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Characteristics and origin of the Zhulazhaga gold deposit in Inner Mongolia, China



Chengwu Ding ^{a,b,*}, Fengjun Nie ^a, Sihong Jiang ^a, Yifei Liu ^a, Yi Cao ^a

^a Institute of Mineral Resources, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Xicheng District, Beijing 100037, China ^b Faculty of Earth Resources, China University of Geosciences (Wuhan), Wuhan 430074, China

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ABSTRACT

The Zhulazhaga gold deposit in the northern margin of the North China Craton (NCC) is a large tonnage hydrothermal deposit with a reserve of about 50 t at about 4 g/t Au. The deposit is characterized by an epigenetic style of mineralization in metasedimentary rocks dominated by slates, low-grade metamorphic clastic rocks and minor volcanic rocks. Gold mineralization is dominantly controlled by structures, manifested by stratabound orebodies located immediately to the east and west of a major N–S-trending fault and associated extensional fractures and NE-trending fault zones. The mineralization is also preferentially located in the fourth submember of first member of the Agulugou Formation. There are many auriferous quartz veins parallel to the bedding of the host rocks which contain the orebodies, and high-grade ore preferentially occurs near to these quartz veins. The structures provided pathways for transportation of gold-bearing fluids within the formation that appears to form a particularly favorable host rock and depositional setting.

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 some sulfur and lead came from the magmatic fluid. The metallogenic age (280 Ma) of this deposit and the crystallization age (280–290 Ma) of the granite porphyry in the district indicate a link between the Hercynian magmatism and gold mineralization. The Hercynian tectono-magmatism and associated hydrothermal activity remobilized gold and drove ore-forming fluids to the favorable depositional environment.

The northern margin of the NCC is prospective for gold mineralization hosted in metasedimentary rocks which may be one of the most important deposit types for future gold exploration in northern China.

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1. Introduction

The Zhulazhaga gold deposit is the earliest large-scale gold deposit discovered in Proterozoic metasedimentary rocks in the northern margin of the North China Craton (NCC) (Jiang et al., 2001a, 2001b; Jiang and Nie, 2005; Nie et al., 2010; Li et al., 2010). The deposit contains more than 50 t gold averaging 4 g/t (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Meng et al., 2002; Xu, 2009). The deposit was discovered in 1995 by the First Geophysical and Geochemical Exploration Party of Inner Mongolia during geophysical and geochemical survey work. Initially, a 36 km² gold geochemical anomaly was defined. Subsequently, the party carried out a 1:50,000 regional stream sediment survey in the central part of the geochemical anomaly in 1997, and reduced the area of interest to 19 km². The source of the anomaly was found by trenching which resulted in the discovery of the Zhulazhaga gold deposit (Zhang et al., 1999, 2000, 2001; Liu and Yang, 2002; Jiang and Nie, 2005). The gold deposits hosted in the Proterozoic metasedimentary rocks have drawn much attention because of their relatively large size and easy mine development and ore-processing. Other examples of similar deposits are widely distributed both in China and other countries, and possess high economic value, such as the Telfer gold deposit (Australia), Sukhoi Log (Russia), the Olympiada and Witwatersberg goldfields (South Africa), the Blackbird district (USA), and the Yindongpo, Woxi, Mobin, Huangjindong, Hetai and Xinzhou deposits in southern China (Goellnicht et al., 1988; Tu and Gao, 1990; Cox et al., 1991; Harley and Charlesworth, 1992; Luo et al., 1993; Luo, 1995; Arehart, 1996; Kontak and Kemch, 1997; Ramsay et al., 1998; Foster et al., 1998; Jiang et al., 2001a; Jian, 2004; Jiang and Nie, 2005; Ouyang et al., 2005; Killick and Scheepers, 2005; Meffre et al., 2008; Ding and Wang, 2009; Huang et al., 2010; Aleinikoff et al., 2012; Yakubchuk et al., 2014; Gu et al., 2004; Phillips and Powell, 2015).

Proterozoic metasedimentary rocks are widely distributed in northern China, and extend more than 2000 km throughout the northern margin of the NCC (Tu, 1990; Lu, 1997; Shao, 1999; Shen et al., 2004; Nie et al., 2010). A few gold deposits, such as the Haoyaoerhudong deposit (also known as the Changshanhao gold deposit), Saiyinwusu deposit (Wang et al., 2014), and the Zhulazhaga deposit (Yang et al.

^{*} Corresponding author at: Institute of Mineral Resources, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Xicheng District, Beijing 100037, China. *E-mail address*: dingchengwude@163.com (C. Ding).

2001b; Guo, 2008) were discovered recently in the metasedimentary rocks, but their genesis and mineralization process are still a matter of controversy (Wang et al., 2014). Therefore, a study of geological setting, characteristics, and origin of the Zhulazhaga gold deposit is important in improving the understanding of gold mineralization and guiding gold exploration in the Proterozoic metasedimentary rocks in northern China. In this paper we have reviewed the geologic, S–Pb–O–H isotopic, fluid inclusion, and geochronological data on the Zhulazhaga gold deposit previously published in various papers (Jiang et al., 2000, 2001b; Yang et al., 2001a, 2001b; Liu and Yang, 2002; Ding, 2002; Li et al., 2004, 2010; Jiang and Nie, 2005; Xu, 2009), proposed a tentative genetic model, and evaluated gold potential in the Proterozoic metasedimentary rocks in the northern margin of the NCC.

2. Geological setting

The Zhulazhaga gold deposit is located in the western segment of the northern margin of the NCC, with the geographic coordinates of 104°58′ E and 40°11′ N (Fig. 1) (Jiang et al., 2000, 2001a; Yin, 2002; Li et al., 2004, 2010; Xu, 2009).

2.1. Strata

The regional strata of the study area, from bottom to top, include the Archean basement sequence (gneiss, plagioclase amphibolite and marble), the Shujigou (Chs) and Zenglongchang (Chz) Formations of the Calymmian, the Agulugou Formation (Jxa) of the Ectasian, the Suji Formation (Ps) of the Lower Permian, the Wulansuhai Formation (Kw) of the Cretaceous, the Qingshuiying Formation (Eq) of the Tertiary, and Quaternary sediments (Fig. 1) (Zhang et al., 1999; Zhao et al., 2002; Liu and Yang, 2002).

The rocks of the mine district belong to the Zenglongchang and Agulugou Formations, which are comprised of a sequence of metasedimentary rocks (slate, low-grade metamorphic sandstone and siltstone, marble) (Yang et al., 2001b; Jiang and Nie, 2005; Xu, 2009). The mine district is situated in the south limb of the Zhulazhagamaodao anticline, indicating that the strata dip southeast at 30–50°, younging towards the southeast (Figs. 2, 3A).

The Zenglongchang Formation is generally about 3090 m thick and can be subdivided into two members. The lower member comprises clastic sedimentary rocks separated by several intercalated carbonate rock layers, which are formed by coastal sediments; the upper member comprises carbonate rocks intercalated by minor clastic rocks, and belongs to the typical sediments of tidal flat (Yang et al., 2001b; Jiang and Nie, 2005; Xu, 2009; Nie et al., 2010).

The Agulugou Formation is generally about 1190 m thick and can be divided into four members; the first member can be subdivided into 5 sub-members. This formation, considered to be sediments depositing in an extensive and relatively stable shallow sea basin, comprises a sequence of sandy shale, calcareous guartz sandstone, calcareous siltstone, dolomite and microcrystalline marble (Meng et al., 2002; Zhao et al., 2002; Xu, 2009). This formation is the main ore-bearing strata of the deposit; and the average gold content of this formation is 0.3 g/t (Yang et al., 2001b), which is 80 times higher than the average concentration of gold in the crust (0.004 g/t) (Taylor, 1964). Until recently, it was believed that no volcanic activity occurred during sedimentation. However, a large quantity of acidic volcanic rocks alternating with metamorphosed sandstone and siltstone have recently been found in the fourth and fifth sub-members of the first member (Yang et al., 2001a, 2001b; Liu and Yang, 2002). Some scholars concluded that these volcanic rocks were products of submarine volcanism with a Sm-Nd model age of 1200 Ma (Yang et al., 2001a; Liu and Yang, 2002). The acidic volcanic rocks are closely related to gold



Fig. 1. Simplified regional geological map of the Zhulazhaga gold deposit (modified after Xu, 2009; Cong et al., 2009). The Zhulazhaga gold deposit is located in an approximately N–S-trending fault zone near to the boundary between the North China Craton and Tianshan–Xingmeng orogenic belt. A granite porphyry stock crops out 2 km southeast of the ore district.



Fig. 2. Simplified geological map of the Zhulazhaga gold deposit showing the locality and distribution of orebodies and the relationship between orebodies and faults (modified after Jiang and Nie, 2005; Yang et al., 2001b).

mineralization and are one of the major host rocks to the ore (Yang et al., 2001a, 2001b; Liu and Yang, 2002).

2.2. Structural geology

The Zhulazhaga gold deposit is located near to the boundary between the NCC and Tianshan–Xingmeng orogenic belt (Fig. 1). The Bayanxibie–Zhulazhagamaodao anticline is believed to have been formed in Devonian (Meng et al., 2002; Zhao et al., 2002; Xu, 2009), and it is the largest fold in the study area; the fold has a northeast– southwest axial orientation, and the northwest limb dips at 45–65° towards NW, whereas the southeast limb dips at 40–60° to SE (Xu, 2009). The Zhulazhaga gold deposit is situated at the southeast limb of this anticline. The Bayanxibie–Ulan Neihasha thrust nappe structure is located in the northwest part of the study area (Fig. 1), and the Zhulazhaga gold deposit is situated near to the thrust surface (Meng et al., 2002; Zhao et al., 2002).

The study area is cut by approximately N–S-, NE- and NW-trending faults, with subordinate NNE- and approximately EW-striking faults (Figs. 1, 2); these faults are grouped into three stages (Jiang et al., 2001a; Yang et al., 2001b; Ding, 2002; Jiang and Nie, 2005).

- Stage 1 The NE- and approximately EW-trending faults were formed. These faults are reversed in displacement, and cut by late faults. This set of faults has the same strike as the bedding, but the faults dip 45° to north (opposite to the dip direction of the bedding). Extensional fractures associated with these faults are developed in the strata on both sides of these faults and subparallel to the bedding surface (Jiang et al., 2001a; Zhao et al., 2002).
- Stage 2 The ~N–S-trending faults were formed, with a length of >10 km and a width of <10 m. These faults have dextral strike–slip displacement, and generally dip 60° to west, and show a maximum displacement of 50 m (Jiang et al., 2001a). The NNEtrending faults are subsidiary faults of the N–S-trending faults (Jiang and Nie, 2005), and dip to NW with a length of more than 300 m. These major and subsidiary faults were intruded by dykes of plagioclase–amphibole lamprophyre and diabaseporphyry (Fig. 2) (Li et al., 2010).

The orebodies of this deposit are located immediately to the east and west of a N–S-trending fault (Fig. 2). The N–S-, NNE- and NE-trending set of faults and the extensional fractures

associated with the NE-trending faults are the principal orecontrolling structures, which are thought to have provided pathways for the transportation of gold-bearing fluids as well as structural sites for the deposition of gold.

Stage 3 The ~N–S-trending faults and its subsidiary faults were reactivated; the previously formed dykes along these faults were fractured. Some other subsidiary NNE–NE trending faults were also formed (Jiang et al., 2001a; Yang et al., 2001b; Ding, 2002; Jiang and Nie, 2005).

Faulting in stages 1 and 2 appear to be pre- and syn-mineralization in age. In stage 3, no gold mineralization occurred; faults formed at this stage crosscut the orebodies, so they post-date the mineralization process.

2.3. Magmatic rocks

Magmatic rocks are widespread in the study area, including granite porphyry, gabbro, diorite, diorite-porphyry and diabase. Two main periods of magmatism are recognized: Caledonian and Hercynian. The Caledonian magmatic activity is represented by calc-alkaline gabbros consisting mainly of andesine, augite and plagioclase partially replaced by albite (Jiang et al., 2001a; Zhao et al., 2002). The chondritenormalized REE pattern of the gabbro is characterized by enrichment in light REE without Eu and Ce anomalies (Jiang et al., 2001a). The Hercynian magmatic activity is represented by alkaline granite porphyries which were generated following subduction of the Paleo-Asian Ocean plate underneath the NCC. The granite porphyries have yielded a SHRIMP zircon U–Pb age of 280 ± 6 Ma (Li et al., 2010) and a biotite K–Ar isochron age of 291 \pm 4 Ma (Jiang et al., 2000), respectively. They intruded the strata of Agulugou Formation and belong to alkaline series and consist mainly of quartz, feldspar and biotite with phenocrysts of K-feldspar and quartz (Jiang and Nie, 2005). The ratio between light and heavy REE in the granite porphyries is relatively high, and the chondrite-normalized REE pattern is characterized by an obvious negative Eu anomaly (Yang et al., 2001b), indicating that extensive differentiation might have taken place.

No large intrusive body has been observed within the mine district, with the exception of a few plagioclase–amphibole lamprophyre, diabase-porphyry, diorite-porphyry and granite aplite dykes (Fig. 2). The plagioclase–amphibole lamprophyre and diabase–



Fig. 3. Field photographs showing the geology and mineralization of the Zhulazhaga gold deposit. A–Overview photograph showing the open pit; B–Slightly altered host rock, interbedding of low-grade metamorphic calcareous quartz sandstone and silty slate; C–Hand specimen of oxidized ore; D–pyrite-bearing quartz-vein paralleling bedding; E–Primary sedimentary bedding in ore; F–Thin pyrite and pyrrhotite veins parallel to bedding in ore; G–Thick pyrite, pyrrhotite and arsenopyrite veins parallel to bedding in ore, indicative of interbedding of high-grade and low-grade sublayers.

porphyry dykes were fractured and weakly mineralized; they predated gold mineralization. As the granite aplite and dioriteporphyry not only crosscut the pre-ore dykes but also transect orebodies, they are considered to postdate the mineralized dykes. Although these dykes are different in age and lithology, Jiang et al. (2001a) suggested that they may be the products of the evolution of comagmatic magmatism.

The granite porphyry stock cropping out 2 km southeast of the ore district (Fig. 1) appears to be genetically associated with the Zhulazhaga gold deposit (Jiang and Nie, 2005; Li et al., 2010). In addition, the rocks of the area experienced contact metamorphism (Xu, 2009), and the contact between the granite porphyry stock and Agulugou Formation dips outward at a low angle (Li et al., 2010). Geophysical survey shows that there is a high-resistance body in the southwest part of the ore district (Zhang et al., 2001; Zhao et al., 2002), suggesting the presence of a concealed granite porphyry body at depth.

3. Deposit geology

3.1. Host rocks

Gold mineralization is mainly hosted by the fourth sub-member of the first member of Agulugou Formation (Fig. 2), and occurs selectively in metamorphosed siltstone and calcareous quartz sandstone (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Meng et al., 2002; Jiang and Nie, 2005; Xu, 2009). The host member is about 300 m in thickness, and consists mainly of metamorphosed calcareous sandstone (siltstone), quartz siltstone and sandstone, and interlayered with silty slates (Fig. 3B). In addition, the interbedded acidic volcanic rocks, microcrystalline marble and actinolite rocks are sporadically distributed in this sub-member (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Meng et al., 2002; Jiang and Nie, 2005; Xu, 2009).

The Agulugou Formation has great competency contrasts in the succession. The calcareous or quartz siltstone and sandstone are more competent and tend to deform in a more brittle fashion, making them more permeable and susceptible to migration and accumulation of ore fluids; the silty slate and actinolite-bearing rocks, by contrast, are less competent and tend to deform in a more ductile fashion (Meng et al., 2002). The interface between different lithologies provides a locus for dilational sites and extensional structure (Killick and Scheepers, 2005). The intermediate-acidic volcanic rocks are closely associated with gold mineralization and are one of the major ore-hosting rocks (Yang et al., 2001b).

3.2. Alteration

The rocks of the study area have experienced greenschist facies regional metamorphism, and comprise of a sequence of slate, schist and phyllite. Actinolitization, chloritization and carbonatization are pervasive (Jiang et al., 2001a; Yang et al., 2001b; Ding, 2002; Jiang and Nie, 2005).

Extensive hydrothermal alterations are observed in wall rocks adjacent to the orebodies, including actinolitization, silicification, chloritization, epidotization and carbonatization. Locally, greisenization and adularization are observed (Yang et al., 2001b; Jiang et al., 2001a, 2001b; Liu and Yang, 2002; Jiang and Nie, 2005). The alteration mineralogy is controlled by the composition of the original rock; alteration zonation is not present. Although some actinolite, chlorite and carbonate mineralogy is produced by regional metamorphism, this assemblage was overprinted by late hydrothermal alteration. For example, early actinolite is often replaced by late carbonate (Jiang and Nie, 2005).

The strongest alteration (especially chloritization and silicification) of country rocks is associated with elevated gold concentrations. The orebodies are located in the central part of alteration zones that are usually 1–3 times wider than the orebodies (Fig. 2). Besides hydrothermal alteration, chalcedonization, malachitization, ferritization and jarositization are developed in the supergene enrichment zone. Ferritization and kaolinization are closely associated with secondary enrichment in gold (Jiang et al., 2001a; Yang et al., 2001b).

3.3. Orebodies

A total of two ore zones and fifty-six gold orebodies have been identified (Fig. 2) (Jiang et al., 2001a, 2001b; Yang et al., 2001b; Xu, 2009). Ore zone I, consisting of thirteen orebodies, locates in the southeast part of the mine district. It is about 400 m long with a maximum width of 80 m. Ore zone II, consisting of forty-three orebodies, lies in the central part of the mine district; it is the main ore zone with a length of 570 m and a maximum width of 180 m, hosting the largest orebody of the Zhulazhaga gold deposit (Fig. 2). Orebodies are mainly stratiform and lenticular within the strata, commonly dipping to ~140° at 35° (Fig. 4). The orebodies are generally 10 to 300 m long with width of 1 to 30 m, and display a thickening downward pattern (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Ding, 2002; Meng et al., 2002; Zhao et al., 2002; Xu, 2009; Li et al., 2010).

The orebodies are located immediately to the east and west of a N–Strending fault and controlled by extensional fractures and NE-trending faults. Closer to the N–S-trending fault, the orebodies dominate, and further away from the N–S-trending fault they become fewer, thinner, and lower grade (Fig. 2). There are many auriferous quartz veins parallel to the orientation of the orebodies. These veins vary in proportion, with few or no veins in the upper part of the alteration zones, fine veins in the center, and thick veins in the lower part of the alteration zones. The characteristics of the orebodies indicate that gold mineralization is related to ore fluids migrating through the N–S-trending and NEtrending faults as well as through extensional fractures.

3.4. Ore

The gold ores can be divided into primary and oxidized types. The oxidized ores are generally yellowish-brown to reddish-brown in color (Fig. 3C) and occur above 20 m in depth (Meng et al., 2002; Cong et al., 2008; Cong et al., 2009). The ores were products of oxidation and leaching of the primary ores. Some of the gold-bearing minerals were decomposed during oxidation and leaching, releasing gold that



Fig. 4. Simplified typical geological section of the Zhulazhaga gold deposit showing that the orebodies are almost bedding-parallel (modified after Jiang and Nie, 2005). Looking northeast.

was subsequently absorbed by clay minerals and then upgraded by secondary enrichment. These processes would increase the gold grade of the oxidized type ore to concentrations above 5 g/t (Jiang et al., 2001b).

The unoxidized primary mineralization of the Zhulazhaga deposit accounts for >90% of the total gold resources. Gold grade in the primary ore ranges from 2 to 3 g/t. Depending on the nature of the host rocks, the primary ore can be divided into two subtypes: 1. sulfide quartz-vein type (Fig. 3D), and 2. altered host-rock type (Fig. 3E, F, G) (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Liu and Yang, 2002). The quartz vein type is rich in gold (3–10 g/t Au) and located in the central part of the alteration zone, but accounts for only small proportion of the gold resource in the deposit (Meng et al., 2002; Xu, 2009). The altered host-rock type is the main primary ore type, and is the product of pervasive mineralization in the precursor rocks in alternating high-grade and low-grade layers; some of the layers retain evidence of primary sedimentary bedding (Fig. 3E, F, G). High-grade ore preferentially occurs near to quartz veins, which indicates that quartz veins played an important role in the concentration of the gold.

3.5. Mineralogy

Major ore minerals include pyrite, pyrrhotite, and arsenopyrite; subordinate species are chalcopyrite, galena, and sphalerite at abundances of <5 modal percent (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Liu and Yang, 2002). Arsenopyrite and pyrite are often replaced by pyrrhotite, and pyrrhotite by chalcopyrite (Liu and Yang, 2002). Limonite, covelline, bornite and jarosite occur in oxidized mineral zones near to the surface. Gangue minerals comprise mainly quartz, feldspar, chlorite, epidote, actinolite and calcite, with minor sericite, dolomite, muscovite and tourmaline. Malachite, kaolinite and gypsum occur only in the oxidized mineral zones (Jiang et al., 2000, 2001a, 2001b; Yang et al., 2001b; Liu and Yang, 2002).

Gold in the Zhulazhaga deposit occurs mostly in the native form and as electrum, and is generally fine-grained and rarely visible in hand specimen (Jiang and Nie, 2005). The gold grains are irregular granular, flaky and worm-like (Liu and Yang, 2002). Gold coexists mainly with quartz, arsenopyrite and pyrite, and occurs along fractures in the sulfide minerals and along grain boundaries; minor gold also occur as inclusions in arsenopyrite and pyrite. Gold is also concentrated in limonite and kaoline in oxidation zones. Gold grades are positively correlated with the amounts of sulfide (especially arsenopyrite) in the mineralized rocks and ores (Yang et al., 2001b; Zhao et al., 2002; Meng et al., 2002; Liu and Yang, 2002; Xu, 2009; Li et al., 2010).

3.6. Isotope geochemistry

The δ^{34} S values of sulfide minerals from the orebodies are between 1.1 and 7.1‰ with an average of 3.8‰ (Jiang et al., 2001b). Although



Fig. 5. δ^{34} S values of some geologically important sulfur reservoirs (modified after Hoefs, 1997) and sulfur from Zhulazhaga gold deposit (data from Jiang et al., 2001b).

these positive near-zero δ^{34} S values overlap with those of gold deposits hosted in the contact zones of granitic intrusions (Luo et al., 1993) and indicate a possible magmatic source in many magmatic hydrothermal deposits (Hoefs, 1997), they are not diagnostic of the sulfur sources in this deposit, as they vary widely and their average value is compatible with those in granitic rocks, sedimentary rocks and metamorphic rocks (Fig. 5) (Hoefs, 1997; Shan et al., 2009). The large variation of δ^{34} S can be explained by either mixing different sources or the oxidation effect of a reduced fluid (Hodkiewicz et al., 2009). Since sulfate minerals are absent in this deposit, a mixing model is preferred. Thus, the δ^{34} S values of ore at Zhulazhaga indicate a magmatic sulfur source which may be contaminated by contributions from crustal S sources.

The ore sulfides have present day ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb values of 17.034–17.725 (average 17.302), 15.297–15.552 (15.457), and 36.599–37.489 (37.043) (Jiang et al., 2001b), respectively. The metasedimentary rock has ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb values of 16.971, 15.031, and 36.347 (Jiang et al., 2001b), respectively. The granite porphyry has ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb values of 17.776, 15.491, and 37.676 (Jiang et al., 2001b), respectively. When the isotope ratios are plotted against each other (Fig. 6A, B), the lead isotopic compositions of ore sulfides plot across the fields of upper crust, orogen, mantle and lower crust lines (Zartman and Doe, 1981), indicating a complex lead source. The lead isotope ratio data indicate that the lead isotopic compositions of sulfides range between those of metasedimentary rock and granite porphyry (Fig. 6A, B), indicating that the ore lead might be sourced from both metasedimentary rocks and magmatic fluids.

Hydrogen and oxygen isotopes are important monitors for the evolutionary history of ore-forming fluids. The δ^{18} O values of the auriferous quartz from the Zhulazhaga deposit vary from 11.9 to 16.3‰, and the calculated $\delta^{18}O_{H_2O}$ values of ore-forming fluids by using model of 10001n α = 3.38 * 10⁶/T² – 2.9 at homogenization temperature range from 1.06 to 9.60‰. The δD_{H_2O} values of the inclusion fluids in the auriferous quartz vary from – 67 to – 109‰ (Ding, 2002; Jiang and Nie, 2005). The H–O isotopic compositions indicate that the ore fluids may be of mixtures of meteoric water and magmatic water, with a larger contribution from magmatic water (Taylor, 1974; Jiang and Nie, 2005).

3.7. Fluid inclusions

There are more fluid inclusions within the deep-seated quartz veins relative to those from the surface or near the surface. Three types of fluid inclusions were identified by Jiang and Nie (2005), and they are represented by two-phase H₂O-rich (V_{H₂O} + L_{H₂O}), CO₂-rich (V_{CO₂} + L_{H₂O} + L_{CO₂}), and daughter crystal-bearing (V_{H₂O} + L_{H₂O} + S) three-phase inclusions.}

Two-phase H₂O-rich inclusions are the dominant type in the auriferous quartz, in where water vapor contents range from 5 to 25 vol.% (mainly from 10 to 20 vol.%). These aqueous inclusions, ranging from 3 to 36 μ m in diameter, exhibit regular (round or ellipsoid) or incomplete negative crystal shapes. In comparison, the CO₂-rich and daughter crystal-bearing three-phase inclusions are uncommon, and can only be indentified within few quartz samples. The daughter crystal-bearing three phase inclusions range in diameter from 5 to 16 μ m, with the H₂O phase accounting for 60–85 vol.% and daughter crystals accounting for 5–20 vol.%. The three-phase CO₂-rich inclusions vary from 7 to 19 μ m in diameter, with L_{CO₂} phase accounting for 15–30 vol.% and V_{CO₂} phase accounting for 5 vol.% (Ding, 2002; Jiang and Nie, 2005).

The homogenization temperatures of the two-phase H₂O-rich inclusions are 155–401 °C, with an average temperature of 284 °C and peak values of 240–260 °C and 300–320 °C (Fig. 7). The homogenization temperatures of the three-phase daughter crystal-bearing inclusions range from 210 °C to 435 °C (Ding, 2002; Jiang and Nie, 2005). The homogenization temperatures of the fluid inclusions gradually increase with



Fig. 6. The ²⁰⁷Pb/²⁰⁴Pb versus ²⁰⁶Pb/²⁰⁴Pb (A) and ²⁰⁸Pb/²⁰⁴Pb versus ²⁰⁶Pb/²⁰⁴Pb (B) diagrams showing the lead isotopic features of ore and related lithologies (after Jiang et al., 2001b). The lead isotopic compositions of ore sulfides plot across the fields of upper crust, orogen, mantle and lower crust lines, and range between those of metasedimentary rock and granite porphyry.

depth, and this indicates a moderate to high ore-forming temperature, consistent with the appearance of pyrrhotite.

The salinities of two-phase H₂O-rich inclusions range from 9.22 to 24.30 wt.% NaCl equiv., with an average of 21.66 wt.% NaCl equiv. and a peak value of 23–24 wt.% NaCl equiv. (Fig. 8). The salinities of the three-phase daughter crystal-bearing inclusions range from 29.13 to 32.62 wt.% NaCl equiv. (Jiang and Nie, 2005). Although most of the fluid inclusions in the auriferous quartz can be approximately represented by NaCl-H₂O system (Ding, 2002), the ice-melting temperatures of some inclusions are lower than those in the pure H₂O-NaCl system (Liu, 2001), indicating that these inclusions belong to the H₂O-NaCl-CaCl₂ system (Jiang and Nie, 2005).

Therefore, the ore-forming fluids of the Zhulazhaga gold deposit are characterized by moderate to high temperature and high salinity, consistent with formation from magmatic hydrothermal fluids (Chen et al., 2009; Liu et al., 2014; Adeli et al., 2015).

4. Discussion and conclusions

4.1. Deposit genesis

The Zhulazhaga gold deposit is genetically associated with the magmatic hydrothermal activity based on the following evidence.

(1) The deposit is structurally controlled, where the orebodies are present immediately to the east and west of a N–S-trending fault, but are controlled by extensional fractures and NEtrending faults. More orebodies are present nearer to the N–Strending fault, and they become thinner and lower in grade farther away from the N–S-trending fault.



Fig. 7. Histogram of homogenization temperatures of two-phase H_2O -rich fluid inclusions in the Zhulazhaga gold deposit (after Ding, 2002; Jiang and Nie, 2005), ranging from 155 to 401 °C (average 284 °C) with two peaks at 240–260 °C and 300–320 °C.

- (2) There are many auriferous quartz veins parallel to the orientation of the orebodies. These veins vary in proportion, with few or no veins in the upper part of the alteration zones, fine veins in the center, and thick veins in the lower part of the alteration zones. High-grade ore preferentially occurs near to the quartz veins.
- (3) Hydrothermal alterations are well developed in the mine district. Usually, the stronger the alteration (especially chloritization and silicification), the higher gold concentration is present. The orebodies are located in the central part of the alteration zone.
- (4) The δ^{34} S values of ores at Zhulazhaga indicate a magmatic sulfur source contaminated by crustal material, supported by lead isotope data.
- (5) The H–O isotopic compositions reflect that ore-forming fluids may be of mixed meteoric water and magmatic water, and mainly derived from magmatic water.
- (6) The ore-forming fluids of the Zhulazhaga gold deposit are characterized by moderate to high temperature and high salinity, consistent with magmatic hydrothermal fluids.

4.2. Towards a genetic model

The data presented above are now incorporated into a tentative genetic model (Fig. 9A, B) that may be useful for gold exploration in the northern margin of the NCC.

4.2.1. Protore

The average gold content of rocks in the first member of the Agulugou Formation is up to 0.3 g/t (Yang et al., 2001b), which is 80



Fig. 8. Histogram of calculated salinities of the two-phase H_2O -rich fluid solutions in the Zhulazhaga gold deposit (after Jiang and Nie, 2005; Ding, 2002). The salinities of the two-phase H_2O -rich inclusions range from 9.22 to 24.30 wt.% NaCl equiv., with an average of 21.66 wt.% NaCl equiv. and a peak value of 23–24 wt.% NaCl equiv.



Fig. 9. A genetic model for the Zhulazhaga gold deposit. A—Lithostratigraphic control: the first member of the Agulugou Formation appears to be a protore for gold; tectonic activities produced shear zones, extensional structures and dilational sites. The more competent sublayer deformed in a more brittle fashion; B—Intrusion of granite porphyry and related hydrothermal events that generated ore fluids may have been enhanced by remobilizing gold from wallrocks (protore) along the pathways (structures) and migrated favorable depositional environment forming the gold deposit. High grade ore and quartz veins are preferentially formed in the extensional structures and more permeable and susceptible sublayers.

times higher than the average concentration of gold in the crust (0.004 g/t) (Taylor, 1964). Although elevated gold in the Agulugou Formation may be induced by hydrothermal fluids that resulted in

extensive alteration in the mine district, and there is presently no strong evidence to suggest that the Agulugou Formation is the source of the metal, the protore source model is supported by several facts. Wang



Fig. 10. Regional map showing the distribution of Mesoproterozoic metasedimentary rocks that host major deposits (modified after Nie et al., 2010).

Table 1

Isotope geochronology data of ore and granite porphyry from the Zhulazhaga gold deposit.

Test object	Method	Age (Ma)	References
Granite porphyry	Zircon U–Pb	$304 \pm 5280 \pm 6291.48 \pm 4.2208 \pm 5258.6 \pm 5.7258.6 \pm 5.7$	Li et al. (2004)
Granite porphyry	SHRIMP zircon U–Pb		Li et al. (2010)
Biotite from granite porphyry	K–Ar		Jiang et al. (2000)
Whole rock granite porphyry	K–Ar		Meng et al. (2002)
Post-mineralization diorite-porphyrite	Zircon U–Pb		Li et al. (2004)
Post-mineralization diorite-porphyrite	SHRIMP zircon U–Pb	279.7 ± 5.2	Li et al. (2010)
Auriferous quartz vein	⁴⁰ Ar/ ³⁹ Ar	282.3 ± 0.9	Li et al. (2004)
Whole-rock ore	Rb–Sr	275 ± 6	Yang et al. (2001b)

et al. (2014) suggested that the Proterozoic metasedimentary rocks in the northern margin of the NCC, composed of clastic rocks, carbonate rocks, and minor volcanic rocks, are rich in gold, and may be a potential source for gold mineralization. There are many polymetallic deposits, such as the Dongshengmiao, Tanyaokou, Huogeqi and Jiashengpan deposits, present in this rock series (Fig. 10), and a Mesoproterozoic exhalative–sedimentary (i.e., syngenetic) model is the most popular genetic model proposed for these deposits (An et al., 2004; Shen et al., 2004; Peng et al., 2005, 2006; Fu et al., 2010; Zhong et al., 2012, 2013). Au grade in these deposits is about 0.2 g/t (Shao, 1999).

The volcanic interlayers within the fourth sub-member of the first member of the Agulugou Formation are closely related to gold mineralization. The volcanic rocks may have been able to interact with auriferous fluids and cause precipitation of gold. The host rocks are also characterized by high reduced carbon content (Wang et al., 2014), which may have been able to reduce auriferous hydrothermal solutions and cause deposition of gold. In summary, the lithogeochemical control to gold mineralization may be a protore for gold and a favorable depositional environment.

4.2.2. Lithostratigraphic control

The most important lithostratigraphic control is the competency contrasts between rock types. The Agulugou Formation has great competency contrasts in the succession. The calcareous or quartz siltstone and sandstone are more competent and tend to deform in a more brittle fashion; the silty slate and actinolite-bearing rocks, by contrast, are less competent and tend to deform in a more ductile fashion (Meng et al., 2002). The mechanical effect of competency contrast has an important bearing on the migration and localization of the mineralizing fluids and is critical to the development of favorable depositional site for several reasons (Killick and Scheepers, 2005):

- (1) The interface between different lithologic beds provides a locus for shear zones and extensional structures (Fig. 9A).
- (2) Buckling of the beds with different competency and thickness will induce folds of different wavelength (Ramsey, 1968). The resultant disharmony will create dilational sites and voids or areas of relatively low stress through which the fluids migrate (Fig. 9A).
- (3) The more competent calcareous or quartz siltstone and sandstone deformed in a more brittle fashion, makes them more permeable and susceptible to ore deposition (Meng et al., 2002).

4.2.3. Magmatic-hydrothermal mineralization

In order to determine the trigger event and timing of magmatic-hydrothermal mineralization, we assembled isotope ratio dating data from works undertaken by various research teams (Table 1). Based on these data we conclude that magmatic-hydrothermal mineralization of Zhulazhaga gold deposit took place at about 280 Ma, consistent with the age of granite porphyry in the district that was dated around 280– 290 Ma. They are close in age and were both formed during the Hercynian epoch. The lead and sulfur isotope data for the ores indicate a close genetic relationship with the granite porphyry. During the formation of the granite porphyry, extensive differentiation likely took place, releasing large amounts of magmatic fluid. There are no other synmetallogenic magmatic rocks in the district, so it is reasonable to link the genesis of the Zhulazhaga gold deposit to the Hercynian granite porphyry.

4.2.4. Gold precipitation

The subduction of the Paleo-Asian Ocean plate towards the NCC in Hercynian epoch resulted in the extensive intrusion of granite porphyry (Li, 2006). The Hercynian granite porphyry may have been the heat source, and the source of ore-forming elements and fluids in the formation of the deposit. Hercynian tectono-magmatic and subsequent hydrothermal events may have remobilized gold and driven the oreforming fluids to favorable depositional environments along the approximately N–S-trending, NE-trending faults and into the associated extensional fractures (Fig. 9B).

The fluid inclusion investigation on the Zhulazhaga gold deposit indicates that NaCl-rich brines with subordinate amounts of CO₂ (Ding, 2002; Jiang and Nie, 2005) remobilized and transported gold at temperatures in excess of 240 °C. Either chloride, sulfide or hydrocarbonate complexes of gold are possibly to transport ore materials depending upon the conditions of T–P–X– fO_2 – fS_2 . Chloride complexes (HAuCl₄) are likely to be more important at higher temperatures (Fyfe and Kerrich, 1982) whereas thio-complexes (AuHS) were more likely present at lower temperatures (Henley and Ellis, 1983). A better understanding of the nature of ore fluid, vein composition and wall-rock alteration is required to constrain the processes responsible for the deposition of gold in the fourth sub-member of the first member of Agulugou Formation. Nevertheless, it is speculated that gold precipitation could have been due to one or more of the following factors.

- It is possible that interaction between the host rock and hydrothermal fluid could have resulted in Eh or pH shifts that resulted in de-stabilization of gold complexes (Killick and Scheepers, 2005). The extensive hydrothermal alterations present at the Zhulazhaga gold deposit indicate that this process is likely to have been important in gold precipitation.
- (2) A drop in temperature is one of the most common causes for precipitation of gold carried as a chloride complex at temperatures above 300 °C (Barnes, 1979). The fluid inclusion data show the presence of brines related to the formation of this deposit.
- (3) Mixing of two fluids with different attributes on either side of the stratigraphic barrier (Killick and Scheepers, 2005) may have also caused the development of gold mineralization.

4.3. Regional scale mineral potential

The Proterozoic metasedimentary rocks (e.g., the Zhaertaishan Group in the west, the Bayan Obo Group in the east) are widely distributed in the northern margin of the NCC, and extend more than 2000 km from east to west (Fig. 10) (Tu, 1990; Lu, 1997; Nie et al., 2010;

Wang et al., 2014). They were deposited in continental margin rifts when the NCC underwent regional extension and break-up in the Mesoproterozoic (Wang et al., 2014). The rock series, composed of clastic rocks, carbonate rocks, and minor volcanic rocks, are rich in gold, and may be a potential source for the gold mineralization (Wang et al., 2014).

Some other similar gold deposits, such as the Haoyaoerhudong and Saiyinwusu Deposits, have been discovered in the metasedimentary rocks in the northern margin of the NCC (An et al., 2004; Nie et al., 2010; Wang et al., 2014). Field observations and geochronology research also show an intimate spatial and temporal relationship between the Haoyaoerhudong gold deposit and Hercynian granitoid intrusions (Xiao et al., 2012; Wang et al., 2014).

The structures and Hercynian granitoids were well developed in the northern margin of the NCC due to the Hercynian tectono-magmatism associated with subduction of the Paleo-Asian Ocean plate underneath the NCC (Li, 2006). Wang et al. (2014) suggested that the northern margin of the NCC is the eastern part of the Central Asia gold belt. Hercynian is one of the most important gold mineralization epochs in the northern margin of the NCC.

In summary, the northern margin of the NCC is a prospective area for gold exploration. Structure-controlled, magmatic-hydrothermal gold deposits hosted in Proterozoic metasedimentary rocks would become one of the most important targets for gold exploration in northern China and elsewhere.

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References

- Adeli, Z., Rasa, I., Darvishzadeh, A., 2015. Fluid inclusion study of the ore-quartz veins at Haftcheshmeh porphyry copper (Mo) deposit, Ahar–Arasbaran Magmatic Belt, NW Iran. Ore Geol. Rev. 65, 502–511.
- Aleinikoff, J.N., Slack, J.F., Lund, K.I., Evans, K.V., Mazdab, F.K., Pillars, R.M., Fanning, C.M., 2012. Constraints on the timing of Co–Cu ± Au mineralization in the Blackbird district, Idaho, using SHRIMP U–Pb ages of monazite and xenotime plus zircon ages of related Mesoproterozoic orthogneisses and metasedimentary rocks. Econ. Geol. 107, 1143–1175.
- An, C.J., Ding, T.C., Huang, Z.Q., Zhang, Z.X., Leng, F.R., Cong, L.J., 2004. Geochemical characteristics of Pt and Pd in the Zhaertaishan and Bayan Obo groups, Inner Mongolia, and Ore-prospecting suggestions. Geol. Bull. China 23 (11), 1149–1152 (in Chinese with English abstract).
- Arehart, G.B., 1996. Characteristics and origin of sediment-hosted disseminated gold deposits: a review. Ore Geol. Rev. 11 (6), 383–403.
- Barnes, H.L., 1979. Solubilities of ore minerals. In: Barnes, H.L. (Ed.), Geochemistry of Hydrothermal Ore Deposits. Wiley-Interscience, New York, pp. 404–460.
- Chen, Y.J., Pirajno, F., Li, N., Guo, D.S., Lai, Y., 2009. Isotope systematics and fluid inclusion studies of the Qiyugou breccia pipe-hosted gold deposit, Qinling Orogen, Henan province, China: implications for ore genesis. Ore Geol. Rev. 35, 245–261.
- Cong, LJ, Cen, K., Huang, Z.F., Leng, F.R., Liu, J.B., Wang, Z., 2008. Comparative analysis between the altered rock anomaly extracted from ETM + and the geochemical anomaly in the Zhulazhaga gold deposit of western Inner Mongolia. Geol. Miner. Resour. South China 1, 29–35 (in Chinese with English abstract).
- Cong, L.M., Li, G.Z., Liao, L., Song, J.F., 2009. Effect analysis on the multi-source remote sensing data superimposed prospecting—taking Zhulazhaga gold mine in western Neimenggu as the example. Guizhou Geol. 26 (4), 284–289 (in Chinese with English abstract).
- Cox, S.F., Wall, V.J., Etheridge, M.E., Potter, T.F., 1991. Deformational and metamorphic processes in the formation of mesothermal vein-type gold deposits—examples from the Lachlan fold belt in Central Victoria, Australia. Ore Geol. Rev. 6, 391–423.
- Ding, Q.F., Wang, G., 2009. Study on fluid inclusions and genesis of Mobin gold deposit in Hunan Province. Glob. Geol. 28 (4), 467–475 (in Chinese with English abstract).

- Ding, T.C., 2002. Geological Characteristics, Mineralization Regularities and Origin of Zhulazhaga Gold Deposit in Inner Mongolia. (Master Degree Thesis), China University of Geosciences, Beijing (50 pp. (in Chinese with English abstract)).
- Foster, D.A., Gray, D.R., Kwak, T.A.P., Bucher, M., 1998. Chronology and tectonic framework of turbidite-hosted gold deposits in the Western Lachlan Fold Belt, Victoria: ⁴⁰Ar-³⁹Ar results. Ore Geol. Rev. 13, 229–250.
- Fu, C., Wang, J.P., Peng, R.M., Liu, J.J., Liu, Z.J., Liu, Z.M., 2010. Features of sulfur isotope of the Jiashengpan lead-zinc-sulfur deposit in Inner Mongolia and its genesis significance. Geoscience 24 (1), 34–41 (in Chinese with English abstract).
- Fyfe, W.S., Kerrich, R., 1982. Gold: natural concentration processes. In: Foster, R.P. (Ed.), The Geology, Geochemistry and Genesis of Gold Deposits. Special Publication 1. Geological Society of Zimbabwe, pp. 99–127.
- Goellnicht, N.M., Dimo, G., Groves, D.I., McNaughton, N.J., 1988. An epigenetic origin for the Telfer gold deposit. Bicentennial Gold 88, Extended Abstracts. Geological Society of Australia, pp. 79–84 (Abstract 22).
- Gu, X.X., Liu, J.M., Oskar, S., Franz, V., Zheng, M.H., 2004. Syngenetic origin of the Woxi W– Sb–Au deposit in Hunan: evidence from trace elements and sulfur isotopes. Chin. J. Geol. 39 (3), 424–439 (in Chinese with English abstract).
- Guo, S.S., 2008. Analysis on the genesis and ore-controlling factors of the Haoyaoerhudong gold deposit. China Sci. Technol. Rev. 16, 21–23 (in Chinese with English abstract).
- Harley, M., Charlesworth, E.G., 1992. Thrust-controlled gold mineralization at the Elandshoogte Mine, Sabie-Pilgrim's Rest Goldfield, South Africa. Mineral. Deposita 27, 122–128.
- Henley, R.W., Ellis, A.J., 1983. Geothermal systems ancient and modern: a geochemical review. Earth Sci. Rev. 19 (1), 1–50.
- Hodkiewicz, P.F., Groves, D.I., Davidson, G.J., Weinberg, R.F., Hagemann, S.G., 2009. Influence of structural setting on sulphur isotopes in Archean orogenic gold deposits, Eastern Goldfields Province, Yilgarn, Western Australia. Mineral. Deposita 44 (2), 129–150.
- Hoefs, J., 1997. Stable Isotope Geochemistry. 4th edition. Springer-Verlag, Berlin (201 pp.).
- Huang, Q.T., Xia, B., Cai, Z.R., Cui, S.S., Wang, B., 2010. Study on tectonic and metallogenic law in Huangjindong gold ore field, Hunan province. Gold Geol. 31 (2), 9–13 (in Chinese with English abstract).
- Jiang, S.H., Nie, F.J., 2005. Geological and geochemical characteristics of the Zhulazhaga gold deposit in Inner Mongolia, China. Acta Geol. Sin. 79 (1), 87–97.
- Jiang, S.H., Yang, Y.Q., Nie, F.J., 2000. Study of the ore genesis of the Zhulazhaga gold deposit in Inner Mongolia, China. Bull. Mineral. Petrol. Geochem. 19 (4), 228–230 (in Chinese).
- Jiang, S.H., Yang, Y.Q., Nie, F.J., Zhang, J.H., Liu, Y., Li, F.X., Jia, L.Z., 2001a. Geological characteristics of the Zhulazhaga gold deposit in Inner Mongolia, China. Mineral Deposits 20 (3), 234–242 (in Chinese with English abstract).
- Jiang, S.H., Yang, Y.Q., Nie, F.J., Wang, J.M., Li, F.X., Jia, L.Z., 2001b. Studies on the sulfur and lead isotopic geology of the Zhulazhaga gold deposit in the Alxa district, Inner Mongolia, China. Geol. Rev. 47 (4), 438–445 (in Chinese with English abstract).
- Jian, X.L., 2004. Geochemical features of the Yindongpo gold deposit in Tongbai region, Henan Province. Geol. Prospect. 40 (2), 41–45 (in Chinese with English abstract).
- Killick, A.M., Scheepers, R., 2005. Controls to hydrothermal gold mineralization in the Witwatersberg Goldfield; situated in the floor to the south of the Bushveld Complex, South Africa. J. Afr. Earth Sci. 41, 235–247.
- Kontak, D.J., Kemch, R., 1997. An isotopic (C, O, Sr) study of vein gold deposits in the Meguma Terrane, Nova Scotia: implication for source reservoirs. Econ. Geol. 92, 161–180.
- Li, J.J., Luo, H., Zhou, H.Y., Sang, H.Q., Qin, Z.A., Wang, S.G., Sun, Z.P., 2004. Metallogenic epoch of Zhulazhaga gold deposit in Alxa area, Inner Mongolia Autonomous region. Geochimica 33 (6), 663–669 (in Chinese with English abstract).
- Li, J.J., Zhai, Y.S., Yang, Y.Q., Wang, Y.B., Li, C.D., Cui, L.W., Zhou, H.Y., Liu, X.Y., Liu, X.X., Li, S., 2010. Re-discussion on the metallogenic age of Zhulazhaga gold deposit in Alashan area, Inner Mongolia: evidence from zircon U–Pb SHRIMP age. Earth Sci. Front. 17 (2), 178–184 (in Chinese with English abstract).
- Li, J.Y., 2006. Permian geodynamic setting of Northeast China and adjacent regions: closure of the Paleo-Asian Ocean and subduction of the Paleo-Pacific Plate. J. Asian Earth Sci. 26 (3), 207–224.
- Liu, B., 2001. Density and isochoric formulae for NaCl-H₂O inclusions with medium and high salinity and their applications. Geol. Rev. 47 (6), 618–622 (in Chinese with English abstract).
- Liu, J., Mao, J.W., Wu, G., Wang, F., Luo, D.F., Hu, Y.Q., Li, T.G., 2014. Fluid inclusions and H– O–S–Pb isotope systematics of the Chalukou giant porphyry Mo deposit, Heilongjiang Province, China. Ore Geol. Rev. 59, 83–96.
- Liu, Y., Yang, Y.Q., 2002. Petrography and mineralography of volcanic rocks from Zhulazhaga gold deposit in Inner Mongolia and their significance. Mineral Deposits 21 (3), 304–310 (in Chinese with English abstract).
- Luo, Z.K., 1995. Types of large-size gold deposit and ore-searching prospect in China. Gold Geol. 1 (1), 20–26 (in Chinese with English abstract).
- Luo, Z.K., Guan, K., Wang, M.Z., Wang, C.T., 1993. Preliminary Discussion on Gold Deposits in China. Tianjin Science and Technology Publishing House, Tianjin (308 pp. (in Chinese)).
- Lu, S.N., 1997. Thinks and prospects for search gold and silver deposits in Meso-Neoproterozoic systems in the North China Platform. Prog. Precambrian Res. 20 (1), 12–16 (in Chinese with English abstract).
- Meffre, S., Large, R.R., Scott, R., Woodhead, J., Chang, Z., Gilbert, S.E., Hergt, J.M., 2008. Age and pyrite Pb-isotopic composition of the giant Sukhoi Log sediment-hosted gold deposit, Russia. Geochim. Cosmochim. Acta 72 (9), 2377–2391.
- Meng, E.G., Zhang, Y.K., Chen, W., 2002. An initial discussion on the ore-forming condition of Zhulazhaga gold deposit and its prospecting direction. Miner. Resour. Geol. 16 (3), 168–173 (in Chinese with English abstract).

- Nie, F.J., Jiang, S.H., Hou, W.R., Liu, Y.F., Xiao, W., 2010. Geological features and genesis of gold deposits hosted by low-grade metamorphic rocks in central western Inner Mongolia. Mineral Deposits 29 (1), 58–70 (in Chinese with English abstract).
- Ouyang, Y.F., Huang, M.X., Liu, W., 2005. The study on genesis of Hetai Au deposit in Guangdong province. Contrib. Geol. Miner. Resour. Res. 20 (3), 166–169 (in Chinese with English abstract).
- Peng, R.M., Zhai, Y.S., Wang, Z.G., Han, X.F., 2005. Discovery of double-peaking potassic volcanic rocks in Langshan Group of the Tanyaokou hydrothermal-sedimentary deposit, Inner Mongolia, and its indicating significance. Sci. China Ser. D Earth Sci. 48 (6), 822–833.
- Peng, R.M., Zhai, Y.S., Wang, Z.G., Han, X.F., Qin, J.W., Wang, J.P., Mei, J.M., 2006. Characteristics and exploration of submarine SEDEX deposits in the Langshan–Zhaertai ore concentration area, Inner Mongolia. Mineral Deposits 25, 221–224 (in Chinese with English abstract).
- Phillips, G.N., Powell, R., 2015. Hydrothermal alteration in the Witwatersrand goldfields. Ore Geol. Rev. 65, 245–273.
- Ramsay, W.R.H., Bierlein, F.P., Arne, D.C., VandenBerg, A.H.M., 1998. Turbidite-hosted gold deposits of Central Victoria, Australia: their regional setting, mineralising styles, and some genetic constraints. Ore Geol. Rev. 13, 131–151.
- Ramsey, J.G., 1968. Folding and Fracturing of Rock. McGraw-Hill, London (568 pp.).
- Shan, L., Zheng, Y.Y., Xu, R.K., Cao, L., Zhang, Y.L., Lian, Y.L., Li, Y.H., 2009. Review on sulfur isotopic tracing and hydrothermal metallogenesis. Geol. Resour. 18 (3), 197–203 (in Chinese with English abstract).
- Shao, H.M., 1999. Explorating gold prospect in middle-upper proterozoic era stratigraphic in Inner Mongolia. Geol. Inner Mong. 1, 1–5 (in Chinese with English abstract).
- Shen, C.L., Wang, S.G., Su, X.X., Ma, R., 2004. Regional metallogenic characteristics in proterozoic Chaertaishan Group, Inner Mongolia. Earth Sci. Front. 11 (1), 279–286 (in Chinese with English abstract).
- Taylor, H.P., 1974. The application of oxygen and hydrogen isotope studies to problem of hydrothermal alteration and ore deposition. Econ. Geol. 69, 843–883.
- Taylor, S.R., 1964. Abundance of chemical elements in the continental crust: a new table. Geochim. Cosmochim. Acta 28 (8), 1273–1285.
- Tu, G.Z., 1990. Classification of primary gold ore deposit and prospect analysis of different type gold ore deposit in China—report in inaugural meeting of mineral, lithogeochemical society of Guangxi. Miner. Resour. Geol. 4 (1), 1–10 (in Chinese with English abstract).
- Tu, S.X., Gao, Y.J., 1990. Fluid inclusions and stable isotopes in the Xinzhou gold deposit, Guangdong province. Geol. Rev. 36 (8), 200–209 (in Chinese with English abstract).

- Wang, J.P., Liu, J.J., Peng, R.M., Liu, Z.J., Zhao, B.S., Li, Z., Wang, Y.F., Liu, C.H., 2014. Gold mineralization in Proterozoic black shales: example from the Haoyaoerhudong gold deposit, northern margin of the North China Craton. Ore Geol. Rev. 63, 150–159.
- Xiao, W., Nie, F.J., Liu, Y.F., Liu, Y., 2012. Isotope geochronology study of the granitoid intrusions in the Changshanhao gold deposit and its geological implications. Acta Petrol. Sin. 28 (2), 535–543 (in Chinese with English abstract).
- Xu, Y., 2009. Gold-ore Resource Assessment of Zhulazhaga Gold Deposit in Inner Mongolia. (Master Degree Thesis), China University of Geosciences, Beijing (54 pp. (in Chinese with English abstract)).
- Yakubchuk, A., Stein, H., Wilde, A., 2014. Results of pilot Re–Os dating of sulfides from the Sukhoi Log and Olympiada orogenic gold deposits, Russia. Ore Geol. Rev. 59, 21–28.
- Yang, Y.Q., Zhang, J.H., Liu, Y., Wang, J.M., Li, F.X., Jia, L.Z., 2001a. Discovery of volcanic rocks in the Zhulazhaga gold deposit, Inner Mongolia. Geol. China 28 (9), 13–18 (in Chinese with English abstract).
- Yang, Y.Q., Jiang, S.H., Nie, F.J., Zhang, J.H., Liu, Y., Li, F.X., 2001b. Geology and genesis of Zhulazhaga gold deposit, Inner Mongolia, China. Geol. Res. 10 (3), 146–152 (in Chinese with English abstract).
- Yin, Z., 2002. The distribution and preferable ore-finding area of gold deposit in Inner Mongolia. Geol. Inner Mong. 4, 8–14 (in Chinese with English abstract).
- Zartman, R.E., Doe, B.R., 1981. Plumbotectonics—the model. Tectonophysics 75, 135–162. Zhang, Z.F., Li, C.Y., Niu, Y.Z., Yang, W.J., Li, F.X., Gao, Y.S., Ge, C.B., 1999. Synthetic prospecting model of Zhulazhaga gold anomaly area, Inner Mongolia. Geol. Inner Mong. 3, 1–14 (in Chinese with English abstract).
- Zhang, Z.F., Ge, C.B., Niu, Y.Z., Li, C.Y., Wu, B., 2001. Synthetic geophysical and geochemical exploration application in expanding Zhulazhaga gold deposit of Inner Mongolia. Geol. Inner Mong. 4, 17–28 (in Chinese with English abstract).
- Zhang, Z.F., Niu, Y.Z., Li, C.Y., Yang, W.J., 2000. The application of integrated geophysical and geochemical techniques to the exploration of Zhulazhaga gold deposit. Geophys. Geochem. Explor. 24 (4), 250–262 (in Chinese with English abstract).
- Zhao, Y.M., Huang, Z.Q., Zhang, Z.X., Ma, R., Song, J.F., He, L., 2002. Features and prognosis of Zhulazhaga gold deposit in Inner Mongolia. Geol. Miner. Resour. South China 4, 47–53 (in Chinese with English abstract).
- Zhong, R.C., Li, W.B., Chen, Y.J., Huo, H.L., 2012. Ore-forming conditions and genesis of the Huogeqi Cu–Pb–Zn–Fe deposit in the northern margin of the North China Craton: evidence from ore petrologic characteristics. Ore Geol. Rev. 44, 107–120.
- Zhong, R.C., Li, W.B., Chen, Y.J., Yue, D.C., Yang, Y.F., 2013. PTX conditions, origin, and evolution of Cu-bearing fluids of the shear zone-hosted Huogeqi Cu–(Pb–Zn–Fe) deposit, northern China. Ore Geol. Rev. 50, 83–97.