Original Article

Zircon U–Pb and Wolframite Sm–Nd Dating of the Bayinsukhtu Tungsten Deposit in Southern Mongolia and its Geological Significance

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Abstract

The Bayinsukhtu tungsten deposit is a newly discovered quartz-vein tungsten deposit in the Xing’an–Mongolia Orogenic Belt (XMOB) in southern Mongolia, hosted by the Bayinsukhtu granite porphyry. The granite porphyry is located mainly south of the study area, over 3 km². The rock consists of quartz and feldspar phenocrysts in a fine-grained matrix, also mainly composed of feldspar and quartz. The granite porphyry samples demonstrate high SiO₂ and high alkalinity. All samples also straddle the high-potassium calc-alkaline series. In a plot of the molar ratios of A/NK versus A/CNK, the granites are metaluminous. The chondrite-normalized REE patterns are characterized by large negative Eu anomalies and fractionated LREEs. The U–Pb age of zircons from the granite porphyry is 298.8±1.8 Ma, and the Sm–Nd age of the five wolframite samples from the tungsten deposit is 303±19 Ma. The cooling age of the granite porphyry and tungsten mineralization is within the error of measurement and is of the Late Carboniferous age. Geological and geochronological evidence shows that the tungsten mineralization and the granite porphyry at Bayinsukhtu are genetically closely related and that they are results of Carboniferous magmatism. Their tectonic setting is related to the accretion of the Central Asian Orogenic Belt during the late Paleozoic era.

Keywords: Bayinsukhtu tungsten deposit, granite porphyry, southern Mongolia, wolframite Sm–Nd, zircon U–Pb.

1. Introduction

A new tungsten deposit was discovered in the Bayinsukhtu Study District of southern Mongolia by Zhang Baolin. The Bayinsukhtu tungsten deposit is located approximately 60 km (km) southeast of the city of Erdenetsagaan in Mongolia’s Sukhbaatar Province. The deposit is located at 45°35’N, 115°40’E in the Xing’an–Mongolia Orogenic Belt (XMOB) (Xu et al., 2015) (Fig. 1a).

Exploration of the Bayinshukthu district began in 2007. The Institute of Geology and Geophysics (IGG) of the Chinese Academy of Sciences completed 1:10,000-scale geological mapping in 2009. During 2009 and 2010, the IGG conducted 1:2000-scale geological mapping, which identified areas where
magmatic events had occurred in Bayinsukhtu and adjacent areas. Since the discovery of the Bayinsukhtu tungsten deposit Guo et al. (2011) studied the local geology and identified the important structural boundary. Shen et al. (2012) and Guo et al. (2013) discussed the origins of the granitic bodies in the area, and Jia (2012) discussed the origins of the volcanic rocks in the area.

Because the Bayinsukhtu tungsten deposit was discovered only seven years ago, few studies are available on the geochemistry and geochronology of the host granitic intrusions and their relations to the tungsten mineralization. These studies are necessary to understand the ore genesis of the deposit. The absence of accurate geochronological data has particularly increased the difficulty of understanding the ore genesis for the tungsten deposit and for regional metallogenesis in southern Mongolia.

This paper presents new data about the main geological features and geochemistry of the granite porphyry and age of the Bayinsukhtu tungsten deposit to better understand the ore genesis. To accomplish this, we conducted U–Pb isotope studies on zircon and Sm–Nd isotope studies on wolframite (a tungstate mineral) to constrain the relationships between tungsten mineralization, the intrusion system, and regional geodynamic evolution.
2. Regional geology

Mongolia is situated between the Siberian and North China platforms and is characterized by several Precambrian continental blocks that are surrounded by Paleozoic and Mesozoic magmatic arcs, accretionary complexes, and trapped oceanic crusts. (Sengor et al., 1993; Wang et al., 2014; Ding et al., 2015). In particular, it is a host for tungsten deposits, which are closely related to the widespread, late Paleozoic magmatic rocks within different tectonic assemblages (Liu et al., 2005; Chen et al., 2007). Due to a complex geological background and abundant mineral resources, it has attracted much attention during the past decade (e.g. Nie et al., 2002; Qin et al., 2003; Zuo et al., 2003; Cai et al., 2012; Zheng et al., 2013; Song et al., 2013a, 2013b, 2015; Tian et al., 2014). However, the geological evolution of the orogen belt, especially the Carboniferous tectonic affinity of its southern part, is poorly known, largely due to a lack of detailed geological and geochemical data from contemporary magmatic rocks.

The Central Asian Orogenic Belt (CAOB) is a giant accretionary orogen for Cu, Fe, Sn, W, Ag, Au, and rare metal mineralization (Hong et al., 2003; Xiao et al., 2008; Pirajno et al., 2011; Pirajno, 2013; Pirajno & Santosh, 2014) that separates the Siberian Craton from the Tarim and North China Cratons (Fig. 1a). The Xing’an–Mongol Orogenic Belt (XMOB) is one of its major tectonic components (Fig. 1b). The XMOB is composed of blocks, including island arcs, oceanic crust, and ancient microcontinental blocks (Jahn et al., 2000; Jahn, 2004; Li, 2006; Sengor et al., 1993; Wu et al., 2012; Liu et al., 2016).

The Bayinsukhutu tungsten deposit is in the Uliastai continental margin between the Deergeugan and Chagan Obo-Aronggi faults (Fig. 1b). The late Paleozoic accretionary-type orogen of the northern Da Hinggan area is located in the North China Craton and Siberia Craton between the Paleozoic orogenic belt, east of CAOB, in the north of Chagan Obo-Wuchagou deep fault. In the south side of Black slave- orogen deep fracture belongs to the southeast margin of Siberian Craton, giving the Paleozoic orogenic belt and the Mesozoic Daxinanling Orogenic Belt of southern superposition (Fig. 1c) (Zhang, 1993; Ren et al., 1999; Badarch et al., 2002; Nie et al., 2007; Zhou et al., 2009; Zeng et al., 2011).

In the Bayinsukhutu study district, the upper Paleozoic, Mesozoic, and Cenozoic geological units are exposed; the Devonian, Carboniferous, Permian, Cretaceous, and Quaternary strata are the most extensive (Fig. 1c). Devonian rocks are mainly distributed in the southeastern part of the area and include both marine and volcanic sedimentary formations consisting mainly of limestone; sandy and argillaceous shale; and siltstone, metamorphic rhyolite, and quartzose sandstone. The exposed Carboniferous and Permian rocks, the largest concentration distribution in the Middle and East, consist mainly of sandstone, conglomerate, tuff, and andesite. Cretaceous rocks are mainly located in the western and southwestern parts of the region and consist of continental volcanic sedimentary units, mainly rhyolite, trachyte, basalt, tuff, tuffaceous sandstone, tuffaceous conglomerate, and siltstone. Quaternary rocks are widely distributed and include sand, mud, and gravel deposits.

3. Geology of the Bayinsukhutu tungsten deposit

The geology of the Bayinsukhutu tungsten deposit includes Ordovician fine-grained biotite granite and plagioclase granite, Carboniferous monzogranite and granite porphyry, and Jurassic syenite porphyry (Fig. 2). However, the majority of the outcrop in the vicinity consists of monzogranite and granite porphyry, which are commonly associated with tungsten mineralization.

3.1 Stratigraphy

The Devonian strata, into which the granite porphyry intruded, includes a thick sequence of clastic and carbonate rocks (representing both neritic and litoral facies) and volcanic rocks: feldspar- and quartz-rich sandstone and sandy conglomerate; tuffaceous, feldspar-rich sandstone; argillaceous siltstone; and volcanic rocks.

3.2 Intrusive rocks

The tungsten district is situated in the southern area (Fig. 2a). The rocks exposed in the immediate area of the tungsten district are mainly granite porphyry, syenite porphyry, biotite granite, dacite, and arkose.

The granite porphyry is located mainly south of the study area, over an area of about 3 km²; however, outcrops of the rock are small. The rock consists of quartz and feldspar phenocrysts in a fine-grained matrix also mainly composed of feldspar and quartz.
Locally, the rock may be similar in appearance to a grayish-green or dark gray lithic sandstone, with grain sizes ranging from a few millimeters (mm) to 1.5 cm (Fig. 4a). Elsewhere, the rock may be white with purple fluorite mineralization in the quartz veins.

Fig. 2 Geological sketch map (a) and the distribution of rocks in wolframite district (b) from the Bayinsukhtu W deposit in Mongolia.
Paleozoic and Mesozoic granitic intrusive rocks of varying types and extents cover about 80% of the exposed area (Fig. 2). They include monzogranite, biotite granite porphyry, diorite, granodiorite, and various types of felsic veins. Tungsten and molybdenum deposits are closely associated with the granite porphyry.

### 3.3 Alteration

The main types of wall rock alteration are silicification, pyritization, and limonitization. A large limonite–quartz vein, about 300 m long and about 10 m wide, is present in the area and trends nearly east to west (Fig. 2b). Limonite and quartzose sandstone are widespread in local mine settings. Limonite veins trend mainly in 50° as well as at 45° and 145°.

### 3.4 Mineralization

In the Bayinsukhtu Ore District, wolframite mainly occurs in granite porphyry and in carbonatite along the contact area with the Middle to Upper Devonian sedimentary rocks. Wolframite is mostly found in granite porphyry in the form of veins, tabular, and breccia. Veins occur on a range of scales, from large to fine, and they are 0.02-0.4 m wide. The veins generally strike NNE, with some locally striking nearly E–W.

The main metallic minerals are wolframite, chalcopyrite, sphalerite, galena, pyrite, and stannite; gangue minerals include quartz, feldspar, fluorite, biotite, sericite, and ilvaite, among others. The main wolframite orebody occurs in granite porphyry in a strongly silicified vein that is 20–300 m long and 0.54 m wide (Fig. 2b). Veins containing wolframite vary in thickness, from fine (0.02 m) to wide (0.4 m) (Fig. 3), and trend mainly from north to northeast but, locally, may trend from east to west. The ores exhibit a hypidiomorphic granular structure, and the breccia exhibits a crumbly, blocky texture (Fig. 3). Altered sandstone is anomalous As, Sb, Sn, and Ag.

### 3.5 Petrography

Under microscopic observation, the granite porphyry exhibits a porphyritic texture with potassium feldspar and quartz phenocrysts (Fig. 4b, c). Orthoclase crystals range from 0.4 to 10 mm in size, and some exhibit Carlsbad twinning and brown submicron clay alteration. Quartz phenocrysts range from 0.4 to 2.6 mm
in size, with the edges exhibiting resorption. The phenocrysts granite porphyry contains many mineral inclusions, including plagioclase exhibits, polythetic twinning, and a small extinction angle under microscopic observation. Groundmass comprises quartz, orthoclase, and biotite ranging from 0.3 to 0.6 mm in size. Biotite is green with strong birefringence and is partially replaced by chlorite and has inclusions of magnetite and prismatic apatite fine columnar grains in the middle.

3.6 Structural controls
Wolframite may be seen in veins within granite porphyry, as tabular crystals in alteration zones, and as detritus within breccia. By the later stages of mineralization, the mineral composition becomes more complex. The ore structure is mainly comprised of breccia, with granite porphyry and clasts cemented by fine wolframite and quartz, as well as wolframite as vein and net vein filling in granite porphyry and granite porphyry and dacite fracture (Fig. 2b). The host rock in contact with the granite porphyry tends to exhibit wolframite mineralization in locally visible quartz veins. Northeast-trending fractures appear to be the region’s main controlling features that influence the formation of wolframite-bearing veins.

4. Sampling and analytical methods
Five samples of wolframite were collected from the Bayinsukhtu tungsten deposit. Of these, three samples (mgg77, mgg78, and mgg84) are from the No. 2 trench, one sample (EJ10-29) is from an open pit, and one sample (mgg123) is from the No. 3–6 drill hole. Granite porphyry samples were collected from open pits and drill holes, including sample S06 from diamond drill hole zk3-7, which was selected for laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U–Pb zircon dating (Fig. 4). All samples were fresh or weakly altered, as determined either from the hand specimens or microscopically.

4.1 Major and trace elements
Samples were crushed into granules of less than 200 mesh and then analyzed for major and trace elements. All analyses were conducted at the IGG’s State Key Laboratory of Lithospheric Evolution in Beijing, China. Major elements were determined by X-ray fluorescence spectrometry on fused glass disks using an Axios mineral separation tool, with analytical uncertainties ranging from 1% to 5%, following the procedures of Chu et al. (2009). Trace element and rare earth element concentrations were determined by ICP-MS using an ELEMENT system. According to Chinese national standards GSR-1 and GSR-2, the error was <5% for trace elements with concentrations of 10 ppm and <10% for trace elements with concentrations of <10 ppm.

4.2 Zircon LA-ICP-MS dating
Zircon grains were separated from two samples (S06) from granite porphyry at the Bayinsukhtu tungsten deposit. Each sample was about 3.0 kg. Samples were crushed through 80–120 mesh; dust and magnetite were removed by washing and magnets; and then, the zircons were separated using a conventional gravity method and handpicked at the Langfang Institute of Regional Investigation in Hebei Province, China.

Fig. 4 Photograph of the granite porphyry and minerals in Bayinsukhtu ore district. (a) Hand specimen of granite porphyry, (b) microscope image in plane light, and (c) microscope image, crossed polar, showing quartz phenocryst and orthoclase.
These zircon grains were mounted in epoxy together with the reference zircon 91,500 (1065 Ma, uranium content: 81*106; Wiedenbeck et al., 1995), which was used to calibrate U, Th, and Pb concentrations. The zircons were polished and photographed in transmitted light and cathodoluminescence (CL). CL imaging was completed at the Electron Microprobe Laboratory at the IGG.

Zircon LA–ICP–MS U–Pb isotope analyses were performed at the Chinese Academy of Geological Sciences using an LA system (193 nm (nm), GeoLas 200 M) coupled to a Neptune (Thermo Fisher) Multicollector–Inductively Coupled Plasma Mass Spectrometer (MC–ICP–MS). Zircon U–Th–Pb measurements were made on 32 nm diameter spots on single grains. NIST 612 was used as an internal standard for U, Th, and Pb analyses, and zircon GJ-1 was used as the external standard calibration. Common lead was corrected using the method of Andersen (2002). Isotopic ratios and element concentrations were calculated using the ICP–MS Data Cal software (Liu et al., 2009). Ages were calculated using ISOPLOT 3 (Ludwig, 2003).

4.3 Wolframite Sm–Nd dating

All the wolframite samples were unweathered and taken from the main ore-bearing vein in the granite porphyry. Microscopic observation shows that the wolframite was very pure; therefore, the age of the samples represents an accurate time of formation. Based on field investigations and microscopic observations, fresh individual fragments of wolframite weighing 1–3 g each were handpicked under a binocular microscope. The purity of these mineral grains (0.08–0.15 mm) was more than 99%. For this study, the samples for Sm–Nd dating were ground to less than 200 mesh.

Sm–Nd isotopic analysis followed procedures similar to those described by Yang et al. (2010) and Li et al. (2012a) at the State Key Laboratory of Lithospheric Evolution at the IGG. Whole rock powders were dissolved in a Savillex Teflon screw-top capsule after being spiked with mixed $^{149}$Sm–$^{150}$Nd tracers prior to HF + HNO₃ + HClO₄ dissolution. Sm and Nd were separated using the classical two-step ion exchange chromatographic method and measured using a Triton Plus™ Multicollector Thermal Ionization Mass Spectrometer at the IGG. The whole procedure was lower than 100 pg for Sm–Nd. The isotopic ratios were corrected for mass fractionation by normalizing to $^{146}$Nd/$^{144}$Nd = 0.7219.

The international standard sample, JNd1-1, was used to evaluate instrument stability during the period of data collection. The measured value for the JNd1-1 Nd standard was $^{143}$Nd/$^{144}$Nd = 0.512118 ± 0.000014 (n = 9, 2 standard deviation). USGS reference material BCR-2 was measured to monitor the accuracy of the analytical procedures, with the following results: $^{143}$Nd/$^{144}$Nd = 0.512635 ± 0.000014. The $^{143}$Nd/$^{144}$Nd data for these samples are in good agreement with the BCR-2 standard and with previously published data on age dating using MC–ICP–MS techniques (Li et al., 2012a, 2012b; Chu et al., 2014a, 2014b).

5. Results

5.1 Major and trace element composition

Major and trace element data for the granite porphyry from the Bayinsukhtu tungsten deposit are listed in Table 1. Major element compositions show that the granite porphyry samples have high SiO₂ contents, ranging from 69.36 to 79.31 wt.%. The samples also have high alkaline contents, with K₂O ranging from 2.97 to 3.51 wt.%, Na₂O ranging from 1.78 to 2.17 wt.% and total K₂O + Na₂O values ranging from 5.06 to 5.54 wt.%; however, the samples also have low MgO content (0.75–1.16 wt.%) and MnO content (0.03–0.15 wt.%). In a total alkali versus silica diagram, monzogranite and granite porphyry are plotted in the granite field (Table 1 and Fig. 5a). All samples also straddle the high-potassium calc-alkaline series in the K₂O versus SiO₂ plot (Fig. 5b). In a plot of the molar ratios of A/NK versus A/CNK, the granites are metaluminous (Fig. 5c).

The primitive mantle-normalized trace element and chondrite-normalized REE patterns for the porphyritic syenogranite are shown in Fig. 5e and d. The chondrite-normalized REE patterns are characterized by (i) large negative Eu anomalies and slightly negative anomalies; (ii) enrichment in REE ($\sum$REE = 86.8–138.82 ppm); and (iii) a slight enrichment in light REE (LREE) relative to heavy REE (HREE), with LREE/HREE ratios ranging from 6.48 to 9.82 and LaN/YbN ratios ranging from 6.53 to 9.83. The granite porphyry in Bayinsukhtu is enriched in Th, U, La, and Hf and is depleted in Ba, Sr, Nb, Ta, and Ti.

5.2 Zircon U–Pb age

Although the geology, alteration, and mineralization of these deposits have been described in
Table 1  Major (wt%), rare earth, and trace element (ppm) data for granite porphyry in Bayinsukhtu tungsten deposit

| Sample no. | EX09–114 | SB02 | SB03 | SB04 | SB05 | SB06 |
|------------|----------|------|------|------|------|------|
| SiO2       | 79.31    | 74.31| 76.26| 69.36| 77.28| 70.15|
| TiO2       | 0.27     | 0.24 | 0.24 | 0.3  | 0.25 | 0.27 |
| Al2O3      | 9.49     | 9.04 | 8.82 | 10.36| 9.07 | 9.4  |
| TFe2O3     | 1.75     | 1.94 | 1.88 | 2.26 | 1.57 | 1.95 |
| MnO        | 0.03     | 0.04 | 0.03 | 0.15 | 0.04 | 0.12 |
| MgO        | 0.75     | 1.16 | 1.08 | 1.03 | 0.76 | 0.86 |
| CaO        | 2.03     | 4.28 | 3    | 7.11 | 3.11 | 7.49 |
| Na2O       | 2.17     | 1.93 | 1.78 | 2.09 | 2    | 2.09 |
| K2O        | 3.16     | 3.32 | 3.51 | 3.45 | 3.08 | 2.97 |
| P2O5       | 0.1      | 0.09 | 0.09 | 0.1  | 0.09 | 0.1  |
| LOI        | 0.48     | 4.4  | 3.42 | 3.76 | 2.4  | 4.22 |
| TOTAL      | 100.01   | 100.01 | 100 | 100 | 100 | 99.98 |
| A/CNK      | 0.89     | 0.62 | 0.72 | 0.52 | 0.74 | 0.46 |
| /NK        | 1.36     | 1.34 | 1.31 | 1.44 | 1.37 | 1.42 |
| Ga         | 9.93     | 11.47| 11.32| 12.98| 9.45 | 11.76|
| Rb*        | 102.72   | 101.69| 112.16| 125.94| 87.14 | 108.93|
| Sr         | 145.7    | 202.07| 155.09| 235.65| 171.57| 224.35|
| Y          | 17.02    | 19.63 |14.81| 21.66 |16.82| 24.3 |
| Zr         | 195.26   | 179.55| 154.22| 148.18| 192.1| 181.06|
| Nb         | 5.22     | 5.88 | 5.85 | 6.86 | 5.48 | 6.6  |
| Cs         | 3.77     | 3.14 | 4.81 | 3.62 | 2.28 | 2.56 |
| Ba*        | 627.86   | 813.03| 754.6| 839.83| 663.63| 660.24|
| La         | 16.87    | 26.76 |26.37| 27.11 |24.8| 29.44|
| Ce         | 34.39    | 50.76 |50.32| 51.34 |46.9| 55.55|
| Pr         | 4.24     | 6.36 | 6.26 | 6.37 | 5.85 | 6.79 |
| Nd         | 15.76    | 23.4 | 23.19| 23.88 |21.69| 25.28|
| Sm         | 3.12     | 4.21 | 4.13 | 4.41 | 3.9  | 4.69 |
| Eu         | 0.81     | 0.88 | 0.84 | 0.9  | 0.79 | 1.03 |
| Gd         | 3.13     | 3.65 | 3.39 | 3.96 | 3.26 | 4.27 |
| Tb         | 0.52     | 0.6  | 0.53 | 0.64 | 0.54 | 0.71 |
| Dy         | 3.18     | 3.44 | 2.84 | 3.84 | 3.1  | 4.22 |
| Ho         | 0.66     | 0.71 | 0.56 | 0.81 | 0.66 | 0.92 |
| Er         | 1.82     | 2.02 | 1.63 | 2.24 | 1.82 | 2.55 |
| Tm         | 0.27     | 0.32 | 0.26 | 0.34 | 0.29 | 0.4  |
| Yb         | 1.76     | 2.07 | 1.83 | 2.27 | 1.91 | 2.58 |
| Lu         | 0.27     | 0.32 | 0.28 | 0.34 | 0.3  | 0.39 |
| Hf         | 5.77     | 5.27 | 4.77 | 4.6  | 5.84 | 5.39 |
| Ta*        | 0.45     | 0.47 | 0.48 | 0.56 | 0.45 | 0.53 |
| Ti*        | 0.57     | 0.63 | 0.79 | 0.76 | 0.61 | 0.62 |
| Pb         | 12.04    | 15.41| 12.35| 16.98| 15.75| 16.52|
| Bi*        | 0.06     | 0.06 | 0.05 | 0.11 | 0.09 | 0.19 |
| Th         | 8.81     | 12.1 | 11.83| 11.47| 10.94| 12.17|
| U          | 1.28     | 2.24 | 2.56 | 1.72 | 1.47 | 1.95 |
| LREE       | 75.19    | 112.37| 111.11| 114.01| 103.93| 122.78|
| HREE       | 11.61    | 13.13| 11.32| 14.44| 11.88| 16.04|
| ∑REE       | 86.8     | 125.5| 122.43| 128.45| 115.81| 138.82|
| LREE/HREE  | 6.48     | 8.56 | 9.82 | 7.90 | 8.75 | 7.65 |
| LaN/YbN    | 6.53     | 8.79 | 9.83 | 8.13 | 8.85 | 7.77 |

DI, differentiation index; Cm, corundum; ACNK = (Al2O3)/(K2O + Na2O + CaO) molar ratio. ANK = (Al2O3)/(K2O + Na2O) molar ratio.
Fig. 5 Geochemical diagrams of the granite porphyry from the Bayinsukhtu W deposit. (a) Total alkalis versus silica plot. Fields for rock classification are abbreviated. (b) K2O versus SiO2 diagram. (c) Al2O3/(CaO + Na2O + K2O) versus Al2O3/(Na2O + K2O) diagram. The ratios fall in the metaluminous zone. (d) Chondrite-normalized REE distribution pattern (chondrite values after Sun & McDonough, 1989). (e) Primitive mantle-normalized spidergram (primitive mantle values after Sun & McDonough, 1989).

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explanatory reports accompanying geological maps (Zabotkin, 1988), only few geochronological studies have been conducted on the hydrothermal deposits (Sotnikov et al., 1974, 1995; Lamb & Cox, 1998; Murao et al., 1998). Geological researchers in southern Mongolia have re-examined the geology, magmatism, and mineral deposits in the Bayinsukhtu region (Fig. 1), where previous research indicated that many hydrothermal deposits are associated with granitoids. Zircons from the granite porphyry have clear oscillating zones (Fig. 6), indicating a magmatic origin. Separates from 13 zircon grains from the granite porphyry were measured, and their analytical results are listed in Table 2. These geochemical data exhibit a tight cluster in the concordia diagram and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 298.8 ± 1.8 Ma (mean square weighted deviation (MSWD) is 1.08) (Fig. 7) for the granite porphyry. This high-quality zircon age is the best estimate of the crystallization age of the Bayinsukhtu granite porphyry.

5.3 Wolframite Sm–Nd age

The results of the Sm–Nd isotopic dating are presented in Table 3 and are plotted in an isochron diagram in Fig. 8. The Sm–Nd dated samples are from different locations in the Bayinsukhtu tungsten deposit; thus, the ages accurately reflect the time of formation time for the wolframite. The results show that the Sm–Nd age of the wolframites samples is 303 ± 19 Ma (MSWD is 1.6, measurement error is 2$\sigma$) (Fig. 8).

6. Discussion

6.1 Classify the granite porphyry magmatic affinity

The petrogenesis of granitic rocks has a clear bearing on models of tectonic setting (Whalen et al., 1987; Sylvester, 1989), and the correct classification of felsic granites is particularly important. Granitic rocks have been divided into I-, S-, M-, and A-types according to their

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Table 2  LA-ICP-MS U–Pb analytical zircon data from the granite porphyry S06

| Apot no. | Isotopic ratio $^{207}\text{Pb}/^{206}\text{Pb}$ $^{207}\text{Pb}/^{235}\text{U}$ $^{206}\text{Pb}/^{238}\text{U}$ | Age (Ma) $^{207}\text{Pb}/^{206}\text{Pb}$ $^{207}\text{Pb}/^{235}\text{U}$ $^{206}\text{Pb}/^{238}\text{U}$ |
|----------|---------------------------------|---------------------------------|
| Zircons from granite porphyry | | |
| S06-1 | 0.0552 0.0035 0.3658 0.0029 0.0478 0.0006 422 11 299 7 302 4 | |
| S06-3 | 0.0523 0.0045 0.3404 0.0088 0.0472 0.0007 299 16 297 7 297 4 | |
| S06-4 | 0.0549 0.0018 0.3617 0.0041 0.0478 0.0004 409 15 299 8 301 2 | |
| S06-6 | 0.0522 0.0066 0.3432 0.0052 0.0477 0.0009 295 25 300 8 300 5 | |
| S06-8 | 0.0523 0.0042 0.3399 0.0066 0.0471 0.0006 299 15 297 7 297 4 | |
| S06-9 | 0.056 0.0041 0.3568 0.0087 0.0462 0.0006 452 13 310 5 291 4 | |
| S06-10 | 0.0534 0.0065 0.3533 0.0054 0.048 0.0009 346 27 307 5 302 5 | |
| S06-12 | 0.0524 0.0019 0.3459 0.0044 0.0478 0.0004 306 16 299 9 301 2 | |
| S06-18 | 0.0572 0.0038 0.3723 0.0043 0.0471 0.0006 502 12 321 8 297 4 | |
| S06-21 | 0.0555 0.0033 0.3583 0.0057 0.0468 0.0006 433 10 311 6 295 3 | |
| S06-25 | 0.0575 0.0035 0.3673 0.0047 0.0463 0.0006 512 10 318 6 292 4 | |
| S06-26 | 0.0533 0.0038 0.3499 0.0043 0.0476 0.0006 343 13 299 6 300 4 | |
| S06-27 | 0.054 0.0059 0.358 0.0084 0.048 0.0008 374 21 311 5 302 5 | |
protolithic nature (Pitcher, 1983, 1997; Xu et al., 2007).

According to the discrimination criteria proposed by Chappell (1999), the monzogranite and granite porphyry in the Bayinsukhtu deposit most closely resemble I-type granites because of their moderate to slightly peraluminous character \((A/CNK < 1.1)\) (Chappell, 1999). However, Sr–Nd isotopic data of the Bayinsukhtu granites matched both I-type and A-type classifications. Generally, A-type granites are characterized by alkaline dark mineral content (such as arfvedsonite and riebeckite); enrichment in high-field-strength elements (such as Zr, Nb, Y, and REEs); and strong depletion of Ba, Sr, P, Ti, and Eu. The granites in the Bayinsukhtu deposit contain no mafic alkaline minerals and show no enrichment in Nb or strong depletion of Sr and Eu, which indicate that they are not A-type granites. When plotted on discrimination diagrams, all Bayinsukhtu granite samples belong to highly fractionated I-type granites.

It had already been demonstrated that Sm–Nd isotopic analyses of the five wolframite samples yielded an isochron age of \(303 \pm 19\) Ma, which is regarded as the age of the Bayinsukhtu tungsten deposit. The metallogenic epoch usually postdates emplacement of host plutons by several million years (Reynolds et al.,...
What is more, the granite porphyry host is in close proximity to the tungsten mineralization, and the metallogenic fluids were predominantly of a magmatic origin at the Bayinsukhtu tungsten deposit. Thus, the granite porphyry and tungsten mineralization at Bayinsukhtu are nearly related genetically; at 299 Ma, they are Carboniferous.

6.2 Implications for geodynamic setting and regional exploration

The respective 298.8 ± 1.8 Ma and 303 ± 19 Ma ages of the host rocks and mineralization documented here indicate that the Bayinsukhtu tungsten deposit may be the result of a Carboniferous tectonomagmatic event probably related to the accumulation of the CAOB (Mao et al., 2004; Abzalov, 2007; Guo et al., 2010; Qing et al., 2011, 2012; Xu et al., 2013, 2015; Wang et al., 2014; Ding et al., 2015). The granite porphyry at Bayinsukhtu is a potassium-rich calc-alkaline intrusive (Fig. 5b). High-potassium calc-alkaline rocks maybe related to the collision of continents (e.g. Turner et al., 1996; Flower et al., 1998; Liegeois et al., 1998). The geochemical characteristics of the granite porphyry at Bayinsukhtu indicate that it was enriched in Th, U, La, and Hf and was depleted in Ba, Sr, and Nb, which is indicative of an accretionary tectonic setting (Fig. 5d, e).

In addition to the Bayinsukhtu tungsten deposit, there are several other metalliferous deposits in southern Mongolia and northern China (Fig. 9). Typical examples include the Batewa (Nie et al., 2007), Baolige in Jilin (Cong et al., 2014), Chaobulen (Nie et al., 2007), Arhada (Gao and Qian, 2005), Aououte (Zhang et al., 2008), Ulander (Tao et al., 2009), and Zhunsujihua (Liu et al., 2012). Previous studies indicated that these deposits formed in Carboniferous, which coincides with the age of the Bayinsukhtu tungsten deposit. Although these deposits vary in their content, their occurrence and the host rocks are spatially and temporally associated with Carboniferous magmatism in the region. Numerous studies have shown that most of these deposits are genetically related to Carboniferous magmatism of the continental accretion (Nie et al., 2007; Zhang et al., 2008; Liu et al., 2012). These coeval Carboniferous metal deposits and intrusive rocks indicate that the Carboniferous period may be a significance metallogenic period in the evolution of the CAOB.

A regional fracture structure is present and consists mainly of two groups of intersecting faults, one trending northeast to southwest and the other trending northwest to southeast (Fig. 1). In the northeastern part of the area, regional deep fracturing produced two groups of secondary faults, which created a grid pattern of faults that, in turn, controlled the distribution of volcanic structures, magmatic rocks, and ore deposits (Hong et al., 2003; Xiao et al., 2008; Pirajno et al., 2011; Pirajno, 2013; Pirajno & Santosh, 2014). The northeast-to-southwest trending fault exhibits tension–torsional characteristics, and altered rock and mineralization may be seen along either side of this fault zone. Specifically, the faults provided channels through which magma and ore-forming fluids migrated during tectonic activity, and it is along these fault structures that tungsten and molybdenum deposits are located.

7. Conclusions

To better understand the ore genesis of the Bayinsukhtu tungsten deposit, precise geochronological data were required. LA-ICP-MS U–Pb zircon analysis
Dating of the tungsten deposit in Mongolia

shows that the crystallization age of the host granite porphyry at Bayinsukhtu is 298.8 ± 1.8 Ma. Sm–Nd dating of five wolframite separates from the Bayinsukhtu tungsten deposit yield an isochron age of 303 ± 19 Ma. The tungsten mineralization period is contemporary with the petrogenetic period of the granite porphyry, within error range.

Geological and geochronological evidence shows that the tungsten mineralization and the granite porphyry at Bayinsukhtu are genetically closely related and that they are results of Carboniferous magmatism. Their tectonic setting is related to the accretion of the CAOB during the late Paleozoic era.

Acknowledgments

This study was funded by the Ministry of Science and Technology of China (973 Project 2006BAB01A02). We obtained support and help from Yu-Bin Li from the No. 5 Geological Team, Tibet Bureau of Geology and Exploration. We also obtained specific guidance and assistance on trace element analyses from He Li and Xin-Di Jin and on Sm-Nd isotope analyses from Chao-Feng Li at the Institute of Geology and Geophysics, Chinese Academy of Sciences.

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