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Re-Os dating of magnetite from the Shaquanzi Fe-Cu deposit, eastern Tianshan, NW China

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Magnetite separates from the Shaquanzi Fe-Cu deposit in the eastern Tianshan are used for Re-Os geochronological study. Re-Os data show that magnetite separates contain ca. 0.7 to 50.9 ppb Re and ca. 16 to 63 ppt Os. Eight samples yield a model 3 isochron age of (303 ± 12) Ma (2σ), which is within uncertainty consistent with of the Re-Os date (295±7 Ma) of associated pyrite. Tectonic evolution shows that the Late Carboniferous Aqishan-Yamansu belt was a back-arc rift. Therefore, the Re-Os age of ca. 300 Ma indicates that the Shaquanzi Fe-Cu deposit may have formed in a back-arc extensional environment and was closely related to mantle-derived magmatism. The successful application of Re-Os magnetite geochronology in the Shaquanzi Fe-Cu deposit suggests that the purity of magnetite, relatively high Re and Os contents, and the closure of Re-Os systematic are base factors for a successful Re-Os geochronology. There would be a good prospect for Re-Os geochronology for magnetite.

Re-Os isotopes, magnetite, Fe-Cu deposit, Shaquanzi, eastern Tianshan

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Numerous Fe deposits or occurrences in the Hami region of Xinjiang are distributed in the Aqishan-Yamansu belt of eastern Tianshan, including the Yamansu, Shaquanzi, Heifengshan, and Shuangfengshan Fe(-Cu) deposits. These deposits have been studied for a long time, but the genesis of them remains controversial. These deposits were thought to be skarn type because of their close association with felsic intrusions (Song 1985; Xu et al., 2010). They were also thought to be typical volcanic-hydrothermal deposits (Song et al., 1983), ore slurry eruption-injection deposits (He et al., 1994), contact metamorphic volcanogenic-sedimentary deposits (Jiang et al., 2002), and sedimentary exhalative deposits (SEDEX) (Wang et al., 2006), because the Fe(-Cu) deposits are hosted in the strata of volcanic rocks or volcanoclastic rocks. The Shaquanzi Fe-Cu deposit is a middle-sized Fe deposit along with significant copper mineralization. The geological features, tectonic setting, and ore-forming process of the deposit have been described mainly in some Chinese literature (Li et al., 1978; Song et al., 1983; Song 1985; Yan 1985; Jiang et al., 2002; Fang et al., 2006). However, the age of mineralization is not known owing to the lack of suitable minerals for dating.

Rhenium and Os are siderophile/chalcophile and enriched in sulfide minerals (e.g., molybdenite, arsenopyrite, pyrite, and chalcopyrite), and hence Re-Os isotopic systematic is a powerful tool for dating sulfide minerals (Stein et al., 1997, 2000; Arne et al., 2001; Morelli et al., 2004; Selby et al., 2009). However, studies of Re-Os systematic of magnetite are rare (Davies 2010). Magnetite commonly occurs as the main ore mineral in various types of Fe deposits, and thus Re-Os dating of magnetite may provide more

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direct mineralization age than sulfide Re-Os dating. Ore minerals are dominated by magnetite, pyrite and chalcopyrite at the Shaquanzi Fe-Cu deposit. In this study, we attempt to use Re-Os isotope to date magnetite and compare it with that of associated pyrite. The Re-Os data are also used to constrain the origin and tectonic setting of the Shaquanzi deposit. The key factors for further application of Re-Os dating of magnetite were also discussed in this paper.

1 Regional geology

The eastern Tianshan is bounded by the Xiaorequanzi to the west and the junction of Gansu Province and Xinjiang Uygur Autonomous Region to the east, covering an area of about 60000 km^2 (Figure 1). The eastern Tianshan has been an important target for mineral exploration in China (Wang et al., 2006). Several approximately east-west-trending faults separate the eastern Tianshan into four main tectonic units from north to south, the Dananhu-Tousuquan arc belt, the Kanggurtag belt, the Aqishan-Yamansu belt, and the Central Tianshan belt (Figure 1).

The Dananhu-Tousuquan arc belt, southern margin of the Tu-Ha basin, extends from Xiaorequanzi, Dananhu to Tousuquan. The arc belt is made up of the Devonian to Carboniferous island arc volcanic rocks (Yang et al., 1996). The Kanggurtag belt is composed of mylonite, tectonic lenses and breccias and considered to have formed by the deformation and metamorphism along the early extensional faults (Qin et al., 2002). The Aqishan-Yamansu belt between the Kushui and Shaquanzi faults consists of the Carboniferous volcanic and sedimentary rocks intercalated with the Permian clastic rocks (Yang et al., 1996). The Central Tianshan belt south of the Shaquanzi fault is composed of the Precambrian basement rocks of amphibolite facies, overlain by calc-alkaline basaltic andesite, volcanoclastics, minor I-type granite, and granodiorite (Yang et al., 1996). The Precambrian basement consists of gneiss, quartz schist, migmatite, and marble.

The study area, located at the eastern part of the Aqishan-Yamansu belt, is an important cluster of Fe(-Cu) deposits, including Heifengshan, Shaquanzi deposits and some Fe occurrences (Figure 2). The strata at this area include the Proterozoic central Tianshan Group, the Early Carboniferous Yamansu and Dikan'er Formations, the Early Permian Aqikebulak Formation and Cenozoic rocks. The Yamansu Formation is composed of bimodal volcanic and clastic rocks, including andesitic tuff, andesitic tuff breccia, limestone, potash-keratophyre and felsic porphyry (Yang et al., 1996). The Dikan'er Formation consists of intermediate-mafic volcanic rocks, clastic rocks, and carbonate rocks, and has a zircon U-Pb age of ca. 320 Ma (Li et al., 2011). The Aqikebulak Formation consists of basaltic to rhyolitic rocks and sandstone. The Carboniferous intrusions are widespread in the Shaquanzi area, including granite, diorite and granodiorite.

2 Deposit geology

The Shaquanzi Fe-Cu deposit is located at ca. 180 km south

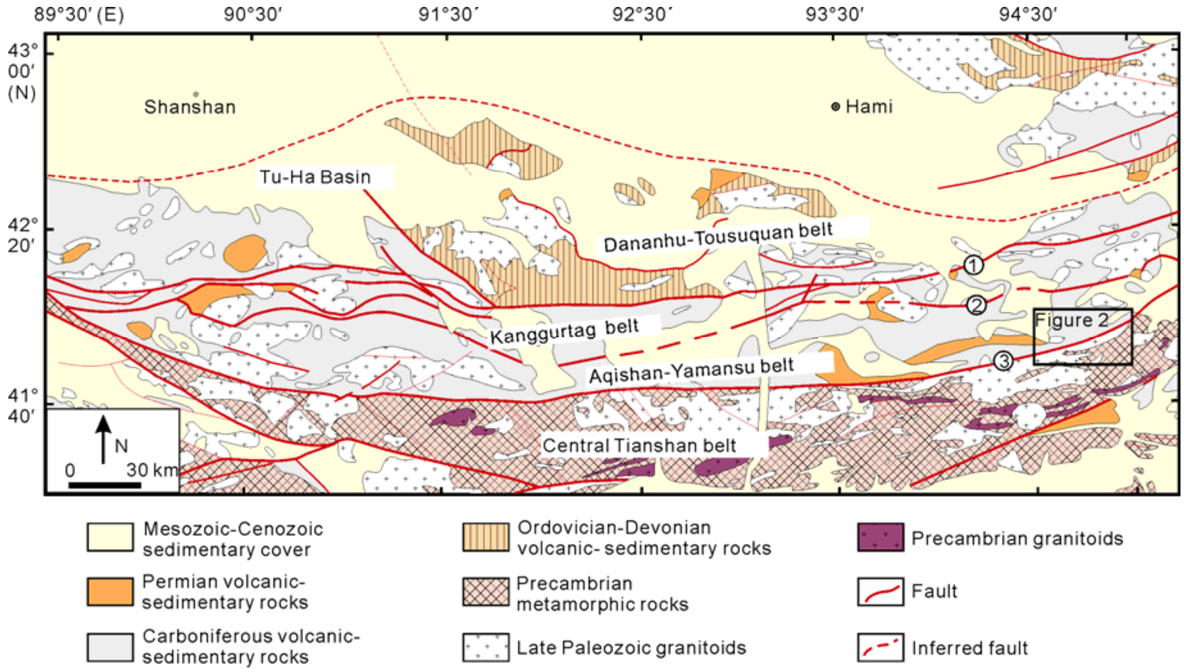

Figure 1 A simplified geological map of the eastern Tianshan (modified from 1∶1000000 Geological Map of Mineral Resources in Eastern Tianshan). Faults: ①-Kanggur fault; ②-Kushui fault; ③-Shaquanzi fault.

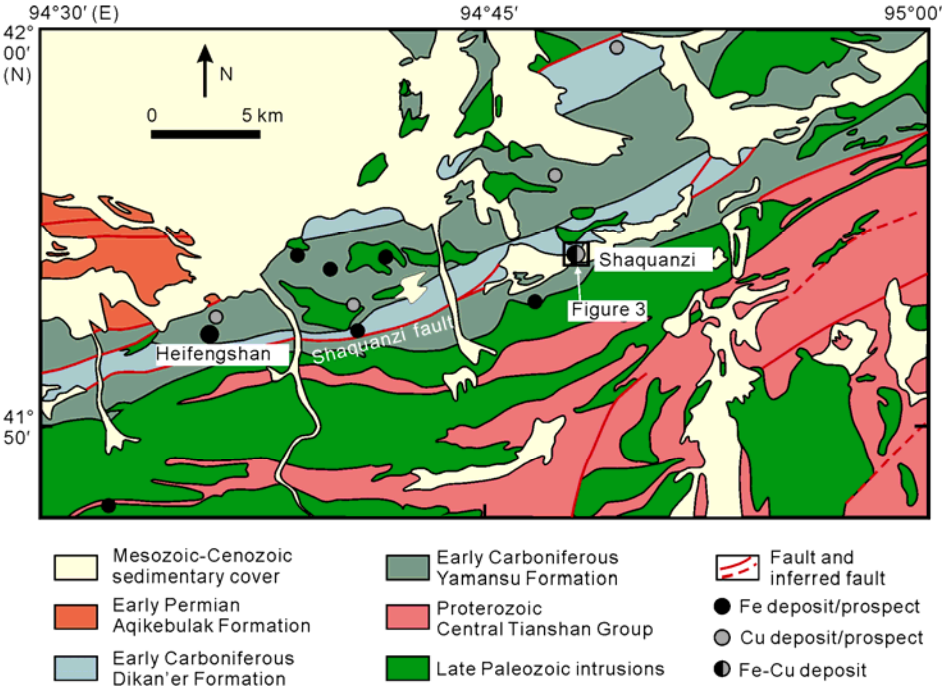

Figure 2 A sketch geological map of the Shaquanzi area (modified from 1∶200000 Geological Map of Shaquanzi area numbered K-46-23).

of Hami city and ca. 500 m north of the Shaquanzi fault (Figure 1). The Shaquanzi Fe-Cu deposit consists of ore bodies hosted in the Early Carboniferous Dikan'er Formation (Figure 3). The deposit contains Fe-Cu ores with grades of 25 wt%–36 wt% Fe and 0.5 wt%–2.3 wt% Cu (Ma et al., 1997; Yang et al., 2008a). Ore bodies are usually lens-shaped and controlled by faults. There are more than four ore bodies, which are 5–500 m in length and 2–6 m in thickness (a maximum thickness of 11.3 m). The copper-rich ore body occurs at a depth of 20–40 m, with a general length of 230 m and thickness of 2–5 m (Ma et al., 1997). It has a maximum depth of 165 m and a maximum thickness of 6.13 m (Ma et al., 1997). Extensive hydrothermal alteration includes chloritization, epidotization, carbonation, pyritization, and albitization. Ore minerals are magnetite, pyrite, and minor chalcopyrite, whereas gangue minerals include chlorite, epidote, calcite, and quartz.

3 Sample description

The ore samples are collected from the Shaquanzi Fe-Cu ore district. Two types of ores were used for separating the magnetite, including massive and disseminated ores (Figure 4). Both types of ores are composed of magnetite, pyrite, chalcopyrite, and calcite (Figure 4). Magnetite separates are prepared by magnetic separation at the Geological Service Company, Langfang of China. To ensure the purity of the magnetite separates, electron microprobe and trace element analyses of magnetite power were carried out. The detailed discussion on the purity of magnetite can be seen in the later section.

4 Analytical method

Re-Os isotopic analyses were performed in the State Key Lab of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. A detailed description of the Re-Os isotope analytical procedure is available in Qi et al. (2010). Approximately 3–5 g of magnetite powder were accurately weighted and placed in a 120 mL Carius tube. Appropriate amounts of ^{185}Re and ^{190}Os spikes and reverse aqua regia were then added. The Carius tube was sealed and then heated to 200℃ for about 24 h. After being cooled to room temperature, the Carius tube was further frozen in a refrigerator for 2 h and then opened to distill Os as OsO_4 from the matrix using an in-situ distillation equipment. To overcome the Claus effect (Frei et al., 1998), about 5 mL of H_2O_2 was added during Os distillation. Rhenium was separated from the remaining solution after Os distillation using anion exchange resin (Biorad AG 1×8, 200–400 mesh) technique as described by Qi et al. (2007). Because the large amounts of Fe^{3+} remaining in the solution will seriously lower the recovery of Re, dilution the solution to enough volume (about 30–40 mL) is necessary (Huang et al., 2012).

Re and Os isotopes were measured using a PE ELAN DRC-e ICP-MS in the Institute of Geochemistry, Chinese Academy of Sciences. Total blanks of Re and Os were 6.4 and 2.0 pg, respectively. The analytical results are monitored by molybdenite reference materials, HLP and JDC (Qi et al., 2010). Iridium was added to Re and Os-bearing solu-

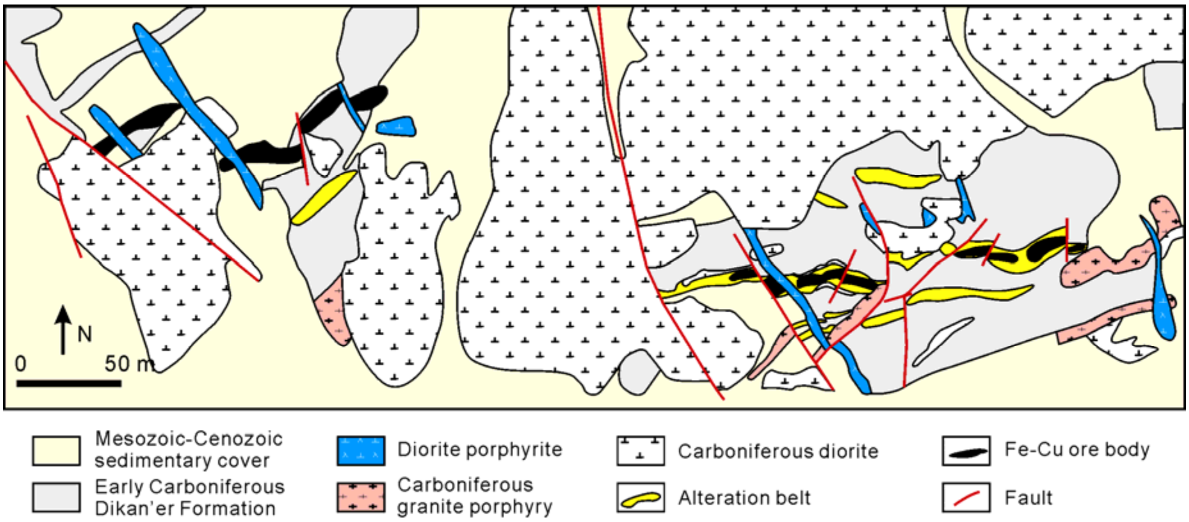

Figure 3 Geological map of the Shaquanzi Fe-Cu deposit (modified after Xu et al. (2010)).

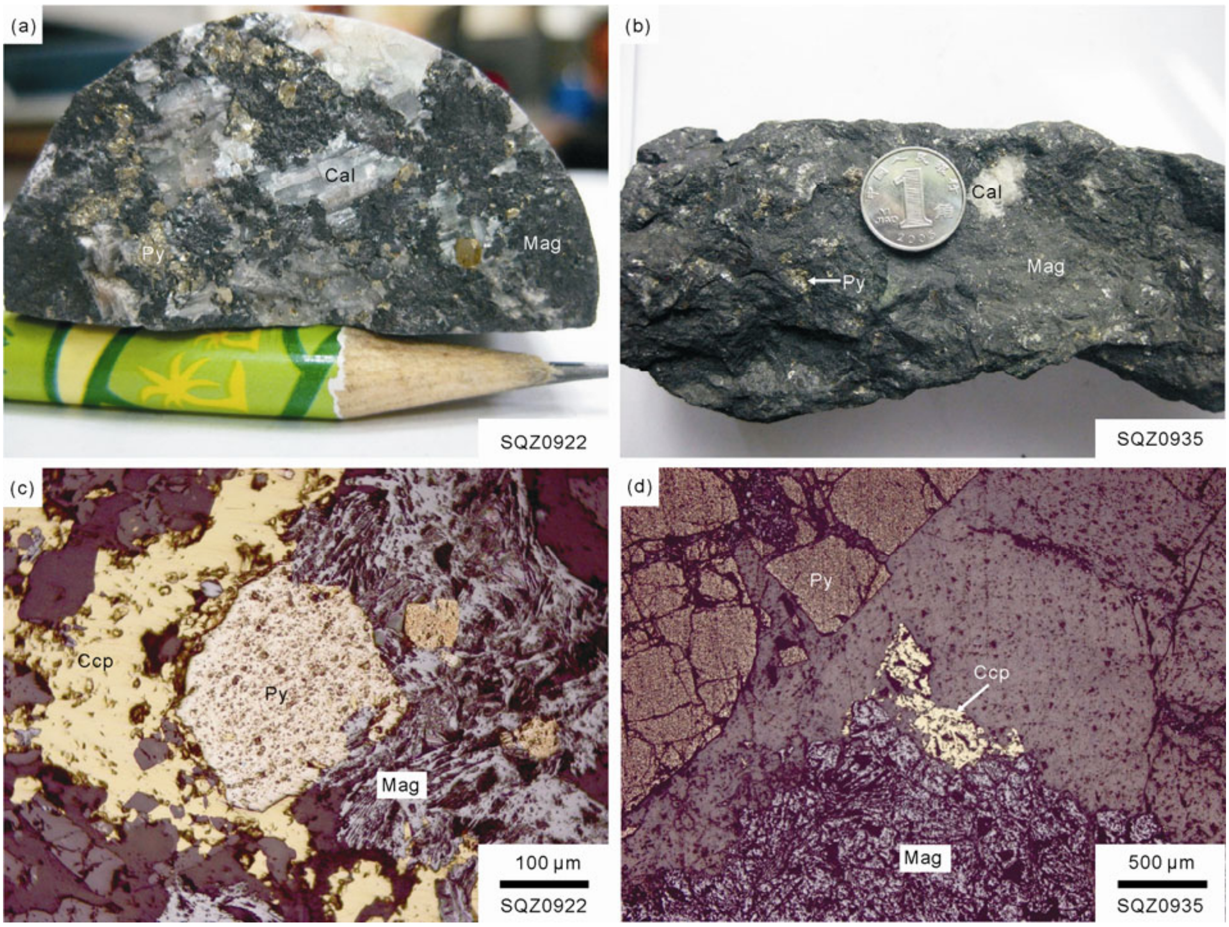

Figure 4 Photos and micrographs of the disseminated ore (SQZ0922) and massive ore (SQZ0935) from the Shaquanzi Fe-Cu deposit. Abbreviation: Mag, magnetite; Py, pyrite; Ccp, chalcopyrite; Cal, calcite.

tion for mass discrimination correction according to the method of Schoenberg et al. (2000). Absolute uncertainties are reported at a 2-sigma level and acquired by propagation of uncertainties of the blank, the ^{185}Re and ^{190}Os spike calibrations and uncertainties in Re and Os mass spectrometer measurements.

5 Analytical results

Re-Os data of magnetite from the Shaquanzi Fe-Cu deposit are listed in Table 1. Magnetite has ca. 0.7 to 50.9 ppb Re and ca. 16 to 63 ppt Os. Regression of ^{187}Re/^{188}Os and ^{187}Os/^{188}Os data by ISOPLOT software (Ludwig 2003) considering the uncertainty correlation factor (rho; Ludwig 1980) yields a model 3 isochron age of (303±12) Ma (2σ, MSWD = 2.3; Figure 5(a)). The mean standard weighted deviation (MSWD) of the isochron is close to the expected value of 2.26 (Wendt et al., 1991) and the samples with low Re/Os ratios also plot on the isochron (Figure 5(b)), indicating that the isochron age is reliable.

6 Discussion

6.1 Purity of magnetite

Because magnetite is associated with pyrite and chalcopyrite, the separated magnetite is susceptible to contamination by sulfides. Previous studies have shown that magnetite commonly contains <1 ppb Re with the highest of <10 ppb (Morgan et al., 2000; Mathur et al., 2002, 2005). However, magnetite from this study has the highest Re content of ca. 50 ppb and associated pyrite contains ca. 71.9 to 110.6 ppb Re (Table 2). Therefore, it is necessary to assess whether magnetite was contaminated by sulfides.

Two magnetite samples (SQZ0935 and SQZ0936) with the relative high Re contents are chosen for electron microprobe analyses. Energy spectrum analyses of magnetite powder were carried out by an EPMA-1600 using a beam spot of 100 μm at the Institute of Geochemistry, Chinese Academy of Sciences. The results show that magnetite is composed mainly of Fe and O with minor Mg, Al, Si, and Ca (Figure 6). Sulfur was not detected in magnetite, which indicates that there are no micron-sized sulfides in the magnetite.

Trace element compositions of magnetite and pyrite also support that conclusion. Because pyrite contains high Co, Ni, and Cu, minor pyrite in magnetite will significantly increase the contents of these elements in magnetite (Table 2). Taking the sample SQZ0932 as an example, if the purity of magnetite reaches 99% and only 1% pyrite was mixed with magnetite, Co content in magnetite would be 36.9 ppm. However, the Co content (2.09 ppm) in magnetite is obviously lower than the expected value. Moreover, ~14% pyrite addition to magnetite is needed to explain the high Re contents (10.2 ppb) in magnetite. All magnetite samples also contain very low Pb, Zn and Mo (Table 2), precluding the contamination of galena, sphalerite, and molybdenite.

Table 1 Re-Os isotopic data of magnetite from the Shaquanzi Fe-Cu deposit[a)]

Sample No.	Mass (g)	Re (ppb)	2σ	^{187}Os (ppb)	2σ	Common Os (ppb)	2σ	^{187}Re/^{188}Os	2σ	^{187}Os/^{188}Os	2σ	Rho
SQZ0927	4.9949	0.70	0.07	0.007	0.005	0.063	0.047	53	40	0.9	0.7	0.66
SQZ0925	4.9481	1.33	0.08	0.005	0.001	0.024	0.006	270	74	1.6	0.4	0.68
SQZ0922	2.9970	3.51	0.14	0.013	0.001	0.038	0.007	447	90	2.5	0.5	0.85
SQZ0924	3.0000	3.39	0.10	0.012	0.001	0.037	0.006	445	77	2.4	0.4	0.82
SQZ0933	2.9830	8.52	0.39	0.027	0.002	0.017	0.002	2397	243	11.7	1.1	0.64
SQZ0932	2.9756	10.24	0.29	0.031	0.001	0.016	0.002	3000	344	14.4	1.6	0.92
SQZ0936	2.9821	34.53	2.22	0.114	0.004	0.020	0.001	8298	780	42.9	3.1	0.63
SQZ0935	3.0313	50.87	0.92	0.168	0.003	0.032	0.001	7726	354	39.9	2.0	0.84

a) Magnetite separates SQZ0927, 25, 22, 24 are from disseminated ores and magnetite separates SQZ0933, 32, 36, 35 are from massive ores.

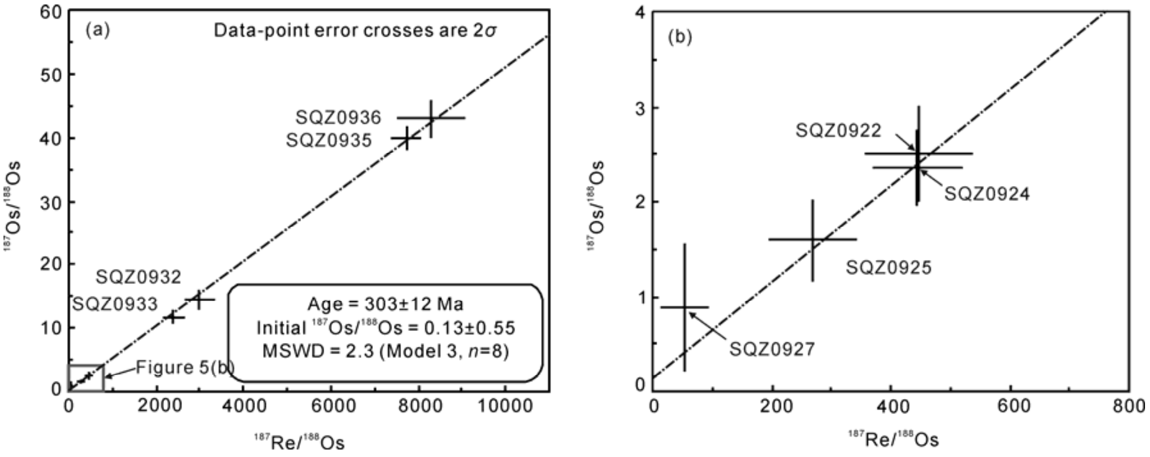

Figure 5 (a) Plot of ^{187}Re/^{188}Os against ^{187}Os/^{188}Os for eight magnetite samples; (b) the diagram of partial enlargement of the isochron.

Table 2 Trace element (ppm), Re and common Os contents (ppb) of magnetite and associated pyrite

	SQZ0922	SQZ0924	SQZ0925	SQZ0927	SQZ0932	SQZ0933	SQZ0935	SQZ0936
Co (magnetite)	4.40	2.97	3.47	5.55	2.09	6.63	17.8	11.5
Co (pyrite)		894	2875		3693	1037		
Ni (magnetite)	3.30	3.14	4.64	5.50	8.20	7.69	7.10	1.30
Ni (pyrite)		188	175		309	334		
Cu (magnetite)	14.1	28.5	15.6	15.8	13.0	33.9	106	53.3
Cu (pyrite)		644	2222		720	1194		
Zn (magnetite)	29.1	48.8	52.8	36.4	35.7	21.5	63.1	33.2
Zn (pyrite)		12.0	10.3		12.1	10.1		
Mo (magnetite)	0.56	0.72	0.53	0.99	3.81	2.08	1.17	3.22
Mo (pyrite)		0.49	0.26		2.17	11.2		
Pb (magnetite)	2.40	2.44	2.50	2.82	2.03	2.13	12.5	2.56
Pb (pyrite)		17.3	19.4		9.46	3.75		
Re (magnetite)	3.51	3.39	1.33	0.70	10.24	8.52	50.9	34.5
Re (pyrite)		116	79.4		71.9	111		
Common Os (magnetite)	0.038	0.037	0.024	0.063	0.016	0.017	0.032	0.020
Common Os (pyrite)		0.019	0.024		0.024	0.023		

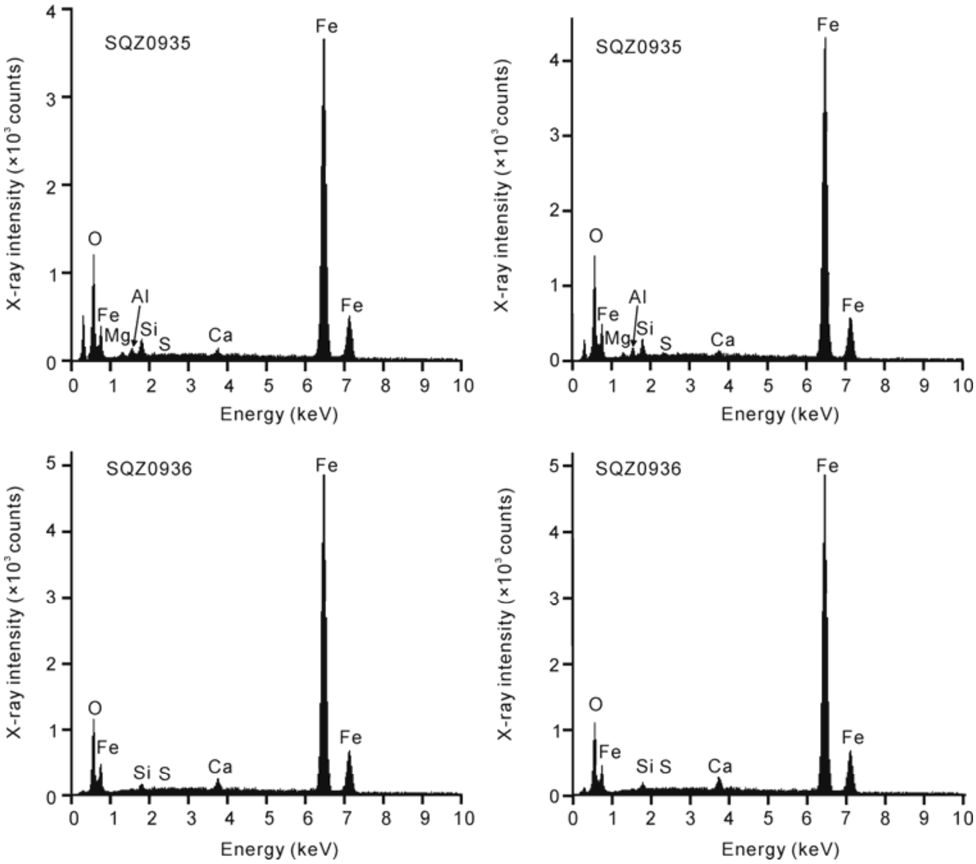

Figure 6 Energy dispersive X-ray spectrum of magnetite powder.

Therefore, there is no addition of sulfides to magnetite, and Re in magnetite is derived from itself.

6.2 Significances of Re and Os contents

Magnetite from the Shaquanzi Fe-Cu deposit has variable Re contents that are significantly higher than the reported values (most <1 ppb) (Table 3). The Os contents in magnetite are similar to those in magnetite from other Fe deposits (Table 3). Morgan et al. (2000) show that magnetite from the Fe-Ti-V oxide and Fe-Cu-Ni sulfide deposit at northeast Poland has 0.4–1.5 ppb Re, and explain variations of Re

Table 3 Rhenium and Os contents of magnetite from various geological environments

Occurrences	Re (ppb)	Os (ppt)	Isochron age (Ma)	Ref.
Flood basalt	0.8–17	8–313	177.3	Brauns et al. (2000)
Flood basalt	0.9–7	47–690	175.4	Zhou et al. (2005)
Flood basalt	0.5–3	39–670		Chesley et al. (1999)
Volcanics	0.1–1	7–169		Hart et al. (2002)
Volcanics	0.3–1	2.6–44		Hart et al. (2003)
Kimberlite and related rocks	0.1–0.8	35–8000	2025	Graham et al. (2004)
Impact melt rock	3.2–3.6	30–33	215	Davies (2010)
Altered BIF	0.1–3.4	10–48000		Ripley et al. (2008)
Fe-Ti-V oxide and Fe-Cu-Ni sulfide deposits	0.3–1.5	36–114	1559	Morgan et al. (2000)
Fe oxide copper (gold) deposit	0.3–6	6–76	110	Mathur et al. (2002)
Cu-Au deposit	1.5–2	6–51		Mathur et al. (2005)
Fe-Ti oxide deposit	0.04–0.7	1.8–24		Davies (2010)
Fe-Cu deposit	0.7–51	16–63	303	This study

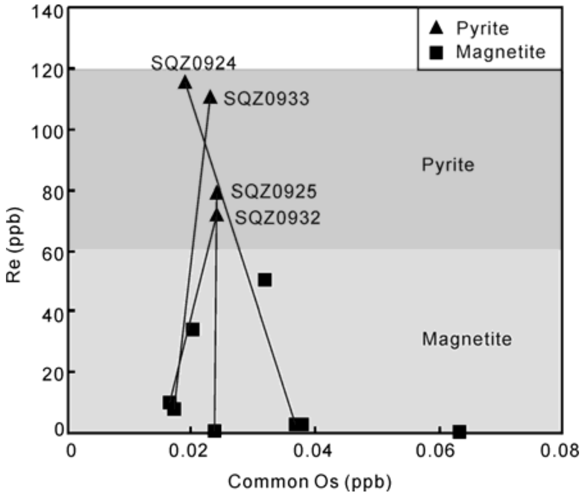

Figure 7 Correlation diagram of Re and common Os contents (Tie lines represent associated minerals).

contents to be the contaminant of sulfides at submillimeter. However, trace element and electron microprobe analyses demonstrate that the wide variations of Re contents in magnetite from the Shaquanzi deposit cannot be due to the contamination of micron-sized sulfides. The variations of Re contents may indicate the heterogeneous fluid compositions. Rhenium contents in magnetite are obviously lower than those in associated pyrite (Table 2 and Figure 7), indicating that Re is more incompatible in magnetite than associated pyrite. The behaviors of Re are the same as those in magmatic deposit (Morgan et al., 2000). There are no differences of common Os between magnetite and pyrite (Figure 7). Very low Os contents in both magnetite and pyrite indicate that Os shows similar incompatible behaviors in oxides and sulfides. Because we do not know the distribution coefficients between fluids and magnetite and between fluids and sulfide, we cannot calculate original concentrations of Re and Os in the ore-forming fluids.

In magmatic system, Re and Os contents in magnetite are controlled by the original Re and Os compositions of melts and the distribution coefficients (Righter et al., 1998). The principle should be also applicable in the hydrothermal system. Table 1 shows that magnetite from different ore types has different Re contents. Moreover, chondrite-normalized (Sun et al., 1989) trace element patterns show that magnetite from different ore types also shows different trace element behaviors (Figure 8). The disseminated ores with low Re contents (<5 ppb) show the relative depletion of Pb, whereas the massive ores with high Re contents (>8 ppb) show the relative enrichment of Pb (Figure 8). Lead is thiophilic and is commonly partitioned into sulfides or occurs as galena at the late stage of hydrothermal evolution. The different Pb contents in magnetite indicate magnetite from the massive ores may have formed earlier than those from the disseminated ores. In the early ore-forming stage, magnetite can trap amounts of Re due to the lack of sulfides, whereas most Re would be partitioned into sulfides due to the chalcophile behavior of Re in the late stage. Therefore, the variations of Re in magnetite from the Shaquanzi Fe-Cu deposit probably result from the evolution of ore-forming fluids.

6.3 The mineralization age and geological significances

Magnetite from the Shaquanzi Fe-Cu deposit yields an isochron age of 303±12 Ma, with the initial Os isotopic composition of 0.13±0.55. There is no correlation of Re with common Os (Figure 7), indicating that ^{187}Os is derived from the radioactive decay of ^{187}Re and no Os was added before the Re-Os system started. The Re-Os age of magnetite is within uncertainty consistent with the Re-Os age of pyrite (295±7 Ma)1), indicating that the ages are reliable. The ca. 300 Ma age indicates that the Shaquanzi Fe deposit

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1) Huang X W, Qi L, Gao, J F, et al. First reliable Re-Os ages of pyrite and stable isotope compositions of Fe(-Cu) deposits in the Hami region, Eastern Tianshan Orogenic Belt, NW China. Resour Geol. (in press)

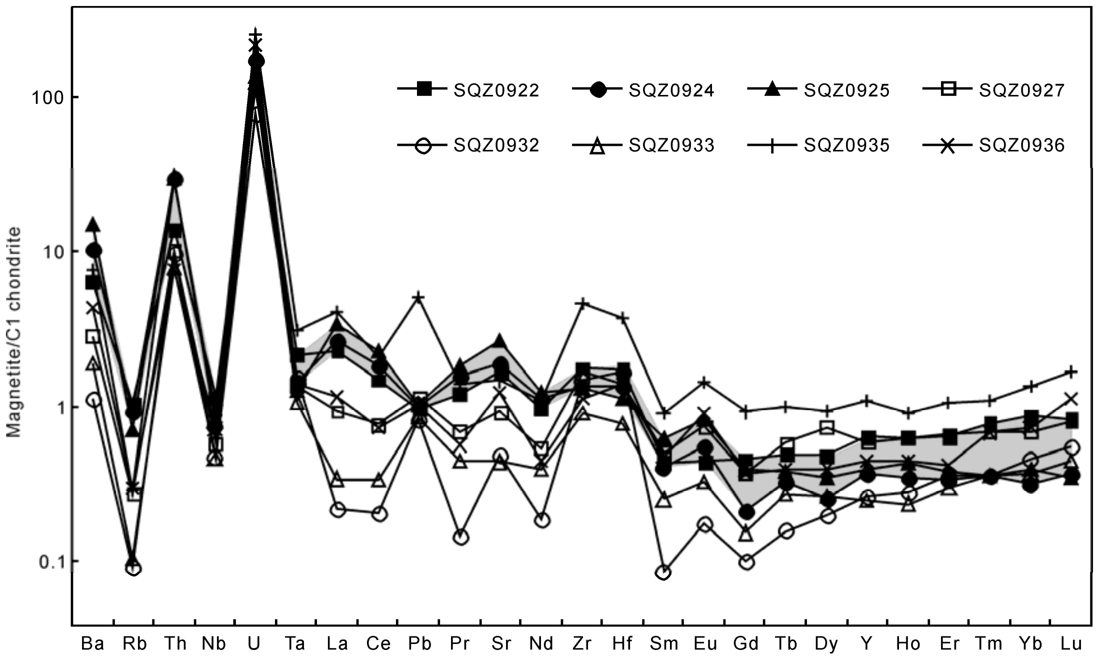

Figure 8 Chondrite-normalized trace element patterns of magnetite. The grey field represents the range of chondrite-normalized values of SQZ0922, SQZ0924 and SQZ0925; normalization values are after Sun et al. (1989).

has formed in the Late Carboniferous.

The Re-Os age of magnetite has important implications for the origin of the Shaquanzi Fe-Cu deposit because it provides direct mineralization age. The genesis of the deposit was debated and it was considered as skarn type deposits (Song 1985; Xu et al., 2010), volcanic-hydrothermal deposits (Song et al., 1983), ore slurry eruption-injection deposits (He et al., 1994), contact metamorphic volcanogenic-sedimentary deposits (Jiang et al., 2002), and sedimentary exhalative deposits (SEDEX) (Wang et al., 2006). The Re-Os age is significantly older than the age of host Dikan'er Formation (320±1.2 Ma) (Li et al., 2011) and sulfides are dominated by pyrite and chalcopyrite rather than Pb/Zn sulfides, precluding the sedimentary exhalative origin. The δ^{34}S values of pyrite range from 1.2‰ to 4.7‰ (average 2.8‰)1), indicating that sulfur was derived from the mantle or magma. Therefore, the formation of the deposit was likely related to the ca. 300 Ma mantle-derived magmatism. Due to lack of the age of intrusions, discriminating the types of the deposit requires the further study.

The Re-Os age also has important significances for the regional mineralization. Several models have been proposed for the regional mineralization of the eastern Tianshan (Feng et al., 2002; Mao et al., 2002, 2005; Wang et al., 2006; Zhang et al., 2008), but the ore-forming processes of the Fe(-Cu) deposits were not sufficiently discussed. Mineralization in the eastern Tianshan occurred mainly in the following four stages. From the Devonian to Early Carboniferous, the North Tianshan ocean was subducted beneath the Dananhu-Tousuquan (Ordovician-Silurian?) island arc, forming the Devonian arc volcanic rocks and the Kanggurtag accretionary wedge. From the Early to Middle Carboniferous, N-dipping subduction beneath the Dananhu-Tousuquan arc may have caused the back-arc extension, forming the Aqishan-Yamansu rift zone. Large volumes of the Carboniferous intra-plate rift-related volcanic rocks with ages of ca. 354–319 Ma were produced in the Aqishan-Yamansu zone (Xiao et al., 1992; Qin et al., 2002; Xia et al., 2003, 2008). The arc magmatism has produced porphyry Cu deposits, including the well-known Tuwu and Yandong deposits (Rui et al., 2002; Chen et al., 2005; Zhang et al., 2006). During the Late Carboniferous, continent-continent and arc-continent collisions resulted in ductile deformation and thrusting (Zhang et al., 2008). Associated with this was the formation of orogenic-type gold deposits. Associated with this event was also the emplacement of igneous intrusions in the Aqishan-Yamansu rift belt and the northern margin of the Central Tianshan belt. Hydrothermal activities associated with this magmatism resulted in extensive alteration of the Carboniferous volcanic rocks and volcanoclastic rocks and the formation of the Fe(-Cu) deposits hosted in the Carboniferous rift-related volcanic rocks along major faults in the eastern Tianshan. From the Latest Carboniferous to Permian, post-collisional extensional events are dominant in the eastern Tianshan. Numerous mafic-ultramafic intrusions (300–270 Ma) (Qin et al., 2003; Han et al., 2004; Zhou et al., 2004; Wu et al., 2005) were emplaced along the eastern section of the Kanggurtag belt, resulting in the formation of magmatic Cu-Ni sulfide and Fe-Ti oxide deposits.

6.4 The further application of magnetite Re-Os systematic

Eight magnetite samples from the Shaquanzi deposit constitute a well-fitted isochron, indicating the Re-Os systematic of magnetite may keep closed. The successful application of Re-Os dating of magnetite indicates a promising prospect of the dating method. There are very limited studies of Re-Os dating of magnetite mainly because of low Re and Os contents in magnetite (Table 3). Three factors may control the successful application of Re-Os systematic of magnetite, including the purity of magnetite, Re and Os contents in magnetite, and the closure of Re-Os system of magnetite. Morgan et al. (2000) suggest that variations in the Re and Os contents and ratios of magnetite grains in the Suwaøki Anorthosite Massif in Poland may be due to micron-sized inclusions of sulfides. If this were the case, the isochron age would represent the age of sulfides rather magnetite. The same problem may also exist in the studies of Mathur et al. (2002) and Yang et al. (2008b). These studies assumed that Re and Os isotopes in both magnetite and sulfides behave in the same manner and acquired the erroneous isochron ages. Therefore, the purity of magnetite is the prerequisite for Re-Os dating of magnetite.

High Re and Os contents in magnetite are also very important. Rhenium and Os contents in magnetite depend largely on the nature and compositions of ore-forming fluids. Xiong et al. (1999) show that hard ligands such as F^-, OH^-, O^{2-}, Cl^- are important in the transport of Re during geological processes at elevated temperatures because hard acids prefer to form complexes with hard bases. If Re occurs as Re^{4+} in oxide phase such as magnetite, changes in oxygen fugacity will not induce the precipitation or dissolution of the Re-bearing phase. On the other hand, if the Re-bearing phase is a sulfide such as molybdenite, then oxidation-reduction reactions involving sulfur will have a significant effect on Re solubility. Xiong et al. (2002) demonstrate that the solubility of ReS_2 is about two orders of magnitude less than that of ReO_2 under supercritical conditions. The study also suggests that the mixing of an oxidized, Re-bearing solution and a solution with reduced sulfur is one of the most effective mechanisms for deposition of Re.

It is significant that the Re-Os systematic keeps closed after the formation of magnetite. Mathur et al. (2002) suggest that the lack of age information from the magnetite at Chile Fe deposit is attributable to leaching of Re and Os from surrounding sediments during mineralization. Naslund et al. (2003) provide another explanation that the lack of age information could be due to multiple generations of magnetite rather than Re-Os disturbances from hydrothermal alteration. Peucker-Ehrenbrink et al. (1998) show that oxidative weathering of magnetite mobilizes Os, but did not evaluate the impact of hydrothermal fluid interaction on the isotope system. The closure temperature of the Re-Os system of magnetite remains controversial. For example, Yang et al. (2008b) suggest a low closure temperature of ca. 500°C and the Re-Os system will be reset due to Os diffusion. Lambert et al. (2000) also show that Re-Os systematic of magnetite appears to have been reset by a Grenville event but do not discuss the possible temperature and pressure conditions required for resetting. Davies (2010) suggests that magnetite has a low closure temperature to Os diffusion (ca. 200–300°C) and is therefore not suitable for dating the crystallization of systems that have cooled slowly or have been metamorphosed.

In summary, the purity of magnetite, the high contents of Re and Os in magnetite, and the closure of Re-Os system after the formation of magnetite are very important for successful Re-Os dating of magnetite.

7 Conclusions

Re-Os dating of magnetite was attempted to constrain the mineralization time of the Shaquanzi Fe-Cu deposit. The Re-Os age of magnetite is within uncertainty consistent with that of associated pyrite, indicating the age is reliable and the deposit has formed in the Late Carboniferous. Combined with tectonic evolution, the deposit was considered to have formed in back-arc extensional environment. The successful application of magnetite Re-Os method in the Shaquanzi deposit indicates that Re-Os analysis of magnetite is also capable of providing reliable ages if no other technique is available.

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