Geology and molybdenite Re–Os age of the Dahutang granite-related 
veinlets-disseminated tungsten ore field in the Jiangxin Province, China

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ABSTRACT
This is a brief research report about the recently-discovered and currently being explored Dahutang tungsten de-
posit (or ore field) in northwestern Jiangxi, south-central China. The deposit is located south of the Middle–Lower
Yangtze River valley Cu–Au–Mo–Fe porphyry–skarn belt (YRB). The mineralization is genetically associated with
Cretaceous porphyryic biotite granite and fine-grained biotite granite and is mainly hosted within a
Neoproterozoic biotite granodiorite batholith. The Dahutang ore field comprises veinlets-disseminated (~95% of
the total reserve), breccia (~4%) and wolframite– scheelite quartz vein (~1%) ore styles. The mineralization and
alteration are close to the pegmatite shell between the Cretaceous porphyritic biotite granite and Neoproterozoic
biotite granodiorite and the three styles of ore bodies mentioned above are related to zoned hydrothermal
alteration that includes greisenization, K-feldspar alteration, silicification, carbonatization, chloritization and
fluoritization arranged in time (early to late) and space (bottom to top).
Five samples of molybdenite from the three types of ores have been collected for Re/Os dating. The results show
Re/Os model ages ranging from 138.4 Ma to 143.8 Ma, with an isochron age of 139.18 ± 0.97 Ma (MSWD = 2.9).
The quite low Re content in molybdenite falls between 0.5 ppm and 7.8 ppm that is indicative of the upper crustal
source. This is quite different from molybdenites in the YRB Cu–Au–Mo–Fe porphyry–skarn deposits that contain
between 53 ppm and 1169 ppm Re, indicating a mantle source.
The Dahutang tungsten system is sub-parallel with the YRB porphyry–skarn Cu–Au–Mo–Fe system. Both are
situated in the north margin of the Yangtze Craton and have a close spatial–temporal relationship. This pos-
sibly indicates a comparable tectonic setting but different metal sources. Both systems are related to subduc-
tion of the Paleo-Pacific plate beneath the Eurasian continent in Early Cretaceous. The Cu–Au–Mo–Fe
porphyry–skarn ores are believed genetically related to granitoids derived from the subducting slab, whereas
the porphyry W deposits are associated with S-type granitoids produced by remelting of the upper crust by
heat from upwelling asthenosphere.

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1. Introduction
The Middle–Lower Yangtze (or Chang Jiang) River Basin (hereinafter referred to as YRB) is a host to a major metallogenic province in East–Central China that has a great economic value. The massive reserves of high grade Cu and Fe ores and locally supportive mining conditions account for a long mining history that can be traced back to the Bronze Age (~3800 years before present). Even after several millennia of metal mining, the YRB still shows a strong vitality and active exploration and mining continue to this day. YRB is characterized by both porphyry–skarn Cu–Au–Mo–Fe deposits, and magnetite–apatite deposits (Mao et al., 2011). A substantial progress in understanding both types of ore deposits, their relation to granitic magmatism, and their setting has been achieved in the past decades (Chang et al., 1991; Ling et al., 2009; Mao et al., 2006, 2011; Pan and Dong, 1999; Zhai et al., 1992; Zhou et al., 2008).
Recently a number of granite-related W and W–Mo deposits have been discovered and explored to the south of the YRB, along the Yangxing–Changzhou Fault (Fig. 1) and this includes the Dahutang (DHT) ore field. Dahutang was initially discovered by the Jiangxi Bureau of Geology in 1957, by heavy mineral prospecting. Subsequent exploration in 1958, 1966, 1979 and 1984 proved the existence of a small tungsten deposit there. Detailed exploration (including drilling programs, underground working and trenches at surface), restarted in 2010, has so far established a tungsten resource that exceeds 1.1 Mt tons of WO3 (~880 Kt W) at an average grade of 0.152% W. There is also 500 Kt Cu @ 0.12% and 80.2 Kt Mo @ 0.098% Mo. Further
investigation is underway and the local geological survey department speculates that the WO₃ resource could reach up to 2,000,000 t.

There are two distinct metallogenic provinces in South-Central China: 1) the Cu–Au–Mo–Fe porphyry–skarn YRB province, and 2) the broadly contemporaneous W–Sn province in the Nanling area, in the central part of the Cathaysia Block (Chang et al., 1991; Chen et al., 1989; Mao et al., 2004, 2012; Zhai et al., 1992). The newly explored Dahutang ore field and the other previously known veinlets and skarn W–Mo deposits in the same belt (Fig. 1) are situated along the northern margin of the Yangtze Craton, close to the YRB, but their characteristics have more similarities with the granite-related W and W–Sn deposits in the Nanling area (see the inset of Fig. 1). This makes understanding of their geology, formation age and tectonic environment of great scientific and practical importance. This paper is a contribution to understanding the geological characteristics of the Dahutang tungsten ore field, integrated with new molybdenite Re/Os age determinations, leading to a discussion about the metallogeny and geodynamics.

2. Regional geological background

The YRB is located at the northern margin of the Yangtze Craton, south of the North China Craton and Qinling–Dabie orogenic belt, characterized by several large strike-slip fault systems, i.e. the Xiangfan–Guangji Fault in the northwest, the Tancheng–Lujiang Fault in the northeast and the Yangxing–Changzhou Fault (YCF) in the south (Fig. 1). Five successions of exposed rocks are generally found in YRB, from base to top: 1) Mesoproterozoic low-grade metamorphic basement; 2) Neoproterozoic to Silurian clastic rocks; 3) Middle Devonian to Early Triassic carbonates; 4) Middle Triassic to Early Jurassic marine and terrigenous sedimentary rocks; and 5) Early Cretaceous units which comprise four cycles of andesitic volcanic rocks controlled by several parallel NE-trending extensional basins. Rocky outcrops in the south of the YCF zone include the Neoproterozoic Shuangqiaoshan Group phyllite and Banxi Group of metamorphosed slate locally intercalated with basalt–rhyolite volcanics in the Jiangan massif (or shield). SHRIMP zircon U–Pb determination performed by Gao et al. (2011) on volcanic rocks from both Groups indicated their formation ages as 822 Ma ± 10 Ma and 803 Ma ± 7.6 Ma, respectively. A Phanerozoic cover is generally developed outside the Jiangan massif and it includes clastic and carbonate rocks. There, as in the YRB, the Silurian to Early Triassic strata are marine clastic and carbonate rocks, Middle Triassic to Early Jurassic are paralic clastic rocks, whereas Middle to Late Jurassic–Cretaceous are sedimentary and volcanic rocks occur within a series of NE-trending continental basins.

Neoproterozoic and Yanshanian granitic rocks are present in the area. The Jiuling Neoproterozoic granitic intrusion, the largest composite granite complex in south-eastern China with an outcrop area greater than 2500 km² (Zhong et al., 2005). Mesozoic (Yanshanian) granitic rocks (more details below) in the study area occur as many small stocks, intruding in both Neoproterozoic granodiorite batholith and Precambrian strata.

Mao et al. (2011) distinguished two ore types in the YRB: the Cu–Au–Mo–Fe porphyry–skarn type dated at 143–137 Ma, and the “porphyry iron ore” of magnetite–apatite (close to the Kiruna type) dated at 135–123 Ma. The tungsten veinlet-disseminated and skarn belt located south of the YRB includes the Xianglushan, Dahutang, Yangchuling, Qimei, Matou, Jitoushan and other deposits, shown in Fig. 1.

3. Geology of the Dahutang tungsten ore field

The Dahutang tungsten ore field is located in the western segment of the Jiuling–Zhanggong uplift within the Yangtze Craton; all tungsten mineralizations are found within the Neoproterozoic Jiuling
granodiorite batholith (Fig. 2). The relatively monotonous strata in the mine area include the gray–green to dark gray phyllite and slate of the Neoproterozoic Shuangqiaoshan Group, intercalated with meta-sandstone characterized by rhythmic turbiditic (flysch) banding. These rocks are discontinuously distributed as roof pendants in the Jiuling biotite granodiorite and they include a relatively large outcrop area in the southern part of the mine area, south of the Shiweidong ore deposit (Fig. 2). Products of thermal metamorphism in the rock units at contact with the Neoproterozoic biotite granodiorite are hornfelsed and characterized by andalusite and cordierite spots in slate and greywacke, or silicification.

Deformation structures are extensively distributed in the area and include faults and joints. An EW-striking ductile shear zone formed in the Neoproterozoic biotite granodiorite batholith within the Shimensi deposit area, with outcrop width of approximately 100 m. The shear zone crosses the Xin’anli W property (Fig. 2) in the east and extends outside Fig. 2 at both sides. This shear zone displays a significant zoning of the fault rock, from the periphery to the center: mylonitic biotite granodiorite → mylonite → phyllonite → mylonitic schist. In the mine area the shear zone is highly silicified and mainly acted as an ore-controlling structure. North of the Shimensi deposit this shear zone is intersected by the NNE-trending Xianguoshan–Dahutang-Shiweidong basement fault with total length of up to 25 km. These two sets of faults are considered to have been the channels of the ore fluids, and they not only controlled the distribution of the deposits, but also determined the emplacement of Cretaceous granite. In addition to this, several NNE–NE and NNW–NW trending, NW and NE dipping faults of variable length between 100 m and 500 m, can be observed within the mining area, where they contain wolframite–scheelite quartz veins. As another important ore-controlling structure, the stockwork fractures are densely developed at the contact of the Cretaceous porphyritic biotite granite and the surrounding country rocks of the Neoproterozoic biotite granodiorite batholith, and are interpreted as the result of post-emplacement dilation due to volume reduction of the solidifying Cretaceous granite stock.

The exposed intrusive rocks within the mining area are part of the Neoproterozoic Jiuling composite intrusion of predominantly gray, medium to coarse crystalline quartz-phryic granodiorite composed of 25–30% quartz, 20–40% plagioclase, 5–10% K-feldspar, 6–13% biotite, 1–5% cordierite, and 2–5% muscovite. Zircon, apatite, garnet, magnetite and ilmenite are the most common accessory minerals.

The Cretaceous biotite granite emplaced into the Jiuling granodiorite batholith (Fig. 2) consists of porphyritic biotite granite, fine-grained biotite granite, and granite porphyry dykes. The porphyritic biotite granite is gray to white with ~60 vol.% of plagioclase and ~40 vol.% of quartz phenocrysts in fine-grained matrix. The common length of plagioclase phenocrysts is 0.5–1 cm, with the largest crystals reaching up to 2 cm. The matrix is composed of 30 vol.% quartz, 40–50 vol.% plagioclase, and 5–10% biotite. The gray fine-grained granite has 20–21% of plagioclase, 33–34% of K-feldspar, 39–40% of quartz and ~7% of biotite. The tabular plagioclase crystals that measure between 0.6×0.8 and 1.4×2.4 mm are subhedral and commonly exhibit polysynthetic twins, less often as compound carlsbad–albite twins. Biotite flakes are mainly euhedral. Post-mineralization medium to fine-grained, light

Fig. 2. Geological map of the Dahutang tungsten ore field that includes the Shimensi, Yikuangdai and Shiweidong deposits. The tungsten mineralization developed within the Neoproterozoic Jiuling granodiorite intrusion and is genetically related to Cretaceous (Yanshanian) granitic intrusions. (Modified from No. 916 Geological Team, Jiangxi Bureau of Geology, Mineral Resources, Exploration and Development, 2012).
flesh-colored granite porphyry dykes intersect the above-mentioned granitoids and the ore veins. They have 10–15% plagioclase, 20% quartz and 5% biotite phenocrysts in matrix of K-feldspar, quartz and sericite. The Dahutang tungsten ore field consists of three ore deposits (or sections): the Shimensi deposit in the north, Dalingshang (or Yihaomai) deposit in the center and the Shiweidong deposit in the south (Fig. 2). Shimensi was explored by the No. 916 Geological Team, Jiangxi Bureau of Geology, Mineral Resources, Exploration and Development proving a reserve of 758,500 t @ 0.19% WO₃. Shiweidong was explored by the Northwestern Geological Team, Jiangxi Bureau of Geology, Mineral Resources, Exploration and Development who calculated a reserve of up to 299,000 t @ 0.17% WO₃. At present, more drilling is in progress around the Dalingshang deposit. There, the mineralization is predominantly in the Neoproterozoic biotite granodiorite close to contact with the Cretaceous biotite granite stock, although some ore bodies are in Cretaceous biotite granite endocontact (Fig. 3a, b) and a few extend into the Neoproterozoic phyllite and slate (Fig. 4). The ore body has usually a layered to lenticular form with a maximum thickness of ~390 m. Subeconomic tungsten mineralization is more widespread, especially between the delineated higher grade zones.

4. Alteration and mineralization

4.1. Mineralization styles

Three mineralization styles are represented in the Dahutang ore field: 1) Veinlet-disseminated (Fig. 5a, b); 2) quartz vein (Fig. 5c); and 3) hydrothermal breccia (Fig. 5d). Style 1 accounts for more than 90% of total tungsten reserve. These three styles frequently co-exist in space and overlap each other (Fig. 6).

Style 1 mineralization is most common in granitoids of both age groups. The Neoproterozoic biotite granodiorite hosts more than 57.3% of the total tungsten reserves of the veinlet-disseminated
style and the ore has a relatively high grade (0.18–0.40% WO₃). Wolframite is slightly more common than scheelite among the ore minerals. The corresponding ore style in the Cretaceous biotite granite accounts for up to 32.7% of the total resource but the grade of 0.16–0.30% WO₃ is slightly lower. The ore consists of fine-grained anhedral scheelite, wolframite, chalcopyrite and other metallic minerals in a gangue of quartz, biotite and muscovite. The distribution of veinlet-disseminations ranges from sparse to dense (Fig. 5a).

Breccia-hosted mineralization is developed in central parts of the Shimensi and Shiweidong deposits, in apical part of the Cretaceous biotite granite stock (Fig. 6). The breccia fragments have been derived more from the Neoproterozoic granodiorite than from the Cretaceous porphyrytic biotite granite. Most of the breccias exhibit internal jigsaw texture (hydraulic fracturing) filled by quartz-dominated ore component (Fig. 5d). The interfragmental hydrothermal fill has, in addition to quartz, subordinate muscovite, biotite, K-feldspar, fluorite, tourmaline and other gangue minerals. Wolframite, scheelite, chalcopyrite and molybdenite have the form of scattered lumps, disseminations and diffuse admixtures in the gangue and rarely in the breccia fragments. It is interesting to see the presence of dendritic biotite, within the breccia ore, growing inward towards the cementing material. This ore style contributes some 5% of the total WO₃ reserve in the ore field.

Quartz, wolframite, and scheelite veins cut through the entire area. They follow the NE-, NW- and NS-striking faults, are most widespread in the western and central areas, and account for about 1% of the total ore reserve. In these veins, wolframite usually occurs in thick tabular crystals, rooted in both vein walls, forming a symmetrical comb-like structure (Fig. 5c). This ore variety has a higher tungsten grade (average of 0.282% WO₃) compared with the remaining ore types in the deposits, and wolframite is more common than scheelite. It also can be seen that scheelite aggregates replace the wolframite crystals. The ore metals are vertically zoned, from the top downwards: W → W + Cu → Cu + Mo.

4.2. Mineralization and alteration events

In the light of mineral paragenesis, cross-cut relationships, textures/structures and related wall rock alteration, the ore forming events at Dahutang can be divided into three stages: 1) Cretaceous biotite granite emplacement accompanied by thermal metamorphism and pegmatite formation; 2) magmatic-hydrothermal alteration and mineralization that can be further subdivided into a pre-ore K-feldspathization, ore-related silicification and greisenization, and post-ore carbonatization; and 3) post-Cretaceous supergene modification. This paragenetic sequence is illustrated in Fig. 7.

Thermal metamorphism resulted from the intrusion of granitic magma into roof rocks. The degree of resulting changes is controlled by the heat regime and the nature of the rocks undergoing thermal metamorphism, especially their composition. Therefore, changes produced by the emplacement of the Cretaceous granite into Proterozoic granodiorite in the Dahutang area are slight to barely discernible. On the other hand, wall rocks other than this granodiorite were subjected to substantial thermal modifications, such as hornfelsing and porphyroblastic growth of minerals. The Shuangqiaoshan Group schist in Cretaceous granite exocontact is spotted with and andalusite and cordierite porphyroblasts and is locally silicified.

Generally Sn–W granites orthomagmatic pegmatite shells or lenses overlap with hydrothermally altered rocks, dominated by K-feldspar and/or albite (Pirajno, 2012). The pegmatoidal shells in the classical localities such as those of the central European Erzgebirg (Altenberg) (Rössler et al., 1968), seem to combine both volatile magma emplacement and hydrothermal alteration, and are often transitional into greisen (quartz, muscovite) and quartz, topaz, zinnwaldite, cassiterite, and wolframite ore veins that fill concentric dilations in granite parallel with cupola surfaces as in Čínovec, Czech Republic (Šměrkov et al., 1995). In the Dahutang ore field such pegmatoidal shells are developed along contacts of Cretaceous granite cupolas against the Proterozoic granitoid exocontact. They consist of K-feldspar, quartz, and small
amounts of biotite and muscovite perpendicular to the contact zone (Fig. 8a, b). True magmatic pegmatite veins, however, also exist in the cupolas. They have cross-cutting relationships, sharp contacts, and are composed of K-feldspar megacrysts, albite, and quartz with interstitial muscovite. Metallic mineralization, however, is absent here.

In the initial magmatic-hydrothermal stage potassic alteration converted albite in the Neoproterozoic granodiorite to K-feldspar. This was followed by the introduction of ore metals producing the three ore styles described above (veinlets-disseminations, hydrothermal breccias, wolframite-scheelite quartz veins) with the following mineral associations:

- quartz–K-feldspar–wolframite–cassiterite
- quartz–muscovite–wolframite–scheelite–cassiterite
- quartz–wolframite–scheelite
- quartz–scheelite–chalcopyrite
- quartz–scheelite–chalcopyrite–(bornite)
- quartz–molybdenite–chalcopyrite.

Among them the quartz–wolframite–scheelite veins, veinlet and breccias are dominant. Greisen and silica alterations are closely associated with the mineralization. Pervasive quartz–muscovite greisenization is the standard feature of the veinlet-disseminated ore style, whereas the quartz–wolframite–scheelite veins have greisen selvages that are proportional to the vein thickness, ranging from several centimeters to tens of centimeters. In the breccia ore greisenization also occurs in the country rocks along the quartz–wolframite–scheelite cements. Carbonate veinlets and short discontinuous veins of purple fluorite infill dilations in the closing, post-ore stage of the hydrothermal event and they are superimposed on all ore style varieties as well as on unmineralized granitoids.

Retrograde supergene modification of the hypogene ores, as well as their host rocks, took place after erosion that removed several thousand meters of the roof and exhumed the primary mineralization. Oxidation and hydration at the higher supergene levels were responsible for conversion of sulfides into goethite, malachite, covellite and chalcocite, whereas wolframite and scheelite were oxidized into tungstite. In the deeper secondary sulfides zone chalcocite and covellite replaced chalcopyrite and bornite, whereas wolframite and scheelite remained as relics. Silicate minerals weathered into hydromica and kaolinite locally pigmented by manganite, and carbonate and fluorite were leached out.

5. Sampling, analytical methods and results

Re/Os isotope analysis of molybdenite is a powerful method to determine the ore-forming ages. It has been extensively applied to date ores in past fifteen years (e.g. Mao et al., 1999; Stein et al., 1997).
order to establish the precise mineralization age of the Dahutang porphyry tungsten system we collected five molybdenite samples numbered DHT-1, DHT-7, DHT-8, DHT-13 and DHT-14 from the Shimensi deposit for analysis. The sample set comprised two representatives of the veinlet-disseminated style, two from the quartz– wolframite–scheelite veins and one from the breccia style. In the first ore style molybdenites occur as fine-crystals in veinlets-disseminated ores hosted in porphyritic biotite granite (Fig. 9a). In the vein ore style molybdenite flakes tend to accumulate along the vein-wall rock contact and reach into the altered selvage (Fig. 9b). In the breccia-hosted ore molybdenite is scattered in the internal fragmental space.

Molybdenite concentrates for analysis were prepared using the conventional method. After crushing the samples were subjected to gravity and magnetic separation after which the molybdenite grains were handpicked under a binocular microscope to achieve >99% sample purity. The analyzed molybdenite was fine-grained (≤0.1 mm) to minimize possible decoupling of Re and Os within large molybdenite grains (Selby and Creaser, 2004; Stein et al., 2003). The analyses were performed in the Re–Os Laboratory, National Research Center of Geoanalysis, Chinese Academy of Geological Sciences in Beijing using a Thermo Electron TJA X-series ICP-MS. The analytical procedures followed those described by Shirey and Walker (1995), Mao et al. (1999) and Du et al. (2004). The model ages were calculated following the equation: \[ t = \frac{\ln (1 + 187\text{Os}/187\text{Re})}{\lambda}, \] where \( \lambda \) is the decay constant of \(^{187}\text{Re} \), \( 1.666 \times 10^{-11} \text{year} \) (Smoliar et al., 1996).

In our samples the concentrations of \(^{187}\text{Re} \) and \(^{187}\text{Os} \) ranged from 354 to 4952 ppb to 0.82 to 11.60 ppb, respectively. In order to check the accuracy we have ran a duplicate analysis of sample DHT-7. We have obtained a range of Re–Os model ages of 138.4–143.8 Ma, with a weighted mean age of 140.4± 1.9 Ma. All three styles of ore distribution returned the same mineralization age, implying an almost simultaneous emplacement. Our data, processed using the ISOPLOT/Ex program (Ludwig, 2004), yielded an isochron age of 139.2±1.0 Ma, with MSWD = 1.7 (Fig. 10). The identical model ages and isochron ages of the five samples suggest that the analytical results are reliable.

6. Discussion

6.1. Principal characteristics of granite-related tungsten deposits

Both skarn and wolframite–quartz vein types of tungsten deposits are the major source of tungsten metal in China and the world (Černý et al., 2005; Laznicka, 2006, 2010; Li, 1993; Mao et al., 2009; Pirajno, 2009). Compared to the porphyry Cu–Mo deposits, porphyry tungsten deposits are less known. So far, several porphyry W–Mo, W–Mo–Sn deposits are reported in New Brunswick, Canada (Noble et al., 1984; Parrish and Tully, 1978; Sinclair, 2007), the Logtung deposit, south-central Yukon Territory (Noble et al., 1984), the Lianhuashan porphyry W deposit, the Yangchuling W–Mo deposit and Jitoushan porphyry W–Mo deposit (Man and Wang, 1988; Song et al., 2012; Tan, 1985), and Weolag and Dae Hwain Korea (Shelton et al., 1987; So et al., 1983a,b). However, these porphyry W deposits are small scale with less economic value (Sinclair, 2007). Among them the Logtung is described as a large tonnage, low-grade W (scheelite)–Mo porphyry deposit, its WO₃ reserve is 210,600 t (Noble et al., 1984; Sinclair, 2007), much less than the Dahutang tungsten deposit. It’s worth to point out that porphyry Cu–Mo, porphyry Cu–Au and porphyry Mo deposits usually have a typical alteration zoning, i.e. potassic alteration, quartz sericite and propylitic alteration from the core outwards. However, the porphyry tungsten deposits are characterized by strong greisenization, and weak potassic alteration and propylitization. In this case, Davis and William-Jones (1985) named it as porphyry–greisen tungsten deposit.
Rundqvist et al. (1971) recognized greisen Sn (W) at the cupolas of granite intrusions in the Erzgebirge area of Germany and Czech, Tasmania, Australia and Mongolia. The greisen ore mainly consisting of quartz, muscovite, cassiterite and minor wolframite occurs as massive and disseminated ore styles. There are a few typical greisen tungsten deposits in China. Feng et al. (2011a,b) reported a greisen tungsten deposit in China.

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<tr>
<td>Chalcocite</td>
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<tr>
<td>Goethite</td>
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<tr>
<td>Malachite</td>
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<td></td>
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<tr>
<td>Tungstate</td>
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<tr>
<td>Molybdenite</td>
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<td></td>
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<tr>
<td>Manganite</td>
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<td></td>
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<tr>
<td>Kaolinite</td>
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</table>

Fig. 7. Paragenetic sequence of alteration and ore minerals in the Dahutang tungsten deposit. Z. Mao et al. / Ore Geology Reviews 53 (2013) 422–433

Rundqvist et al. (1971) recognized greisen Sn (W) at the cupolas of granite intrusions in the Erzgebirge area of Germany and Czech, Tasmania, Australia and Mongolia. The greisen ore mainly consisting of quartz, muscovite, cassiterite and minor wolframite occurs as massive and disseminated ore styles. There are a few typical greisen tungsten deposits in China. Feng et al. (2011a,b) reported a greisen tungsten deposit in China.

Fig. 8. Pegmatite shell between the Cretaceous porphyritic biotite granite stock and the Neoproterozoic biotite granodiorite batholith in Shimensi (a) and Dalingshang (b), mainly consisting of K-feldspar, quartz and a small amount of biotite and muscovite that are aligned perpendicularly to the contact.
south Jiangxi province, Nanling region, where an elongated greisen ore body mainly consisting of quartz, muscovite, and wolframite developed along a fracture within the Jiulongnao biotite granite batholith. The other example is Shizhuyuan, a world class skarn–greisen W–Sn–Mo–Bi deposit in southern China, where the large stockwork greisen ores comprising quartz–biotite, quartz–muscovite and quartz–topaz ore veins overprint the skarn ores (Mao and Li, 1996). Unlike the typical greisen deposits, the Dahutang contains veinlets-disseminated, wolframite and scheelite quartz vein and hydrothermal breccia-hosted ore styles. They have limited amounts of muscovite and cassiterite but are enriched in wolframite, scheelite, and chalcopyrite within the veinlets and quartz vein and breccia ores. All three ore types have the same mineral associations and are characterized by strong greisenization mainly comprising quartz and muscovite, and weak potassic and propylitic alteration. Hydrothermal potassic (K-feldspar) alteration at the base of carbonatization (in the Shiweidong deposit) or dilatonic filling by quartz-topaz ore (Berzina et al., 2005; Mao et al., 1999, 2008). As shown in Table 1, the Re/Os molybdenite age of 137 Ma for the W ore, and U–Pb zircon age of 138 Ma for the parent granite, in the Jitoushan porphyry W–Mo deposit. Man and Wang (1988) obtained muscovite K–Ar ages of 137.1 ± 3.4 Ma and 137.8 ± 3.1 Ma for breccia ore, and whole rock Rb–Sr isochron ages of 140.5 ± 4.7 Ma for ore-related granodiorite in the Yangchuling porphyry W deposit. It explains the Dahutang granite related tungsten ore field shares a nearly contemporaneous age with the porphyry W–Mo deposits and the porphyry–skarn Cu–Au–Mo–Fe deposits in the mineral province.

The trace Re content in molybdenite has been used to trace the source of the Mo in the ores and by implication of the associated metals such as W. Literature data indicate progressive Re decrease from > 100 ppm in Mo derived from mantle sources through tens of ppm for mixed mantle/crust source to < 10 ppm for crustal sources (Berzina et al., 2005; Mao et al., 1999, 2008). As shown in Table 1, the Re contents in the Dahutang molybdenite are between 0.5 ppm and 7.8 ppm, suggesting an upper crustal Mo source genetically related to granitoid intrusions. The same order of magnitude of trace Re in molybdenite is the YRB porphyry–skarn type Cu–Au–Mo–Fe deposits in the Nanling region in South China. This, however, contrasts with the Re in molybdenite values in porphyry–skarn type Cu–Au–Mo–Fe deposits in the Middle–Lower Yangtze region, reported as ranging from 53 ppm to 1169 ppm and considered sourced from melts derived from the subducting slab (Mao et al., 2006, 2011) and/or oceanic ridge (Ling et al., 2009).

The metallogenic contrast between two roughly parallel mineralized belts of approximately the same age in the Yangtze ore province mentioned earlier: the YRB porphyry–skarn Cu–Au–Mo–Fe belt and the granite-related W–(Mo, Cu) belt but have different metal sources. On the other hand, the latter is comparable with the Nanling W–Sn

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**Fig. 9.** Sample of veinlets-disseminated W ore from which molybdenite samples were collected for Re/Os dating, showing disseminated coexisting molybdenite and chalcopyrite in porphyritic biotite granite (a); Molybdenite in the quartz–wolframite (scheelite) vein usually occurs along the vein/wall rock contact and in altered vein selvages (b).

**Fig. 10.** Molybdenite Re/Os age of the Shimensi ore section constructed using ISOPLOT software of Ludwig (1999). The calculated isochron age using the decay constant: $\lambda(^{187}\text{Re}) = 1.666 \times 10^{-11}/\text{year}$ (Smolar et al., 1996); absolute uncertainty at 2σ has error of 1.02%.

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6.2. Timing of metal introduction and metal sources in the Dahutang ore field and comparison with other W deposits in southern China

We consider the geochronological data obtained by application of the Re/Os dating technique to Dahutang molybdenite samples (model ages ranging from 138.4 Ma to 143.8 Ma; Table 1, Re–Os isochron age of 139.18 ± 0.97 Ma (MSWD = 2.9) (Fig. 10)) to closely approximate the age of molybdenite crystallization and tungsten mineralization. These mineralization age data also compare well with the ages reported from other porphyry W–Mo deposits in the same ore belt in the Middle–Lower Yangtze River region. Song et al. (2012) reported the Re/Os molybdenite age of 137 Ma for the W ore, and U–Pb zircon age of 138 Ma for the parent granite, in the Jitoushan porphyry W–Mo deposit. Man and Wang (1988) obtained muscovite K–Ar ages of 137.1 ± 3.4 Ma and 137.8 ± 3.1 Ma for breccia ore, and whole rock Rb–Sr isochron ages of 140.5 ± 4.7 Ma for ore-related granodiorite in the Yangchuling porphyry W deposit. It explains the Dahutang granite related tungsten ore field shares similarities to both porphyry and greisen ore systems.
province of crustal derivation (Chang et al., 1991; Chen, 1983; Chen et al., 1989; Zhai et al., 1992). In the early 1980’s, the Yangchuling porphyry W–Mo deposit was discovered and explored in the northern margin of the Yangtze Craton, followed by the Xianglushan skarn-type tungsten deposit explored in 1990’s (Fig. 1). Although geographically close to the YRB, the metallogenic type and ore style are more similar to the Nanling Sn–W system related to crustal granitic melts.

Our results integrated with published data, now make it possible to define an independent tungsten metallogenic belt that is parallel with the long known Yangtze River Fe–Cu–Au–Mo porphyry–skarn belt (YRB). We propose to name the Dahutang ore field it also contains Jitoushan and other recently discovered porphyry W deposits (Fig. 1). Both metallogenic belts originated at approximately the same time with ages between 143 and 137 Ma (Li et al., 2010; Mao et al., 2006, 2011; Xie et al., 2007; Zhao et al., 2006; Zhou et al., 2008).

6.3. Geodynamic interpretation

Both metallogenic belts defined above: YRB and NYCT, are close in space and time, but have a different selection of the ore metals. This suggests different source relationships at the onset of development of the ore-forming system.

Chang et al. (1991) and Zhai et al. (1992) proposed a strong interaction between mantle and crust to explain the origin of the Yanshanian I-type granitoids parental to the YRB metallogenic belt. Zhang et al. (2001a,b) compared the same granitoids with the adakites, produced by partial melting of intermediate-mafic granulites in the deep lower crust under high P–T conditions. Mao et al. (2006) placed the origin of the porphyry–skarn Cu–Au–Mo–Fe deposits into the 160 to 135 Ma time interval during which the principal N–S stress field in eastern China continent changed progressively to an E–W orientation, due to the subduction of the Paleo-Pacific Plate beneath the Eurasian Plate. Ling et al. (2009), by contrast, proposed a Cretaceous oceanic ridge subduction to explain the 140–125 Ma magmatism and associated metallogensis. Most recently, using geological observations, petrochemistry and Sr/ Nd isotopic data, Mao et al. (2011) concluded that the eastern part of the Eurasian continent was an active continental margin at ca. 180 Ma, as the Izanagi Plate subducted orthogonally beneath the continent. At ca. 160 Ma this plate rotated clockwise towards the north with subduction orientation becoming oblique with respect to the continental margin. This triggered emplacement of large amounts of granite magma in the back-arc setting associated with metallic mineralization controlled by regional NE–SW strike-slip faults. The geochronological data obtained for the Middle–Lower Yangtze River region consistently indicate that the Tan–Lu regional strike-slip fault zone was initiated between 233 ± 6 and 225 ± 6 Ma and, due to the Izanagi oblique subduction, underwent reactivation at ca. 160 Ma. High-K calc-alkaline granitoid magmas, derived from slab melting with inputs from the crust, were intruded at N–E and E–W fault intersections, followed by the YRB Fe–Cu–Au–Mo-deposits between 143 and 137 Ma.

The peraluminous (S-type, ilmenite-series) granites, generated by partial melting of crustal material, with their genetically-related NYCT tungsten metallogenic belt, developed in the same tectonic setting as the YRB, but from different magma source materials. During the 143–137 Ma period the asthenosphere rising along the window in the subducting slab induced melting of the overlying continental crust producing the peraluminous magma (Fig. 11a). The ascent of the fractionating volatiles-rich buoyant magma into the near-surface region resulted in exsolution of the magmatic

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Table 1

<table>
<thead>
<tr>
<th>Analyzed no.</th>
<th>Sample no.</th>
<th>Ore types</th>
<th>Weight (g)</th>
<th>Re ng/g</th>
<th>Measured</th>
<th>2σ</th>
<th>187Re ng/g</th>
<th>Measured</th>
<th>2σ</th>
<th>187Os ng/g</th>
<th>Measured</th>
<th>2σ</th>
<th>Model ages (Ma)</th>
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<tr>
<td>120605-17</td>
<td>DHT-1</td>
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<td>23</td>
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<td>DHT-13</td>
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<td>2417</td>
<td>24</td>
<td>1519</td>
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<td>DHT-7</td>
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<td>4948</td>
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<td>DHT-8</td>
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<td>0.0082</td>
<td>143.8</td>
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</table>

Note: Type 1: veinlets-disseminated ore, type 2: crypto-explosive brecciated ore, type 3: wolframite (scheelite) vein and breccia ores.

Decay constant: The ISOPLOT software of Ludwig (1999) was used to calculate the isochron age, decay constant: \( \lambda^{(187Re)} = 1.66 \times 10^{-11} \) year (Smoliar et al., 1996), uncertainties are absolute at 2σ with error on Re and 187Os concentrations and the uncertainty in the 187Re decay constant.

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Fig. 11. Proposed model showing the spatial disposition of the W deposits, related to crustal melting along NYCT and the porphyry–skarn Cu–Au–Mo deposits along the YRB (a), triggered by slab window, and the three types of tungsten ores: veinlets-disseminated, quartz–wolframite (scheelite) vein and breccia ores (b).
hydrothermal fluid resulting in strong alkali metasomatism, greisenization and silicification in the roof zones and rock mantles accompanied by, or followed by, the W-(Mo, Cu) metallic mineralization in three styles (Fig. 11b).

7. Conclusions

The recently discovered and explored Dahutang is the world’s largest tungsten ore fields. It is located south of the Middle–Lower Yangtze River Fe–Cu–Au–Mo–porphyry–skarn belt dated at 143–137 Ma. In this contribution we discuss the essential characteristics of the Dahutang deposit in terms of geology, style of mineralization, hydrothermal alteration and mineralization. We also provide new Re/Os isotopic data in molybdenite, resulting in a model age of the W mineralization ranging from 138.4 Ma to 143.8 Ma, and an isochron age of 139.18±0.97 Ma (MSWD=2.9). The very low trace Re content in molybdenite of 0.5 to 7.8 ppm in two subparallel mineralized belts along the northern margin of the Yangtze Craton that, despite the close time–space relationship and comparable setting with the YRB belt, had a different source of magmas; this was responsible for the formation of two subparallel mineralized belts with contrasting selection of ore metals.

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