g. the Xilamulun

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**Figure 7.** (a) $K_2O$ versus $Na_2O$ diagram (Collins et al. 1982) for the Areshan plutonic rocks. (b) $(10,000*Ga/Al)$ versus Nb diagram for A-type granitoids (Whalen et al. 1987); and (c) $(10,000*Ga/Zr)$ versus Zr diagram for A-type granitoids (Whalen et al. 1987). All samples of the Aershan granitoids plot into the field of A-type granitoids. JZSG: Jiaozishan granitoids; XPDGG: Xiaopaodangou granitoids; TLTG: Taolaituo granitoids. (d) Petrographic classification based on the QAPF diagram (Streckeisen 1973) of granitoids from the Aershan.
Mo–Cu metallogenic belt) were also affected by Izanagi plate subduction (Zhang et al. 2009; Zeng et al. 2011). Subduction-related ore deposits in these belts during the Late Jurassic to Early Cretaceous period shared a tectonic setting of lithospheric thinning and magmatic underplating (Zhang et al. 2009). It should be noted that the Late Jurassic to Early Cretaceous interval is an important Sn–Fe–Cu–Mo–Pb–Zn polymetallic mineralization peak in northern China (Mao et al. 2005). Many studies have demonstrated that the Izanagi 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, 2010b; Zeng et al. 2011). Based on the temporal–spatial distribution of granitic rocks in northern China, these occurrences are coordinated with the subduction of the Izanagi plate in the Mesozoic era.

### Table 6. Major element data for 10 granitoids from the Aershan area.

| Sample No. | SiO₂ | Al₂O₃ | Fe₂O₃ | FeO | MgO | CaO | Na₂O | K₂O | MnO | P₂O₅ | TiO₂ | LOI | Total |
|------------|------|-------|-------|-----|-----|-----|------|-----|-----|------|------|-----|-------|
| JZSG1      | 78.19| 11.82 | 1.39  | 0.07| 0.09| 2.76| 4.30 | 0.00| 0.15| 1.13 | 98.87|     |
| JZSG2      | 71.21| 14.15 | 0.52  | 1.20| 0.75| 1.79| 3.32 | 4.49| 0.10| 0.07| 1.95 | 99.90|     |
| JZSG3      | 73.46| 12.86 | 2.55  | 1.25| 0.33| 0.45| 4.41 | 4.33| 0.02| 0.07| 3.33 | 100.16|     |
| JZSG4      | 74.63| 11.61 | 2.93  | 1.90| 0.50| 0.82| 4.15 | 4.27| 0.04| 0.05| 2.22 | 101.12|     |
| JZSG5      | 75.88| 11.33 | 2.17  | 1.55| 0.22| 0.88| 4.02 | 4.19| 0.04| 0.05| 2.01 | 100.54|     |
| JZSG6      | 71.74| 12.80 | 3.25  | 1.85| 0.71| 1.12| 4.63 | 4.50| 0.05| 0.12| 0.24 | 101.11|     |
| JZSG7      | 77.58| 11.19 | 1.81  | 1.25| 0.08| 0.29| 4.26 | 4.42| 0.02| 0.01| 0.12 | 101.04|     |
| XPDGG1     | 77.42| 12.32 | 0.23  | 0.48| 0.13| 0.26| 3.46 | 4.58| 0.00| 0.04| 0.18 | 99.11 |     |
| TLTG       | 76.18| 13.00 | 0.44  | 0.23| 0.11| 0.64| 3.64 | 4.98| 0.01| 0.03| 0.15 | 99.98 |     |
| XPDGG2     | 77.60| 12.38 | 0.15  | 0.30| 0.14| 0.24| 3.45 | 4.50| 0.03| 0.18| 0.74 | 99.03 |     |

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China, Wu et al. (2011) proposed that those granitoids 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. Unlike other areas in the CAOB, Northeast China can be considered to have been one of the most important areas of the eastern Asian active continental margin during the Mesozoic era (Wu et al. 2011). The subduction triggered intensive magmatism and mineralization in the Great Hinggan Range during the Mesozoic era, making this district an important Cu–Mo–Sn–Fe–Ag–Pb–Zn polymetallic metallogenic province.

Several studies suggest that the collision between the Siberian Craton and the North China–Mongolia Block (Mao et al. 2005, 2014) might have been ongoing until the closure of the Mongolia–Okhotsk Ocean in the Late Jurassic (Li 1998; Zorin 1999; Deng et al. 2005). Subduction of the Palaeo-Pacific Ocean beneath the East Asian continental margin began during the Middle Jurassic (Isozaki 1997), and that extrusion and crustal thickening reached a climax in Late Jurassic time. Large-scale magma activity and the NE-trending or NNE-trending tectonic system were the far field response of the Palaeo-Pacific plate beneath the Eurasian Block in the Early Cretaceous, which was the main formation period of the porphyry granitoids (Figure 8).

The Jiazishan deposit is controlled by the NNE-trending and NE-trending faults, and the ages of the emplacement of porphyry granitoid and the Mo mineralization correspond with the large magmatic event. The fine-grained porphyry granitoid also has a calc-alkaline chemistry, enabling us to conclude that the origin of the Jiazishan deposit was linked to the strong folding and thrusting, the geodynamic regime of which was associated with continuous subsidence of oceanic slab and subsequently the magma source region underwent metasomatism and concentration of ancient subducted oceanic slab fluids after the closure of the Palaeo-Asian Ocean. Our geochemical studies indicate that the host granite in the Jiazishan Mo deposit is A-type granite, formed in an extensional setting (Figures 7 and 8). The geodynamic scenario proposed for this Early Cretaceous giant igneous event in eastern China is that continental breakup and rapid plate motion, including Pacific plate subduction, resulted in large-scale lithospheric delamination, leading to asthenosphere upwelling, and subsequent crustal melting in an extensional setting (Wu et al. 2005a, 2005b) (Figure 8).

Table 8. Result of S and Pb isotopic compositions of ore-bearing porphyries.

| Location      | Sample No. | Mineral   | δ34S% | 206Pb/204Pb | 207Pb/204Pb | 208Pb/204Pb |
|---------------|------------|-----------|-------|-------------|-------------|-------------|
| XPDG Deposit  | XP-01      | Pyrite    | 2.0   | 18.256      | 15.589      | 38.198      |
| XPDG Deposit  | XP-02      | Molybdenite | 3.2  | 18.223      | 15.613      | 38.255      |
| XPDG Deposit  | XP-03      | Pyrite    | 2.0   | 18.214      | 15.503      | 37.979      |
| XPDG Deposit  | XP-04      | Pyrite    | 1.3   | 18.178      | 15.613      | 38.236      |
| TLT Deposit   | ZK17-01    | Pyrite    | 4.2   | \           | \           | \           |
| TLT Deposit   | ZK17-02    | Molybdenite | 3.7  | 18.385      | 15.580      | 38.382      |
| JZS Deposit   | JZS-4      | Molybdenite | 2.8  | \           | \           | \           |

Figure 8. A petrogenetic–tectonic model for the Early Cretaceous A-type granites in Aershan, eastern Inner Mongolia. Extension of the back-arc area and lithospheric thinning, enabling the immense emplacement of Cretaceous granitoids and the formation of large-scale Mo mineralization.
7. Conclusions
The zircon SHRIMP II U–Pb and Re–Os molybdenite dating of the Jiazishan deposit and adjacent deposits in eastern Inner Mongolia enables us to draw the following conclusions.

(1) Zircon SHRIMP II U–Pb ages indicate that the fine-grained porphyry granitoid was intruded at about 139 ± 1.5 Ma (related to Jiazishan Mo mineralization) and 133 ± 1 Ma (related to TaoLaiTuo Mo mineralization). Re–Os dating of seven molybdenite samples gives an isochron age of 135.4 ± 2.1 Ma (Re–Os isochron age for Jiazishan deposit two molybdenite samples is 141.7 ± 3.2 Ma). The nearly identical U–Pb and Re–Os ages suggest that the mineralization and porphyry alteration followed the intrusive activity within a short period of time. In addition, we obtained a weighted mean 206Pb/238U age 294.2 ± 2.1 Ma of the oldest granite in Jiazishan area.

(2) The Re content of molybdenite is similar to that found in deposits associated with mantle magmatic inputs. 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. Young accreted materials and enriched continental lithospheric mantle were the dominant sources of Jiazishan and adjacent plutonic rocks.

(3) Intrusive activity and Mo mineralization occurred contemporaneously with the tectonic and magmatic events during the Early Cretaceous tectono-thermal event that affected this region during an extensional regime. Formation of the Early Cretaceous Aershan A-type granites is related to extension following lithospheric delamination in eastern China associated with subduction of the Izanagi plate. The formation of these deposits coincides with lithospheric thinning, which was caused by delamination and subsequent upwelling of the asthenosphere under extensional tectonic regime in NE China. The geodynamic setting for the geological processes should be linked to the subduction of the Izanagi plate beneath the Eurasian plate during the Early Cretaceous.

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