He–Ar isotope geochemistry of iron and gold deposits reveals heterogeneous lithospheric destruction in the North China Craton

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Abstract

The North China Craton (NCC) provides a classic example for extensive destruction of the cratonic lithosphere. The Mesozoic magmatism which contributed to the decratonization of the NCC was also accompanied by the formation of a variety of mineral deposits. In order to gain further insights into the cratonic destruction process, typical iron and gold deposits are investigated here. Helium–argon isotopic data on pyrite, from typical skarn iron deposits of the Beiminghe and Fushan in the Han-Xing district of the central NCC, and the Linglong and Canzhuang gold deposits in the Jiaodong district in the eastern NCC, are presented in this paper. The He/He, 40Ar/39Ar and 40Ar/36Ar ratios show generally uniform patterns within the individual deposits and reveal a complex evolutionary history of the ore-forming fluids with varying degree of crust–mantle interaction. The ore-forming fluids associated with the gold regionalization at the Jiaodong mine have higher content of fluids of mantle origin with mantle helium ranging from 1.24% to 18.02% (average 6.73%; N = 18). In contrast, the ore-forming fluids related to the iron ore deposits contain less mantle contribution with mantle helium ranging from 0.12% to 4.96% (average 1.29%; N = 10). Our results suggest complex and heterogeneous crust–mantle processes associated with the magmatism and metallogeny, where the lithosphere of the eastern NCC was subjected to more extensive thinning and destruction as compared with that in the western part, consistent with the observations from geophysical studies in the region. Our study demonstrates that fluids associated with the Mesozoic metallogenic processes in the NCC provide useful insights into the geodynamics of destruction and refertilization of the cratonic lithosphere.

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1. Introduction

The North China Craton (NCC), one of the major Precambrian nuclei in Asia, offers a classic example for the erosion and refertilization of the cratonic lithosphere since the Mesozoic. Although several investigations employing geological, geochemical, geochronological and geophysical tools have addressed the decratonization process, many issues relating to the temporal and spatial scale, as well as the mechanism and geodynamic implications of the destruction process remain equivocal (Zhu, 2007; Zhu et al., 2009; Chen et al., 2009; Gao et al., 2009; Xu and Zhao, 2009; Zhang, 2009a,b; 2012; Zhao et al., 2009; Zheng and Wu, 2009; Zheng, 2009, 2012; Santosh, 2010; Li et al., 2010, 2013; Liu et al., 2011; Gao et al., 2012; Zhai and Santosh, 2011; Zhang et al., 2012; Kusky, 2011; Peng et al., 2011; Trap et al., 2011; Zhang et al., 2011a,b, 2013; Tang et al., 2013; Xu et al., 2013). Based on the temporal and spatial distribution of magmatic activity in the NCC, Xu (2004a,b, 2006a,b, 2009a,b) suggested that the destruction event commenced in the late Carboniferous to the late Triassic, with a peak during the late Jurassic–Cretaceous, and culminated in the late Cretaceous to the early Cenozoic. The extensive destruction of the sub-continental mantle lithosphere beneath the NCC is also manifested in large-scale lithospheric thinning (“uprooting”) (Yang et al., 2003; Zhang, 2009a,b). Geophysical studies, combined with geological interpretations show significant difference in the scale and intensity of decratonization between the Eastern and Western Blocks of the NCC (Zhao et al., 2000, 2001; Chen et al., 2010; Santosh, 2010). Whereas the Eastern Block experienced extensive lithospheric thinning, the ‘tectosphere’ beneath the Western Block is largely well-preserved since its formation in the Archean (Santosh, 2010). The Xing’an-Taibei gravity lineament located along the central NCC, separating the Eastern and Western Blocks, broadly coincides with the Central Orogenic Belt or the...
Trans-North China Orogen (TNCO) that welds the two blocks (Menzies and Xu, 1998; Kusky and Li, 2003; Xu, 2006b; Zhao et al., 2001; Santosh, 2010). See Fig. 1.

The peak period of the cratonic destruction is remarkably contemporaneous with the timing of formation of endogenous metallic ore deposits in the eastern China (e.g., Mao et al., 2000, 2005; Zheng and Wu, 2009). During this period, the large-scale tectonomagmatic activities in the central and eastern NCC were accompanied by the formation of numerous economic-grade metallic deposits (Yang et al., 2003; Zhai et al., 2004; Zheng and Wu, 2009; Xu et al., 2009a,b; Li and Santosh, 2013; Li et al., 2012, 2013; Shen et al., 2013). The concentrated distribution of the ore deposits in some areas has led to the definition of specific ‘mineralization districts’, such as the Han-Xing iron deposit district in the southern Taihang Mountains in the central NCC (Shen et al., 2013), and the Jiaodong gold deposit district in the eastern NCC (Yang et al., 2013). Systematic studies on these ore deposits with specific relevance to their genetic history and geodynamic setting provide important insights into the craton destruction process in the NCC (Zhu and Zheng, 2009; Zheng and Wu, 2009; Li et al., 2012, 2013; Shen et al., 2013; Yang et al., 2013).

As is well known, pyrite is a common mineral in most of the endogenous metal deposits (Hilton et al., 1993; Hu, 1997). The mineral has very low contents of radioactive elements such as uranium, thorium, and potassium. Therefore, the He–Ar isotope system in pyrite would not be disturbed by radioactive decay, by which the original isotopic composition of ore-forming fluids can be preserved. Experimental studies (e.g., Baptiste and Fougute, 1996) have shown that the He–Ar isotope of fluid inclusions in pyrite is an important record of the mechanism of ore formation and the geodynamic setting.

In this study, we measured the helium–argon isotopic compositions of pyrite grains from the Han-Xing iron deposits and Jiaodong gold deposits from the central and eastern NCC respectively, aiming at tracing the origin of the ore-forming fluids, identifying the affinity between the mineralization and cratonic destruction, and in constraining the temporal and spatial implications of the cratonic destruction in the NCC.

2. Geological setting

The NCC is composed of the Western Block and the Eastern Block separated by the Tran-North China Orogen (Fig. 1, Zhao et al., 2000, 2001; Santosh, 2010; Zhao and Zhai, 2012). Whereas the major crustal growth in the NCC occurred during the Neoproterozoic (e.g., Zhai and Santosh, 2011; Wang and Liu, 2012), the timing of assembly between the Eastern and the Western Blocks, the two major blocks within the NCC is debated (e.g., Kusky, 2011). Recent studies combining geological and geophysical data show that the final cratonization in the NCC occurred through double-sided subduction in the Paleoproterozoic when the Yinshan and Ordos Blocks assembled along the Inner Mongolia Suture Zone to construct the Western Block, the unified Western Block was sutured with the Eastern Block along the Central Orogenic Belt (Santosh, 2010; Zhai and Santosh, 2011). The deep seismic investigations have clearly shown that the Lithosphere–Asthenosphere Boundary (LAB) beneath the NCC extends to over 250 km depth beneath the Western Block, albeit is at a considerably shallower depth beneath the Eastern Block, suggesting extensive erosion of the cratonic keel (Zhu, 2007; Chen et al., 2009).

2.1. Geological background of the southern Taihang Mountain

The southern Taihang Mountains (TM) are located in the southern middle segment of the TNCO (Fig. 1). The Cambrian–Ordovician carbonate sedimentary rocks and the Carboniferous–Permian clastic rocks are the two major rock types exposed in this region. Minor volumes of the Archean basement rocks including the TTG (tonalite–trondhjemite–granodiorite) gneisses and amphibolites, together with the Proterozoic low-grade metamorphic clastic rocks...
are also exposed. The major magmatic phases in the region are dominated by intermediate–mafic and alkaline intrusive complexes emplaced in the middle and late Mesozoic (Peng et al., 2004; Chen et al., 2005; Zhou and Chen, 2005; Shen et al., 2013). These include the Fushan monzonite–diorite complex formed at 125–137 Ma (Peng et al., 2004; Wang et al., 2006; Shen et al., 2013), the Hongshan syenite complex formed at 109–137 Ma (Liu and Shi, 1998; Zhou and Chen, 2005; Li, 1998; Zhou et al., 2007a,b; Liu et al., 2009; Shen et al., 2013; Zheng et al., 2007a,b; Liu et al., 2009; Shen et al., 2013). These complexes emplaced in the middle and late Mesozoic (Peng et al., 2004; Chen et al., 2005; Zhou and Chen, 2005; Chen et al., 2006). The intrusion of the magmatic units into the Ordovician carbonate sedimentary rocks has resulted in contact metamorphism, generating many skarn-type iron deposits that are mainly distributed in the Handan and Xingtai districts in the Hebei province. These skarn-type iron deposits in the southern Taihang Mountains based on investigations of the Beiminghe, the Fushan and the Xishimen deposits. The results show homogenization temperature of the fluid inclusions in diopside–garnet, epidote and calcite as 204–557 °C, 246–398 °C and 89–389 °C, respectively. The fluid inclusion pressure estimates for skarn formation as estimated from diopside–garnet, epidote and calcite show wide range of 52–130 MPa, 35–48 MPa and 12–25 MPa. The decrepitation temperature of inclusions in magnetite also shows a wide range of 258–560 °C.

The skarn and ore minerals in the iron deposits in the southern TM region show a complex assemblage (Shen et al., 2013). The dominant skarn minerals are diopside, sahlite, andradite and phlogopite, and second are amphibole, chlorite, albite, quartz, sericite, calcite, epidote, sphene, and apatite, among the minerals. Importantly, magnetite and pyrite are the dominant metallic minerals, together with minor hematite, maghemite, chalcopyrite and pyrrhotite. Field evidence and petrographic observation indicate four stages of skarn formation: (1) the skarn stage: diopside + sahlite + andradite + albite + phlogopite + amphibole + chlorite + epidote + magnetite, (2) the oxide stage: magnetite + epidote + quartz + phlogopite, (3) the sulfide stage: pyrite + chalcopyrite + pyrrhotite + chlorite + calcite + quartz, and (4) the supergene stage: hematite + malachite + limonite + quartz + calcite.

Field investigation and microscope observation showed that a substantial volume of magnetite as the principal iron ore mineral was formed during the oxide stage, whereas only minor magnetite formed in the skarn and sulfide stages. The pyrite as the representative sulfide phase occurs as disseminations, and although most abundant in the sulfide stage, its formation began at the end of oxide stage. Chlorite commonly occurs as an alteration mineral during the main mineralization stage. Previous studies (Zheng et al., 2007a; Wang et al., 2010; Shen et al., 2013) have also inferred a similar paragenetic history.

The pyrite in the Beiminghe and the Fushan iron deposits were formed in the sulfide-stage, later than the skarn minerals and magnetite. In this study, the pyrite grains collected from the southern TM region were of the sulfide-stage.

2.2. Geological background of the jiaodong region

The Jiaodong region is situated in the southeastern margin of the NCC, proximal to the NNE trending Tan-Lu Fault (TLF) occurring to the west (see Fig. 1). The TLF is one of the world's largest continental strike-slip faults, and cuts across the Eastern Block of the NCC (Xu et al., 1987; Wang and Mo, 1995). Supracrustal rocks in this region are composed of metamorphosed Precambrian crystalline sequences and Cretaceous to Cenozoic sedimentary and volcanic successions (Zhu, 1980; Li et al., 1993). The Precambrian sequences include the upper Archaean Jiaodong Group, the lower Proterozoic Fenzishan Group and the upper Proterozoic Penglai Group. Among which, the Jiaodong Group consists of mafic to felsic volcanic and sedimentary rocks (Qiu, 1989). The Proterozoic Fenzishan and the Penglai Groups consist of low-grade metasedimentary rocks lying unconformably on the Jiaodong Group. According to previous studies (e.g., Zhu, 1980; Qiu and Liu, 1988), two main phases of deformation occurred in the region during the Mesozoic, with the first phase of NW–SE oblique compression producing prominent NNE to NE trending brittle–ductile shear zones with sinistral oblique reverse movements, followed by reactivation,
involving the development of brittle structures accompanied by hydrothermal alteration and gold mineralization (Fig. 3).

Plutonic rocks emplaced within the Jiaodong Group have been traditionally divided into three major granitoid suites. Previous studies (Sang, 1984, 1986; Qiu and Liu, 1988; Qiu, 1990; Sang and You, 1992) based on petrography, geochemistry and isotopes have suggested that all the three granitoid suites were derived from the partial melting of different supracrustal rocks of the late Archaean Jiaodong Group at deep crustal levels. But recent research (Tan et al., 2012) shows that these suites include mantle-derived granitoids or alkaline rocks, crustal S-type granite–granodiorites and granodiorites originated through crust–mantle mixing. The mantle-derived plutonic rocks such as the Xingjia, the Jiazishan and the Chashan mostly intruded from 225 to 205 Ma (Guo et al., 2005; Yang et al., 2005), correlating with the timing of collision between the NCC and the Yangtze craton during the middle–late Triassic (Xu, 2006a; Yang et al., 2007). These intrusions are dominated by quartz syenite, pyroxene syenite and alkali gabbro. The S-type granitoids, such as the Linglong–Luanjiahe, the Wendeng and the Kunyushan suites comprise medium-grained metaluminous rocks including biotite–granite, granodiorite and monzonite. These intrusives are dated as 160–150 Ma (Miao et al., 1997; Guo et al., 2005). The granitoids with mixed crust–mantle signature intruded extensively in the Jiaobei terrain region (Zhang and Zhang, 2007), where the Guojialing, Yashan, Sanfoshan, Haiyang, Weideshan, Laoshan and the Yuangezhuang intrusions to be of 130–105 Ma correlated with the gold metallogeny.

The timing of gold mineralization as established from previous studies (Li et al., 1993, 2006) ranges from 123 Ma to 114 Ma, with the Guojialing, Yashan, Sanfoshan, Haiyang, Weideshan, Laoshan and the Yuangezhuang intrusions to be of 130–105 Ma correlated with the gold metallogeny.

In the Jiaodong region, most of the gold deposits are vein-type and include mainly two categories: the quartz vein type and the fracture alteration type. The ore minerals include native gold, electrum, pyrite, chalcopyrite, galena, sphalerite, siderite, specular-hematite, magnetite, hematite, pyrrhotite, chalcocite, minor native copper, native silver, and hessite. The gangue minerals include quartz, sericite, potash-feldspar, calcite, chlorite, monazite, epidote, dolomite, ankerite, and barite. The mineral assemblages associated with the gold mineralization can be grouped into four stages based on our field investigations and petrographic studies. The first stage is characterized by pyrite + quartz, the second stage by native-gold + quartz + pyrite, the third stage by native-gold + polymetallic sulfides, and the fourth stage by pyrite–quartz–carbonate. Our results are consistent with the previous studies (Chen et al., 1996, 2012; Li et al., 1996; Liu et al., 1999; Fan et al., 2003; Zhou et al., 2011; Yang et al., 2013) in this area.

Although the four stages mentioned above can be identified in the vein-type deposits, these, particularly the first three stages, are not clearly visible in the alteration-type deposits. The second and the third stages, which represent the main mineralized stage accompanied with abundant gold precipitation (Yang et al., 2013), are commonly characterized by fine grained pyrite, and the third stage is characterized by polymetallic sulfide such as chalcopyrite, galena, sphalerite and other minerals in both types of deposits. The carbonate veins, which represent the latest stage of the hydrothermal activity during the metallogenic event, always crosscut the main mineralization.

The pyrite crystals in the Linglong and the Canzhuang gold deposits were formed throughout the mineralization process although the major concentration in the second and the third stage. In this study, the pyrite grains of the Jiaodong region were collected from the main mineralization stage (the second and the third stage).

Estimates on the gold ore formation show mainly medium to low temperatures, and can be divided into the early stage, middle stage (also called main ore-forming stage), and later stage in the Jiaodong region. Based on the investigations in a number of deposits such as the Sanshandao, Jiaojia, Linglong, Jinling, Dazhuangzi, and few others, Xia (2003) recorded a temperature range for the early stage as 320–280 °C, main ore-forming stage as 280–220 °C, and the late stage as 220–140 °C. The pressures estimated for the main ore-forming stage are in the range of 40–60 MPa. However, another study by Shen (2006) showed that the temperature range is much wider than the above, with the early ore-forming stage at...
400–300 °C, main ore-forming stage at 300–200 °C, and the late stage at 200–100 °C.

3. Sampling and analyses

3.1. Fluid inclusion studies

Fluid inclusion microthermometry was performed on the samples from the four representative deposits associated with the different stages. We studied inclusions in diopside, andradite, epidote, calcite, magnetite, and pyrite of the skarn iron deposits of the southern Taihang Mountains, and in quartz and pyrite of the gold deposit of the Jiaodong region. The homogenization temperature measurements were performed using the Linkman THMS G 600 heating-freezing stage (from –196 °C to 600 °C) at the Mineral Typomorphism Laboratory, China University of Geosciences (Beijing). The precision of temperature measurements is about ±0.1 °C on the cooling runs and ±2 °C on the heating runs. The heating/freezing rate is generally 0.2–5 °C/min, but reduced to less than 0.2 °C/min near the phase transformation.

The decrepitation temperature studies were conducted on the fluid inclusions in magnetite grains and pyrite grains of the skarn iron deposit in the southern Taihang Mountains, and pyrite grains of the gold deposit in the Jiaodong region. The samples were analyzed using the DT-5 decrepitation instrument at the Institute of Geology and Geophysics, Chinese Academy of Sciences.

3.2. Stable isotope studies

In this study, 20 pyrite samples from four representative deposits and gold deposits were analyzed (Fig. 1). The Beiminghe iron deposit (BMH, E114°07’30”, N36°45’00”) and the Fushan Iron deposit (FS, E113°46’45”, N36°42’15”) are representatives of large skarn-type iron deposits in the Han-Xing region, the central NCC. Five samples from each of these deposits were analyzed. Among these, samples B-110-6-3, B-230-2-3, B-230-2-5, B-245-3, and B-245-5 were collected from the Beiminghe iron deposit and samples F003-3, F004-4, F006-1, F008-3, and F024-1 were from the Fushan iron deposit. The Linglong gold deposit (LL, E120°31’30”, N37°28’40”) and the Canzhuang gold deposit (CZ, E120°10’00”, N37°26’00”) are representative large gold deposits in the northern Jiaodong gold district. Five samples from each of the Linglong (sample numbers are D670, J50, D420, X90, SZK59, respectively) and Canzhuang (sample numbers are S-220, S-340, S-500, S-560, 287ZK3) deposits were studied. All pyrite samples collected from the four representative deposits were analyzed for He and Ar isotopes. The samples preparation and the analytical procedure are as follows. The fresh rocks containing pyrite were crushed and sieved, and the purified pyrite samples were obtained using the conventional techniques of magnetic separation followed by hand-picking under a binocular microscope fitted with a UV light. The pyrite samples for the helium–argon gas isotope analyses were purified into dry nitrogen at high vacuum conditions. When a pressure lower than 1 × 10⁻⁶ Pa was attained, the samples were heated at 130 °C for at least 10 h to eliminate secondary fluid inclusions and trace gases occurring in cleavages or fractures at the grain surface. Subsequently, the samples were fused at high temperatures of up to 1600 °C, and the released gases were purified through activated charcoal traps at the liquid nitrogen temperature to separate He and Ar from Ne + Kr + Xe for He and Ar analyses on the mass spectrometer, respectively. The minimum heat background for the MM5400 mass spectrometer at 1600 °C is: ⁴He = 1.10 × 10⁻¹⁴ mol; ²⁰Ne = 1.82 × 10⁻¹⁴ mol; ⁴₀Ar = 6.21 × 10⁻¹³ mol; ⁸⁴Kr = 1.37 × 10⁻¹⁰ mol; ¹³²Xe = 5.65 × 10⁻¹⁰ mol.

The standard for normalizing the analytical results is the air in Lanzhou city (AIRLZ, 2003); analytical precision for the noble gases isotopic measurements is better than 10%. Detailed sample preparation and measurement procedures follow those in He et al. (2011) and Ye et al. (2001, 2007).

4. Results

4.1. Fluid inclusions

The homogenization temperatures of the fluid inclusions from the skarn iron deposits (total 23 samples) are shown in Fig. 4. Among these, the diopside and andradite were from the skarnization-stage, the epidote and magnetite from the oxide stage, the pyrite from the sulfide stage, and the calcite from the late sulfide stage representing post-mineralization fluid activity. From the data shown in Fig. 4, 250–550 °C is the temperature range for the skarnization stage, whereas 250–450 °C is for the temperature range from the epidecite representing the oxide stage. Thus, the temperature range for the main magnetite mineralization stage is 250–450 °C. These results are coincident with the decrepitation temperature data (Table 1) from the magnetite (major peak at 326–394 °C) and the pyrite (major peak at 245–272 °C). Apparently, the pyrite crystallized late and at a lower temperature than that of the magnetite. Based on the homogenization temperature of diopside, andradite, and epidote, the ore formation pressure is estimated at 28.4–97.1 MPa, with an average of 57.6 MPa.

From the gold deposits, the two representative members were examined, the Linglong gold deposit which is a typical quartz vein type (31 samples) and the Canzhuang gold deposit which is a typical fracture alteration type (14 samples). The fluid inclusions of the main ore-forming stage were analyzed. The temperature data from the two deposits show little difference (Figs. 5 and 6), with the fluids in the main ore-forming stage showing temperature range of 160–360 °C in the Linglong gold deposit (Fig. 5), and 200–300 °C in the Canzhuang gold deposit (Fig. 6). Thus, the temperature of the gold precipitation stage is estimated to be between 200 °C and 300 °C.

![Fig. 4. Histograms showing fluid inclusion homogenization temperatures for the skarn mineralization stage from the southern Taihang Mountains, central North China Craton.](image-url)
Since the pyrite (as the main mineral hosting Au) was formed abundantly in the main ore-forming stage, its crystallization can be correlated to the temperature range of 200–300 °C. It is coincident with the peak decrepitation temperature of 222–338 °C recorded by fluid inclusions in the pyrite (Table 2).

4.2. He–Ar isotopic

The He–Ar isotopic compositions of the pyrite grains from the Beiminghe and the Fushan skarn-type iron deposits and the Linglong and the Canzhuang gold deposits are listed in Table 3. The 3He/4He ratios obtained in our study range from 0.017 to 1.8508 with an average value of 0.5089. The R/Ra ratios (R: 3He/4He value of samples; Ra: 1.4 × 10−6, standard value of air) range from 0.012 to 1.322. These values are close to the 3He/4He ratio for fluids of the crustal origin (typically less than 0.1 Ra, generally range from 0.1 to 0.05 Ra (Dunai and Touret, 1995; Stuart et al., 1995), and are lower than the general mantle values of 6–7 Ra (Dunai and Touret, 1995; Stuart et al., 1995).

Interestingly, the 3He/4He ratios from the iron deposits in the Han-Xing area are mainly in the range of 0.065–0.189 Ra, whereas the 3He/4He ratios of the gold deposits in the Jiaodong area vary from 0.121 to 1.322 Ra (see Table 3). Obviously, the involvement of mantle-origin fluids in the gold deposits in the Jiaodong area are more than those in the iron deposits in the Han-Xing area.

In 3He–4He correlation diagram, the samples plot in the field between the crust and the mantle (Fig. 7, Table 3), suggesting crust–mantle-mixing process. Notably, the data from the iron deposits in the southern Taihang Mountains and those from the gold deposits in the Jiaodong area fall under two groups. The former is close to the field for fluids of crustal origin whereas the latter fall more close to the field for the mantle fluids.

Similarly, 40Ar/36Ar ratios range from 311.7 to 7935.2 (Table 3) with a few values higher than 10,000, markedly above the 295.5 value estimated for the air saturated water (Kaneoka and Takaoka, 1985; Marty et al., 1989). However, the value is close to that of the fluids of crustal origin (1500), and significantly lower than the value of the fluids of mantle origin (20,000) (Simmons et al., 1987; Hu et al., 1999; Wu et al., 2003; Cai et al., 2004a,b). In 40Ar/36Ar and R/Ra correlation diagrams (Fig. 8), most samples fall in the region between the fields of the fluids of crustal mantle origin.

The data 40Ar/36Ar (40Ar)sample denotes (40Ar)sample ~ 295.5 × (36Ar)sample) of the studied samples range from 0.027 to 0.739 (Table 3), which is higher than the average crustal 40Ar/36Ar value of 0.16–0.25 (Simmons et al., 1987; Stuart et al., 1995; Hu et al., 1999; Feng et al., 2006) and very close to the typical continental lithospheric mantle value of 0.33–0.56 (Simmons et al., 1987; Burnard et al., 1994a,b; Xu et al., 1995; Hu et al., 1999; Cai et al., 2004a,b). This indicates that the ore-forming fluids inherited the mantle components. However, the correlation of 40Ar/36Ar

### Table 1

<table>
<thead>
<tr>
<th>Samples</th>
<th>Minerals</th>
<th>Stage of mineralization</th>
<th>Deposit</th>
<th>Test weight (mg)</th>
<th>Beginning decrepitation temperature (°C)</th>
<th>Main decrepitation peak (°C)</th>
<th>Weak decrepitation peak (°C)</th>
<th>Total frequency (N)</th>
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<td>/</td>
<td>366</td>
<td>440</td>
<td>10,039</td>
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<td>/</td>
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<td>185</td>
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and $^3$He/$^4$He (Fig. 9) demonstrates a crustal origin for the fluid. This feature suggests that the original ore-forming fluid might have been derived from the mantle, but experienced a longer period of evolution through the crust. A scenario where mantle-derived fluids migrated upwards through the crust, mixing with crustal components through remelting of the surrounding rocks can be envisaged.

In summary, the eastern part of the NCC experienced higher degree of crust–mantle-mixing process during the Mesozoic mineralization process, relative to the central part. The mineralization of skarn-type iron deposits in the southern Taihang Mountains involved less input of mantle-origin fluids (Li et al., 2012, 2013; Shen et al., 2013), whereas the mineralization in the Jiaodong gold deposits witnessed relatively larger volumes of the mantle-derived fluids.

Since the atmosphere has very low He content with the $^3$He/$^4$He ratio maintained as 1 Ra, the He content and isotopic composition of the fluids of crustal origin do not undergo any change (Simmons et al., 1987; Stuart et al., 1995; He et al., 2011). Therefore, He isotopic composition in the ore-forming fluid is mainly a reflection of the crust–mantle-mixing ratio in the binary system. Thus, the proportion of the mantle-origin fluid in the mixed system can be estimated based on the following formula (Simmons et al., 1987; Burnard et al., 1994b; Stuart et al., 1995; Li et al., 2004; Zhu et al., 2009, 2012):

$$\frac{40Ar}{36Ar} = \left( \frac{40Ar}{36Ar} \right)_{sample} \left( \frac{40Ar}{36Ar} \right)_{air}.$$
Geophysical data show that the Ordos Basin in the Western Block of the NCC has a thick lithospheric root (200–250 km; Tian et al., 2009); whereas the thickness of the lithosphere beneath the Taihang Mountains is only 100–130 km (Chen et al., 2009). In contrast, most parts of the eastern NCC have only 80–100 km thick lithosphere, and the lithosphere beneath the Bohai Bay near the Jiaodong region is less than 60 km (Zheng and Wu, 2009; Zhu and Zheng, 2009). It is clear that extensive erosion of the NCC’s lithospheric keel has occurred, with increasing intensity of destruction towards the eastern part. Seismic data reveal that the mantle transition zone beneath the eastern NCC preserves remnants of the deep subducted Pacific slab (Li et al., 2006; Zhu and Zheng, 2009). The low-angle subduction of the ancient Pacific Plate under the eastern NCC in the Mesozoic is considered to be the key factor that led to the severe thinning of its lithosphere (Zheng and Wu, 2009; Zhu and Zheng, 2009).

Intense magmatism accompanied the destruction process of the NCC (Luo et al., 1996). Furthermore the REE patterns and the Sr–Nd–Pb isotopic compositions of the intrusives indicate that the magmas were ultimately sourced from the mantle (Niu et al., 1995; Cai et al., 2004a,b, 2006). Particularly, many of these magmatic rocks display low initial strontium isotopic ratio (${\text{$_{87}^{\text{Sr}}$}}/{\text{$_{86}^{\text{Sr}}$}} = 0.7050–0.7069$), implying the input of mantle components (Luo et al., 1997).

The Mesozoic magmatism in the eastern NCC was accompanied by extensive mineralization (Xu et al., 2009a,b; Zheng, 2009; Wang et al., 2010; Li et al., 2012, 2013; Shen et al., 2013; Guo et al., 2013; Zhai and Santosh, 2013). Geochronological data reveal that gold deposits formed much later than the iron deposits (Mao and Wang, 2000; Mao et al., 2005). The skarn-type iron deposits in the southern Taihang Mountains are dated as 125–135 Ma (Zheng et al., 2007a,c; Shen et al., 2013), and are correlated to the magmatic event at 125–138 Ma (Dong et al., 2003; Peng et al., 2004; Cai et al., 2004a,b, 2006; Chen et al., 2007; Shen et al., 2013). The major gold mineralization in the Jiaodong gold deposits took place during 130–110 Ma, associated with the magmatic pulses at 160–135 Ma (Yang et al., 2006). The multiple magmatic and metallogenic events occurred during the broad time interval of the destruction of the NCC (Xu et al., 2009a,b). Therefore, although the ore system in the southern Taihang Mountains region occurred earlier than the gold mineralization in the Jiaodong region, both coincide with the ca. 100 Ma period of intense cratonic destruction process estimated for the NCC (Xu et al., 2009a,b). Compared to the Taihang Mountains region, the intensity of craton destruction was much stronger in the Jiaodong region probably due to the longer duration of the destruction process, and the more effective role of mantle-derived magmas (Cai et al., 2013; Guo et al., 2013; Yang et al., 2013).

The He–Ar isotopic compositions of the pyrite in the main ore-forming stage from the skarn iron and the gold deposits reported in this study indicate that the ore-forming fluids originated at depth and experienced crust–mantle mixing processes (Li et al., 2013; Shen et al., 2013). The $^{3}{\text{He}}/^{4}{\text{He}}$ ratios manifest more input from the crust as compared with that from the mantle. However, there is a distinct contrast in the $^{3}{\text{He}}/^{4}{\text{He}}$ features between the skarn iron deposits in the southern Taihang Mountains and the gold deposits in the Jiaodong region as displayed in the two distinct domains defined by the He isotopic compositions (see Fig. 7), with the latter showing robust evidence for mixing with the mantle-derived fluids. The quantitative modeling of the He isotopes mentioned above shows an average of 1.31% mantle contribution to the ore-forming fluids in the skarn-type iron deposit, whereas this value is substantially higher for the gold deposits (6.73%). The Ar isotope compositions and correlation of $^{40}{\text{Ar}}/^{36}{\text{Ar}}$ and $^{3}{\text{He}}/^{4}{\text{He}}$ bring out distinct differences between the skarn-type iron deposit in the southern Taihang Mountains and the gold deposits in the Jiaodong
region (Figs. 8 and 9). These results also correlate well with the larger degree of destruction of the lithosphere in the jiaodong region by mantle-derived magmas. Geophysical data also confirm that the lithosphere in the jiaodong region is markedly thinner (<60 km, Zhu and Zheng, 2009; Xu et al., 2009a,b) than that in the southern Taihang Mountains region (80–130 km, Zheng and Wu, 2009). It is noted that the He–Ar isotope compositions in the northern Taihang Mountains in the central NCC are broadly comparable with those of the jiaodong region (Li et al., 2012, 2013), but distinct from those of the southern Taihang Mountains (see Figs. 7–9). This suggests that the extent of decratonization or lithospheric thinning in the northern Taihang Mountains in the central NCC was very similar to that of the jiaodong region in the eastern NCC. Our results coincide well with similar inferences drawn from recent geophysical studies (Zhu et al., 2012; Guo et al., 2013).

The temporal and spatial heterogeneity in the decratonization of the NCC is also reflected in the nature and source characteristics of the various mineralizations. In the jiaodong region, a prolonged and intense lithospheric thinning process (160–100 Ma) was accompanied by the formation of large-scale low-medium temperature gold deposits, whereas in the southern Taihang Mountains region, the development of a relatively weak lithospheric thinning during a shorter time duration (140–125 Ma) led to the formation of high-temperature skarn iron deposits.

In summary, our study shows that the He–Ar isotope compositions of metallic ore deposits can effectively trace the ore-forming fluid source, and can be employed to evaluate the contribution of mantle-derived fluids in crust–mantle mixing processes. In the eastern China, the metallic mineralization was accompanied by lithospheric thinning process or crust–mantle mixing associated with the destruction of the NCC during the Mesozoic. A weaker lithospheric thinning corresponds to less contribution of mantle-derived fluids to the ore-forming fluids whereas intense lithospheric thinning results in substantial contribution of mantle-derived fluids.

6. Conclusion

The NCC destruction process in the Mesozoic was not only accompanied by intense tectono-magmatic activities, but also triggered large-scale mineralization. The cratonic destruction is identified as a major geodynamic factor which led to the Mesozoic explosive mineralization event, and in turn, the nature and timing of mineralization reflect the duration and intensity of the decratonization of the NCC.

A significant spatial and temporal heterogeneity is displayed in the craton destruction process of the NCC, which is reflected in the differences in mineralization. The heterogeneous destruction process led to variable degrees of crust–mantle interaction, and consequently different types of mineralization. Distinct He–Ar isotopic compositions are identified between the Han-Xing iron deposits in the central NCC and the jiaodong gold deposits in the eastern NCC, where the mantle-derived fluids involved into the ore-forming fluids were in different proportions. In the central NCC, short-time and weak lithospheric thinning process produced the high-temperature skarn-type iron deposits, with the ore-forming fluids containing less mantle-derived fluids. In the eastern NCC, long-time and intense lithospheric thinning resulted in low-mid temperature gold deposits, with markedly higher volume of mantle input in the ore-forming fluids.

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