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ORIGINAL PAPER

Geological characteristics and origin of the Hadamengou gold deposit in Inner Mongolia, China

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Abstract The Hadamengou gold deposit is located in the western segment of the northern margin of the North China Craton (NCC). It is hosted by Archean metamorphic rocks of the Wulashan Group. The main ore types include gold-bearing quartz vein type, gold-bearing quartz-potassic feldspar vein type, and gold-bearing altered rock type. Gold mineralization is closely related to K-feldspathization. Hydrogen and oxygen isotope data indicate that ore-forming fluids were dominated by magmatic water mixed with minor meteoric water. Sulfur and lead isotope data indicate that metallogenic materials were mainly supplied by the magmatic and Archean Wulashan Group. The gold mineralization was mainly formed during the Early Indosinian tectonic movement, which drove ore-forming fluids to the favorable depositional environment. The northern margin of the NCC is a prospective area for gold exploration. Gold deposits hosted by or related to alkaline intrusions have become one of the most important mineral exploration targets in northern China.

Keywords Hadamengou gold deposit · Wulashan Group · Northern margin of the North China Craton · Gold mineralization

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Introduction

The Baotou-Bayan Obo district, located at the western portion of the northern margin of the North China Craton (NCC), is one of the most important Au metallogenic provinces in China (Nie et al. 2002). Up to now, more than 50 gold deposits and prospects have been discovered, explored, and mined. Among these gold occurrences, the Hadamengou gold deposit is one of the most important one and exhibits instructive similarities to the alkaline-type gold deposits (Nie and Wu 1998; Nie 1998; Nie et al. 2002).

The Hadamengou gold deposit is situated approximately 20 km west of Baotou County, Inner Mongolia. It is hosted in a set of Precambrian high-grade metamorphic rocks (Fig. 1). It is a super large gold deposit in Inner Mongolia and one of the largest gold mines in China, with a reserve of about 100 t of gold at about 4.13 g/t Au (Nie et al. 2002, 2004; Zhang 2012).

Although various aspects of the Hadamengou deposit have been described in geological literature, the genesis and mineralization process of the deposit remain controversial (Xin et al. 2013; Nie and Bjorlykke 1994; Gan et al. 1994; Hou et al. 2014; Li et al. 2008; Xie 2011). Furthermore, few researches on the metallogenic prognosis have been carried out.

In this paper, we have reviewed the geology and geochemistry data on the Hadamengou deposit previously published in geological literature, proposed the major ore-controlling factors, and provided guidance for regional prospecting.

Regional geology

The NCC is the largest and the oldest Precambrian block in China (Zhai and Santosh 2013). The NCC consists of Archean

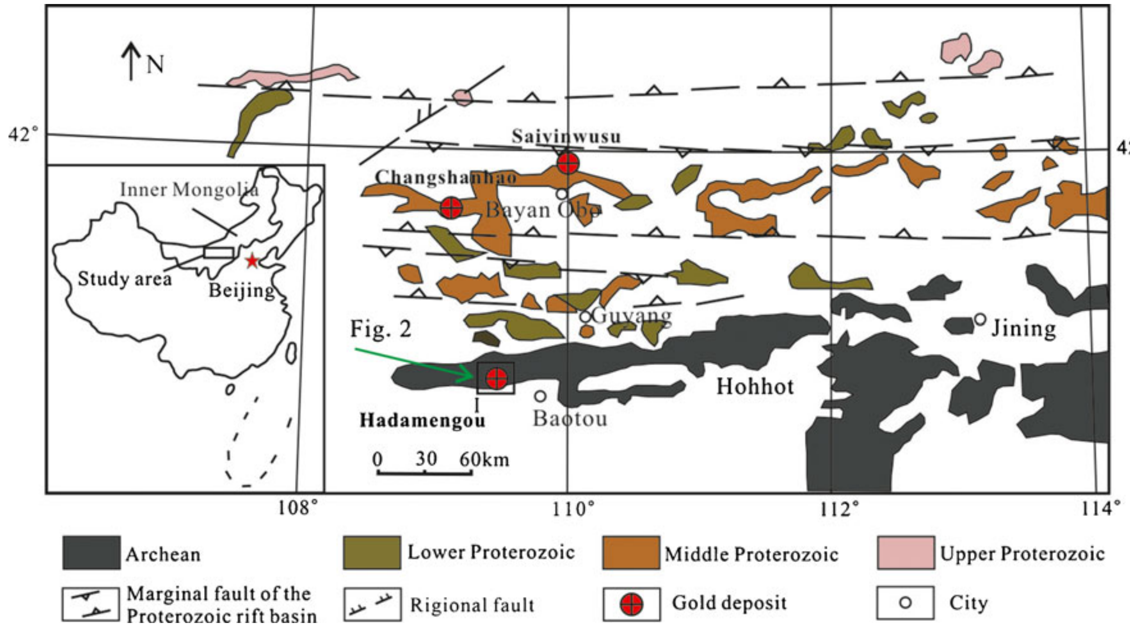

Fig. 1 Simplified regional geologic map of the northern margin of the NCC showing the location of major Au deposits (modified after Xiao et al. 2000)

to Paleoproterozoic basement overlain by a Mesoproterozoic to Cenozoic unmetamorphosed cover (Yang et al. 2003). The development of large areas of Hercynian-Indosinian post-collisional granites marks the final collision between the Siberian plate and the NCC (Wang et al. 2014). The northern margin of the NCC is characterized by complex geological structures, frequent magmatic activities, and lots of gold deposits (Hart et al. 2002; Yang et al. 2003; Nie et al. 2004, 2011; Liu et al. 2015).

The Hadamengou gold deposit is located in the Baotou-Bayan Obo area. The tectonic position is belonging to the southern edge of the Yinshan uplift belt and southern part of Wulashan anticlinorium. Basement rocks in this area consist of granulite, amphibolite, gneiss, and migmatite (Gan et al. 1994).

The Late Archean Jining and Wulashan Groups are widely distributed in the southern region (Fig. 2). The Mesoproterozoic Bayan Obo Group sedimentary rocks are prevalent in the north. Proterozoic metamorphosed volcanics and sediments of the Sertengshan and Erdaowa Groups are sporadically distributed in the central parts of the district. The Mesoproterozoic Chaertai and Bayan Obo Groups are located mainly in the north and northwest parts of the district (Nie et al. 2002).

The magmatic rocks are well developed in the study area. As in most areas of the NCC, the magmatic rocks belong to three groups—Proterozoic, Hercynian, and Yanshanian. The most common intrusive rocks are Hercynian alkaline syenite-monzonites and Yanshanian calcalkaline granitoids (Miao 2000; Luo et al. 2000; Nie et al. 2002; Yang et al. 2003). Vein rocks are also common in the district, including granite pegmatite and sillite.

Deposit geology

Strata and structures

The stratum exposed in the Hadamengou gold deposit area is mainly the lower part of the Wulashan Group. The lower part of the Wulashan Group is mainly composed of basic granulite and gneiss. The upper part of the Wulashan Group is mainly composed of sillimanite-cordierite-garnet biotite plagioclase gneiss, garnet-biotite monzoite gneiss, feldspar-quartzite, and graphite-bearing marble (Zhu et al. 2006; Li et al. 2008).

The Hadamengou mining area was subjected to intensive tectonic and magmatic activities (Fig. 3). The Daqingshan-Wulashan piedmont fault is the most important fault in the mining area and produces several secondary faults. There are mainly three groups of secondary faults: the east-west striking group, the north-west striking group, and the north-east striking group. The ore-bearing faults controlling the gold veins are mainly east-west striking, with some north-east and north-west striking.

Alteration

Hydrothermal alterations are well developed in the Hadamenggou gold deposit. Wall rock alterations are mainly potash feldspathization, silicification, pyritization, carbonation, epidotization, chloritization, and sericitization. Among all these alterations, K-feldspathization is associated very closely with gold mineralization.

The wall rock alterations show the feature of zonal distribution. The intensity of host rock alterations decreases further away from the center of fractures. Wall rock alterations near

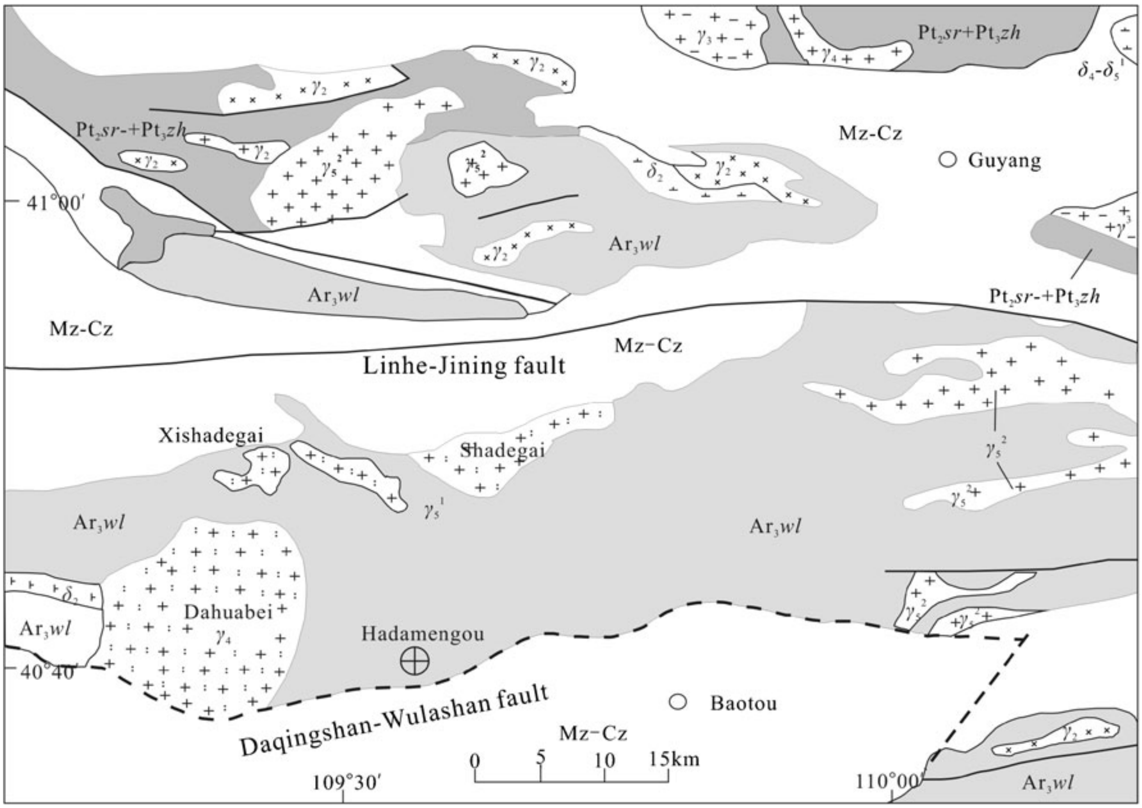

Fig. 2 Simplified geological map of the Hadamengou region, Inner Mongolia (modified after Hou et al. 2014)

ores are mainly potash feldspathization and silicification and gradually transited to epidotization, chloritization, carbonation, and weak sericitization away from ore bodies.

Ore bodies

The gold mineralization of the Hadamengou gold deposit occurs in high-grade metamorphic strata in the Archean Wulashan Group. Ore bodies occur as a nearly EW-trending vein (Fig. 4). The distribution of the ore bodies is strictly controlled by fracture zones. More than 100 gold veins have been discovered in the mine area. Based on the geological features and geographic locations, these gold-bearing veins can be divided into six vein groups. The no. 13 is the largest one and contains about 70 % of the total gold reserve of the Hadamengou gold deposit (Fig. 4).

The ore bodies are generally 100 to 2200 m long with thickness of 1 to 5 m and display a thickening downward pattern. The average grade of gold is 5.18 g/t.

Ore

According to the nature of the host rocks, the primary ores can be classified into three types, gold-bearing quartz-potassic feldspar vein type, gold-bearing quartz vein type, and gold-bearing altered rock type (Fig. 5).

The gold-bearing quartz-potassic feldspar vein type is the main ore type. Gold grade in this type of ore is relatively variable. The gold-bearing quartz vein occurs due to tensional fractures. The boundary between the ore body and the wall rock is obvious. This type of ore is rich in gold concentration. Most ore bodies of the gold-bearing altered rock type are present on either side of both the gold-bearing quartz-potassic feldspar vein type and gold-bearing quartz vein type. The content of gold in this type of ore is relatively low.

Mineralogy

The metallic minerals of the ore in the Hadamengou deposit are predominantly pyrite, magnetite, and hematite, as well as minor chalcopyrite, galena, and molybdenite (Fig. 5). The gangue minerals in the ore consist mainly of quartz, feldspar, and calcite and subordinately of chlorite, epidote, sericite, barite, and biotite. The gold minerals mainly include native gold, as well as minor electrum, petzite, and needle petzite. The gold mineral primarily occurred as gold inclusions, the second is crystal fracture gold, and fissure gold takes only about 16.39 % (Li et al. 1999). The size of gold grains varies between 0.07 and 0.01 mm (Gan et al. 1994). Gold grade increases with sulfide mineral content but apparently does not change with depth.

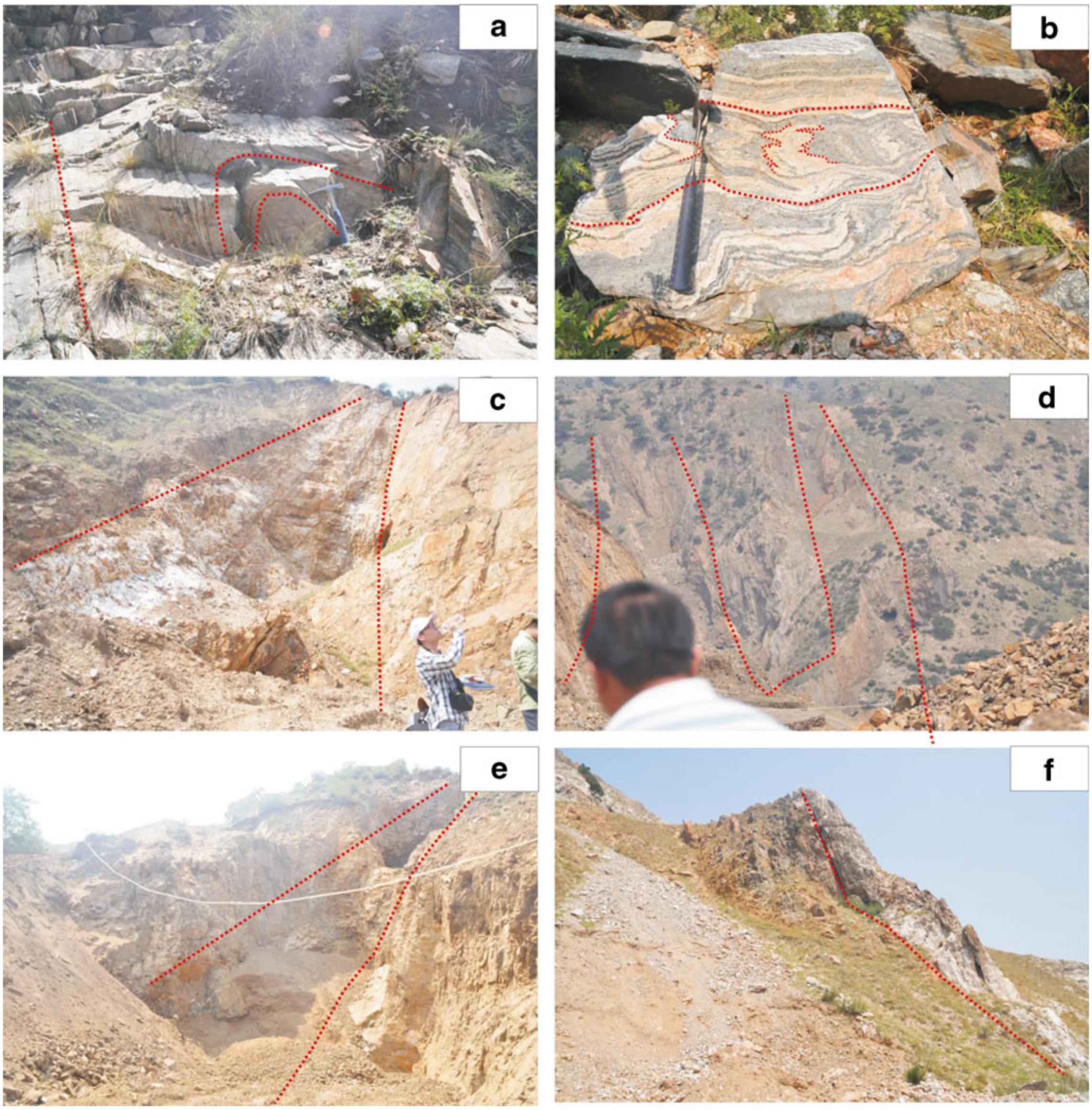

Fig. 3 Photographs showing the tectonics in the Hadamengou gold deposit. **a**, **b** The ductile fold; **c** the late-stage quartz occurred in the tensional tectonic; **d**, **e** gold mineralization occurred in the tensional tectonic; and **f** the quartz occurred in the piedmont fault

Isotope geochemistry

Previous studies have shown that the granitic dikes near gold deposits in the NCC have positive $\delta^{34}S$ values varying from 1 to 7 ‰, with an average value of 3.6 ‰ (Nie et al. 2004). These values are compatible with sulfur of igneous origin. Precambrian metamorphic rocks have striking negative $\delta^{34}S$ values in the range of −20.2 to −2.0 ‰ (Nie et al. 2004). Such depleted sulfur is characteristic of sulfide formed by bacterial reduction of sulfate under anoxic conditions in submarine sedimentary environments (Ohmoto and Rye 1979). Hydrothermal sulfide minerals from the ore bodies at the Hadamengou gold deposit range between −21.7 and 5.4 ‰, with an average of −10.6 ‰ (Hou et al. 2014), indicating a high measure of dispersion (Fig. 6). The $\delta^{34}S$ value of sulfide from the Hadamengou gold deposit falls in between the values of sulfides from the granitic dikes and those of Precambrian metamorphic rocks. The intermediate $\delta^{34}S$ value range of sulfides from the Hadamengou gold deposits suggests that sulfur was partially derived from magma and Precambrian metamorphic rocks.

The ore sulfides have $^{206}Pb/^{204}Pb$ ratios from 15.937 to 18.875, $^{207}Pb/^{204}Pb$ ratios from 15.215 to 15.684, and $^{208}Pb/^{204}Pb$ ratios from 36.067 to 38.501 (Hou 2011). Wall rocks in the Hadamengou gold deposit have variable lead isotopic compositions, with $^{206}Pb/^{204}Pb$ ratios from 15.755 to 17.964, $^{207}Pb/^{204}Pb$ ratios from 15.187 to 15.500, and $^{208}Pb/^{204}Pb$ ratios from 36.002 to 37.140 (Nie et al. 1994).

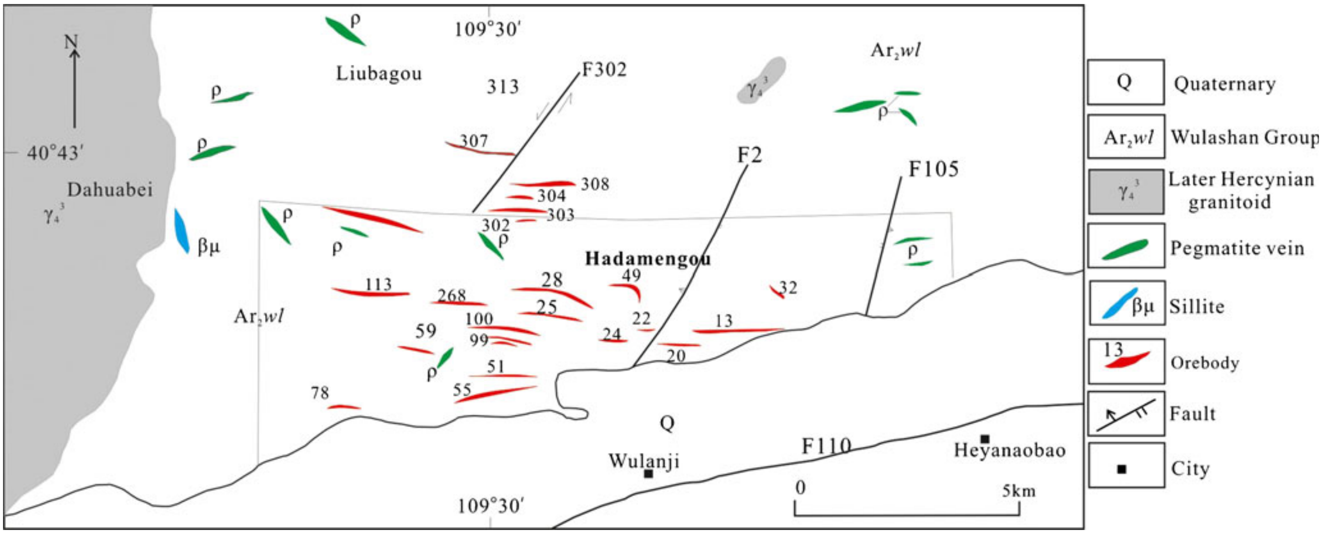

Fig. 4 Geological map of the Hadamengou gold ore field in Inner Mongolia (modified after Xin et al. 2013)

The granitoid batholiths have variable Pb isotopic ratios, with $^{206}Pb/^{204}Pb$ ratios from 18.252 to 19.233, $^{207}Pb/^{204}Pb$ ratios from 15.599 to 15.760, and $^{208}Pb/^{204}Pb$ ratios from 38.216 to 38.417 (Nie et al. 1994). In Fig. 7, Pb isotope data of ore is plotted across the upper crust, orogen, mantle, and lower crust lines, with most clustering between the mantle and orogen lines, indicating a complex lead source. The lead isotopic compositions of sulfides range between those of wall rock and granite batholiths (Fig. 7a, b), indicating that the ore lead might be sourced from both wall rock and magmatic fluids.

The $\delta^{18}O$ values of quartz from auriferous veins range from 12.3 to 13.7 ‰, and the calculated $\delta^{18}O_{H2O}$ values in equilibrium with quartz vary from 3.8 to 5.2 ‰. The hydrogen isotope ratios of the water in fluid inclusions range from −62 to −95 ‰ (Hou 2011). Plots on the $\delta^{18}O_{H2O}$-δD diagram show that most of the data for the Hadamengou gold deposit are between the values of meteoric water and the values of magmatic water, indicating that ore-forming fluids may be derived from meteoric water and magmatic water, with a larger contribution from magmatic water (Fig. 8) (Hou 2011; Xie 2011).

Fluid characteristics

Fluid inclusions can be classified into two types: primary and secondary in accordance with their geneses. Primary fluid inclusions of quartz are characterized by an isolated distribution and a negative crystal shape. The inclusions are usually within the range of 5–30 μm, mostly 5–13 μm, in diameter. According to the phase-state characteristics of inclusions at room temperature (25 °C) and their transformation in the process of freezing, CO_2-rich and gas-liquid inclusions can be classified (Gan et al. 1994; Xin et al. 2013; Hou et al. 2014; Zhang 2012).

The homogenization temperatures of the gas-liquid inclusions from the no. 13 gold vein range from 162 to 317 °C, with an average temperature of 230.7 °C and bimodal distribution from 190 to 240 °C and 270 to 280 °C. The homogenization temperatures of the CO_2-rich inclusions from the no. 13 gold vein range from 220 to 300 °C, with an average temperature of 260.8 °C (Xin et al. 2013; Hou et al. 2014).

The salinities of the gas-liquid inclusions range from 0.53 to 14.97 wt% NaCl equiv., with an average of 9 wt% NaCl equiv. and a peak value of 13–15 wt% NaCl equiv. The salinities of the CO_2-rich inclusions range from 2.02 to 13.98 wt% NaCl equiv. (Xin et al. 2013; Hou et al. 2014).

Preliminary pressure calculations indicated that the ore fluids had an extremely high pressure (139~366 × 10^5 Pa) corresponding to the lithostatic pressure at the depth of 1.5~3 km. Thus, the ore-forming fluids are characterized by intermediate-low temperature and mid-low salinity.

Mineralization age

The mineralization age of the Hadamengou gold deposit is a matter of controversy (Zhang et al. 1999; Miao et al. 1999; Hart et al. 2002; Meng et al. 2002; Nie et al. 2005; Hou et al. 2011a). In the past, the whole-rock Rb-Sr method, the whole-rock K-Ar method, and the zircon SHRIMP U-Pb method were used to constrain the metallogenic ages, giving a larger age range of 477–132 Ma. Nie et al. (2005) reported the Ar-Ar isochron age of sericite from the Hadamengou gold deposit. Sericite separates from the gold-bearing K-altered rock have been dated by an $^{40}Ar/^{39}Ar$ method at 322.58 ± 3.24 Ma. Furthermore, sericite separates from gold ores give an $^{40}Ar/^{39}Ar$ isochron age of 239.76 ± 3.04 Ma. Isotopic age indicates that the Hadamengou gold deposit formed as early as the Middle Hercynian orogen, but the metallization mainly took place in the Early Indosinian epoch (Nie et al. 2005).

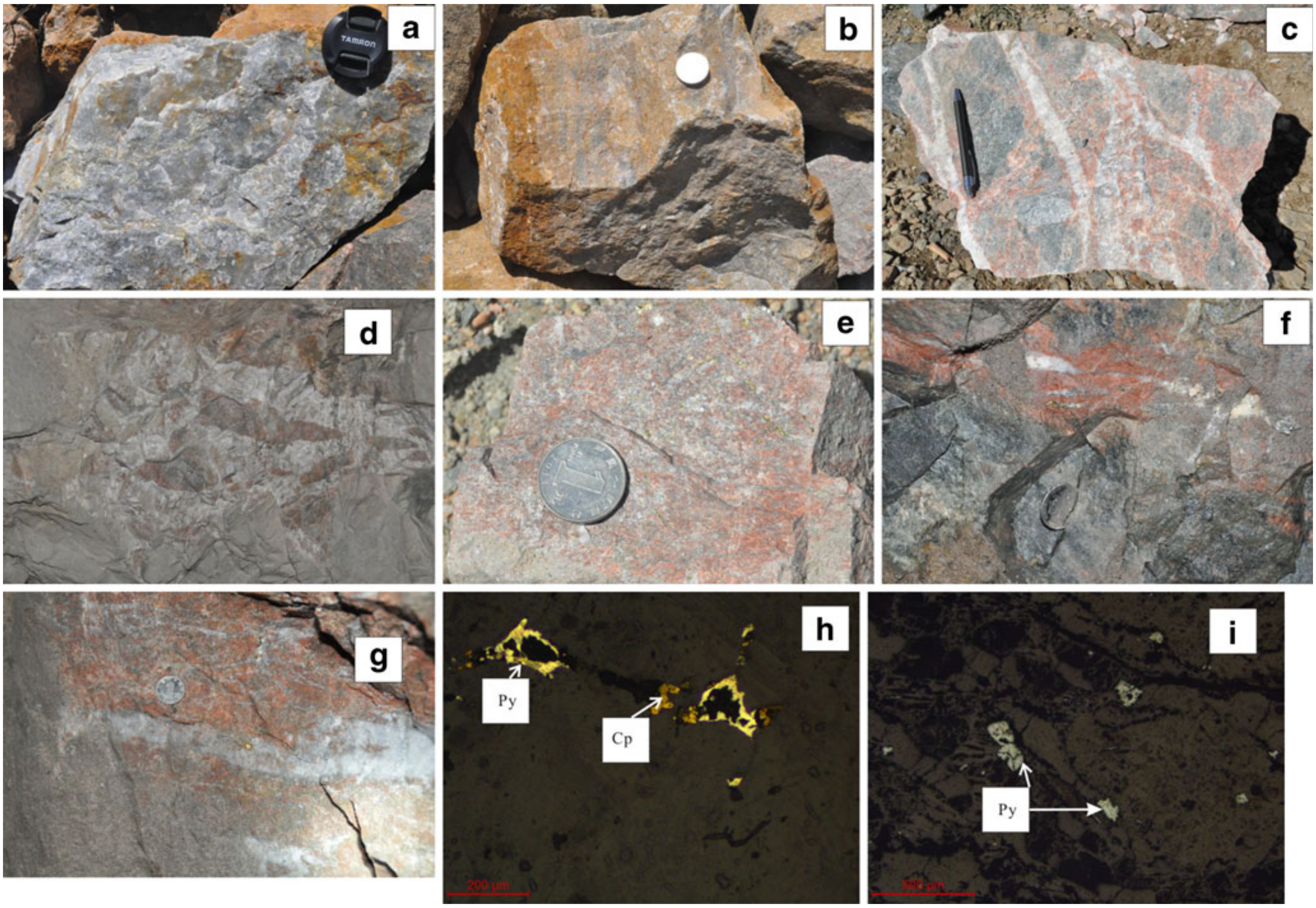

Fig. 5 Photographs showing the geology and mineralization of the Hadamengou gold deposit. **a**, **b** Gold-bearing quartz vein; **c**, **d** gold-bearing quartz vein; **e**–**g** quartz-K-feldspar vein with sulfides; **h** chalcopyrite; and **i** pyrite

The pluton near the Hadamengou deposit also has been reported (Li et al. 1999; Zhao et al. 2009; Hou et al. 2011b; Zhang 2012; Wang et al. 2015). Zircon LA-ICP-MS dating for the Dahuabei pluton yielded 328.3 ± 1.5 Ma (Wang et al. 2015). LA-ICP-MS U-Pb analysis on zircon from the Xishadegai pluton gave an age of 245 ± 10 Ma. A zircon U-Pb LA-ICP-MS age from the Shadegai pluton yielded a date of 231 ± 3 Ma (Zhang 2012). The consistency of the above dating data indicates that there is a temporal relationship between the gold mineralization and granitoid intrusions.

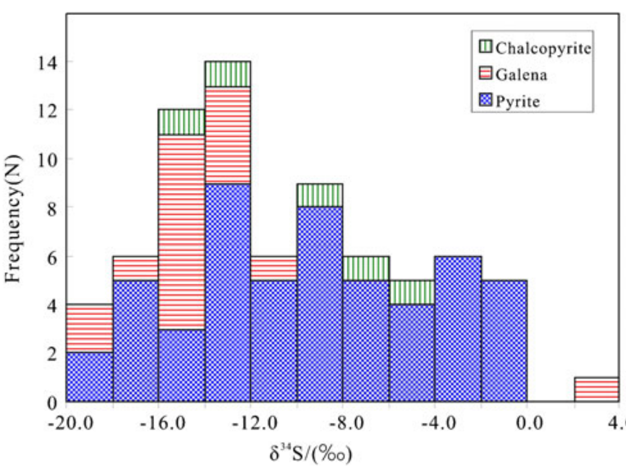

Fig. 6 Sulfur isotope composition of ore minerals from the Hadamengou gold deposit. Data sources are Nie et al. 1994; Hou 2011, and Lang and Li 1998

In combination with the stable isotopic composition, the gold mineralization at Hadamengou is essentially contemporaneous with the emplacement of the regional magmatic activity.

Discussion and conclusions

Genesis of the gold deposit

The geochemistry evidence of the metallogenic material was mainly derived from the wall rock and magmatic fluids. Regional research has demonstrated considerable gold concentrations in the metamorphic rocks.

Through comprehensive geological-geochemical studies and discussion on the problems concerning metallogenesis, the metallogenic model of the Hadamengou gold deposit can be summarized as follows:

During the late Paleozoic, re-subduction of the Paleo-Mongolia Ocean and its conjunction collision with the North

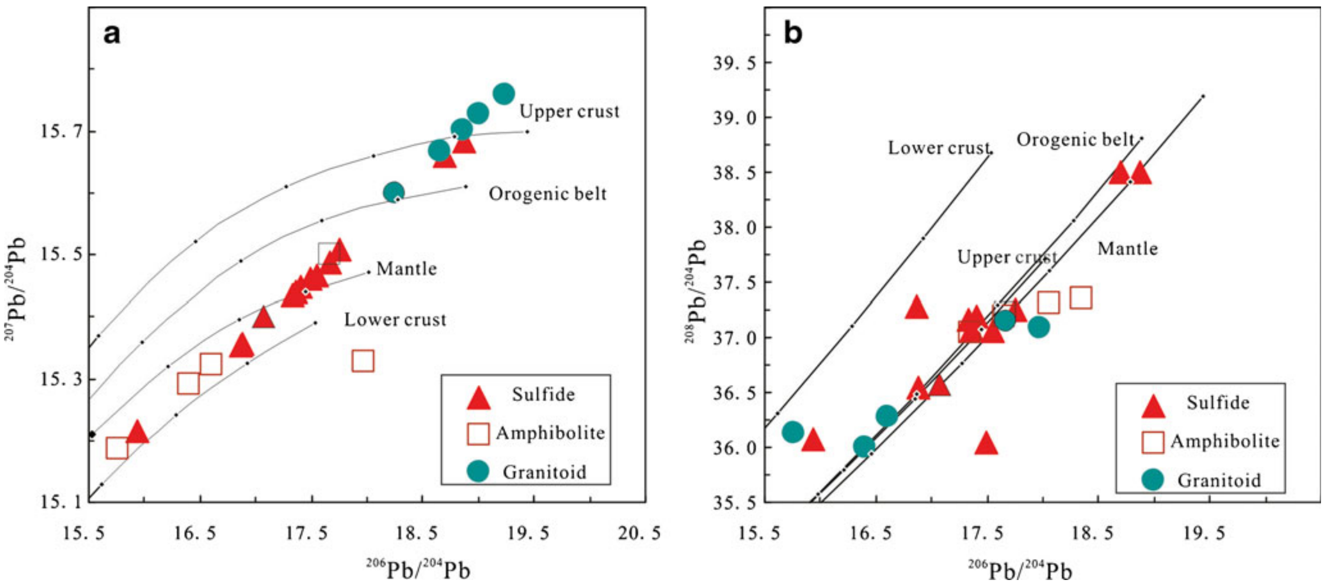

Fig. 7 The $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (**a**) and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (**b**) diagrams showing the lead isotopic features of ore and related lithologies (data from Nie and Bjorlykke 1994). The average growth lines from Zartman and Doe (1981)

China Platform caused not only multiple regional tectonomagmatic activities but also a number of uplifts (Zhang et al. 1999).

In the Triassic, the post-orogenic extension provided favorable conditions for the magmatic activity and the migration of the ore-forming fluids. The granitic plutons were widely distributed in the ore field, such as the Shadegai pluton and Xishadegai pluton. The Indosinian alkaline rocks and the Hercynian alkaline rocks constitute together an E-W-trending alkaline rock belt in the ore field.

Large-scale magmatic activities provide the dynamic force and fluid source for the mineralization. Moreover, the fractured zone provided accumulation conditions for the ore-forming materials.

In the extension environment, the deep potassium-bearing magmatic hydrothermal fluid migration along the piedmont fault extracted the ore-forming elements in the wall rocks. When the ore-forming fluids intruded into the favorable tectonic area, with the rapid change of metallogenic conditions, the complex chemical interactions between the wall rock and ore-forming fluid resulted in an exchange of elements between the wall rock and the fluid. As a result, gold in the ore-forming fluids would be rapidly precipitated and accumulated as gold deposits in the deformation zones.

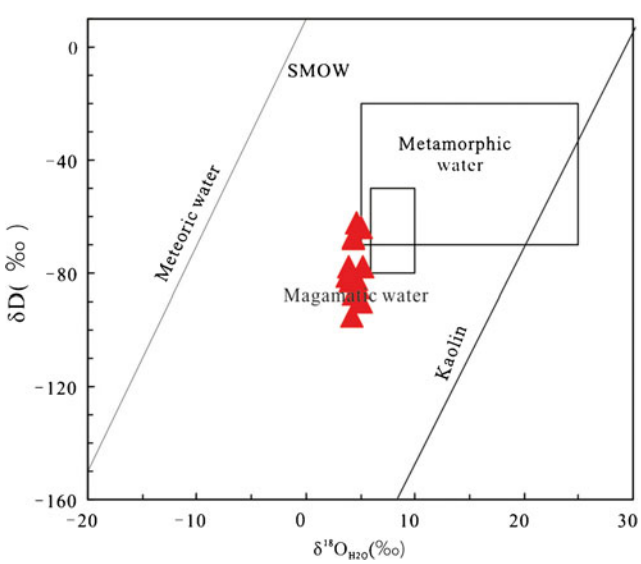

Fig. 8 δD-$\delta^{18}H_2O$ diagram of fluid inclusions from the Hadamengou gold deposit in Inner Mongolia. The base map is cited from Taylor (1974). Data sources are Hou (2011)

Major ore-controlling factors

Stratum

The gold mineralization of the Hadamengou gold deposit occurs in the metamorphic rocks of the Late Archean Wulashan Group. The main ore-hosting rocks are biotite plagioclase gneiss, amphibolite, and garnet plagioclase gneiss. The Wulashan Group rocks experienced Archean granulite facies metamorphism. Regional research demonstrated considerable gold concentrations in the metamorphic rocks (Chen and Wang 1996). The initial Wulashan Group constitutes the ore-bearing formation in the mine area and provides partly ore-forming materials for mineralization.

Structure

As mentioned above, tectonic activity is intense in the mineralization area. The Daqingshan-Wulashan piedmont fault is the important conducting structure for the formation of gold deposits. Furthermore, the secondary faults provide the pathways both for magmatic activities and for hydrothermal activities during the ore-forming process. The nearly E-W-trending fault controls the shape and attitude of the mineralized veins and is the important tectonic ore-search indicator in the mining area.

Magmatic activity

Different ages of alkaline intrusions from Proterozoic to Indosinian have been discovered around the deposit. The deposit was mainly formed in the Early Indosinian tectonic movement (Nie et al. 2005). Field observations and geochronology research show an intimate spatial and temporal relationship between gold mineralization and intrusions of the Indosinian granitoid. The K-feldspathization is associated very closely with gold mineralization. The deposit pervasively develops K-feldspathization. The alkaline magmatic activity provides the energy and material for the alternation. Thus, the Indosinian alkaline granitoid can be regarded as the ore-search indicator in the mining area.

Regional-scale mineral potential

The northern margin of the NCC can be regarded as the Central Asia orogenic belt (Wang et al. 2014). The Indosinian is one of the important gold mineralization epochs in the northern margin of the NCC (Nie et al. 2011). The Hadamengou gold deposit shows features of magmatic hydrothermal alkaline-related gold deposits. Some other similar gold deposits, such as the Jinchangyu and Jinchanggouliang deposits, have been discovered in the northern margin of the NCC (Nie et al. 2004).

During the period of the Late Paleozoic to Early Mesozoic, due to collision of the Xing-Meng amalgamated block and NCC, lithospheric and crustal extension prevailed along the northern margin of the NCC. The post-orogenic extensional activities resulted in the formation of several E-W-trending faults and widespread alkaline or high-K calcalkaline intrusions (Nie et al. 2004). Intensive extension and magmatic activities provide dynamic force and ore-forming material source for gold mineralization. Meanwhile, the structure offered a migration channel for ore-forming fluids.

In summary, the northern margin of the NCC is a prospective area for gold exploration. Gold deposits hosted by or related to alkaline intrusions have become one of the most important mineral exploration targets in northern China and elsewhere.

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