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Geodynamic constraints on orebody localization in the Anqing orefield, China: Computational modeling and facilitating predictive exploration of deep deposits

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ABSTRACT

The Anqing Fe–Cu skarn deposit, with an age of 134 to 142 Ma and resources of 62.4 Mt at 0.906% Cu and 32.2% Fe, is one of the most important deposits in the Yangtze River Metallogenic Belt, East China. To better understand the localization of orebodies and thus facilitate predictive exploration of deep orebodies, computational modeling is used to simulate the coupled geodynamic processes during the syn-tectonic cooling of the ore-related intrusion, based on geological and geophysical investigations in the Anqing orefield.

The occurrences of the ore veins and veinlets in diorite and skarn, as well as the sharp zigzag boundary of the orebody, indicate that the Cu ores were deposited after the solidification of the diorite and skarn formation, and were located in some tensional structural spaces that are unevenly distributed along the contact zone between the felsic intrusion and sedimentary carbonates. The locations of orebodies are closely associated with the contact zone shape. The computational results of two models with two typical contact-shapes show that pore fluid flow was focused into the dilation zones from different sources. All the significant dilation zones, in which the existing orebodies were located, are distributed in some specific places of the south contact zone of the intrusion. In addition, these dilation zones are closely related to the contact zone shape of the intrusion and can control the location of orebodies through the coupled mechano-thermo-hydrological processes during cooling of the intrusion in the extension setting. The skarns are not critical for controlling the localization of orebodies. This means that exploration for deep ore should target deep dilation zones close to the contact boundary of the intrusion. Such recognition may provide a useful guide in selecting exploration targets in the Anqing orefield. As a direct result of computational modeling, an orebody has been discovered in the deep dilation zone in this orefield. It demonstrates that computational modeling is a promising tool for understanding the metallogenic processes and for facilitating the deep exploration of hidden orebodies that are related to intrusions.

1. Introduction

Metallogenic studies have made some impressive contributions to the explanation of the general formation and processes involved in ore deposits (e.g., Candela et al., 2005; Franklin et al., 2005; Kerrich et al., 2005; Meinert et al., 2005). Traditional metallogenic theories are, however, not always suitable for conducting sound exploration strategy. The reason for this is the fact that it can often be difficult to obtain sufficient detail concerning an ore-forming system and the critical geodynamic processes responsible for formation and localization of orebodies (Etheridge and Henley, 1997; Liu, 2007; Liu and Peng, 2005; Liu et al., 2005a,b; Price and Stoker, 2002). From this point of view, mineral exploration is still an activity with high economic risk (e.g., Kreuzer et al., 2008; Liu et al., 2005b). A strategy to reduce exploration risk is to apply new technologies for effective target selection and orebody detection. The generation of targets involves the use of an integrative methodology that comprises metallogenetic concepts, geophysics, spatial analysis, mineral economics, decision making and probability theory (Hronsky and Groves, 2008). Since the appropriate generation of targets has the greatest potential of finding undiscovered orebodies, some new techniques such as fuzzy-logic (Knox-Robinson, 2000; Porwal et al., 2003), mineral systems approach (Knox-Robinson and Wyborn, 1997; Kreuzer et al., 2008; Partington, 2010; Wyborn et al., 1994), fractal analysis (Carranza and Sadeghi, 2010; Ford and McCuaig, 2010), and geodynamic modeling (Hobbs et al., 2000; Liu et al., 2005a; Mair et al., 2000), have been applied in the process of generating targets.

The formation of metallic deposits should involve sources that supply metal, fluid and ligand components, and a geodynamic system for transporting the components and depositing the metallic commodity. The geodynamic system is definitely more responsible for the localization of orebodies. Generally, a geodynamic system involves the full feedback coupling between the following five processes: mechanical deformation, pore fluid flow, heat transfer, mass

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transport and chemical reactions (Zhao et al., 1999). The formation and localization of an orebody in a specific place are due to the fact that the related feedback coupling mechanisms reinforce one another in such a way that the rate of mineralization, integrated over time, is optimized in the 'specific place' (Hobbs et al., 2000). This kind of feedback coupling mechanism results in the complexity of the mineralization system that is usually beyond the capability of the traditional research methods (Liu, 2007; Liu et al., 2005a). Because the complex system has two fundamental characteristics: an emergence and an attractor (Zhao et al., 2008), a slight change in initial conditions would result in entirely different outcomes. The advancement of computer technology and computational algorithms has made computational simulation an indispensable method for solving complex problems such as those described by the geodynamic systems of coupled metallogenic processes (Hobbs et al., 2000; Liu et al., 2005a,b, 2008; President's Information Technology Advisory Committee, 2005; Zhao et al., 2006, 2007, 2009, 2010). During the last two decades, computational modeling has been widely used to understand the geodynamic processes that lead to the formation of ore deposits (Chi and Savard, 1998; Garven and Freeze, 1984; Liu and Zhang, 2007; Oliver et al., 2001; Ord et al., 2002; Raffensperger and Garven, 1995; Schaubs and Zhao, 2002; Sorjonen-Ward et al., 2002; Yang et al., 2006; Zhang et al., 2007). The application of such modeling to brown field has great potential for enhancing the efficiency of exploration and facilitating the predictive discovery of hidden orebodies.

The Anqing orefield is a famous Fe–Cu brownfield ore district in China, and the Anqing deposit is the largest single Fe–Cu skarn deposit in the Yangtze River Metallogenic Belt (YRMB) (Chang et al., 1991; Liu et al., 2008). Because of both economic and scientific importance, the Anqing orefield has been drilled extensively by the Anhui 326 geological team (1976, 1988, 1992), and investigated intensively by many researchers (e.g., Chang et al., 1991; Dong and Qiu, 1993; Liu et al., 2008; Mao et al., 2006; Wang and Zhou, 1995; Zhang et al., 2008; Zhou et al., 2007). This has resulted in the reserve estimation of discovered orebodies and an understanding of ore formation processes. However, as the shallow orebodies have been exhausted by mining, exploration has to inevitably target blind orebodies located at depth. Because of a lack of detectable geophysical or geochemical anomalies, the existing knowledge models and methods cannot predict such blind orebodies. Therefore, it is necessary to develop innovative knowledge models for understanding ore-forming processes in detail, so as to facilitate the predictive discovery of deep orebodies.

The geodynamic system that controls the scale and location of orebodies in the Anqing orefield is very complex. It involves coupled multi-processes and multi-factors rather than a simple geodynamic process or a simple linear combination of several factors. For this reason, computational modeling may become a practicable method for solving such a complex geodynamic problem. In this paper, we construct geodynamic models capturing coupled MTH (mechano-thermo-hydrological) processes, based on detailed geological and geophysical investigations in the Anqing orefield. We then carry out computational modeling experiments of these models. The computational results are used to investigate the ore genesis and to predict the location of orebodies so as to select the appropriate targets and therefore lower the exploration risk.

2. The Anqing orefield

2.1. Geological setting

The Anqing orefield consists of ore deposits originally associated with the Yueshan intrusion in Anqing, Anhui province, eastern China. It is a major deposit in the Tongling–Anqing District (TAD), which is located in the central segment of the Yangtze River metallogenic belt along the northern margin of the Yangtze craton (Yangtze plate) (Fig. 1). The district is bordered by the Dabieshan UHP (ultra-high pressure) metamorphic belt and North China craton (North China plate) to the north (Liu and Peng, 2003; Pan and Dong, 1999). The collision of the Yangtze plate with the North China plate took place in the late Triassic. This tectonic event reactivated the Yangtze River fracture zone and produced extensive intermediate to felsic magmatism with the related mineral deposits (Chang et al., 1991; Pan and Dong, 1999; Zhai et al., 1996).

The Tongling–Anqing district is a major supplier to the Chinese copper industry. Six major Cu and Fe–Cu deposits have been discovered in this district to date (Fig. 1). They are the Fenghuangshan Cu deposit (the ore reserve of 32 Mt at 1.26% Cu), Shizhishan Cu deposit (the ore reserve of 61 Mt at 1.03% Cu), Dongguashan Cu deposit (the ore reserve of 98 Mt at 1.01 Cu), Tongguangshan Cu deposit (the ore reserve of 36 Mt at 1.16% Cu), Tongshan Cu deposit (the ore reserve of 23 Mt at 1.11% Cu), and the Anqing Fe–Cu deposit (the ore reserve of 62.4 Mt at 0.906% Cu and 32.2% Fe). These deposits are all genetically and spatially associated with the felsic intrusions of a late Jurassic age (Fig. 1) (Liu et al., 2008).

Rocks in the Tongling–Anqing district include Precambrian metamorphic rocks and Paleozoic through Mesozoic sedimentary rocks. The mid-Carboniferous to mid-Tertiary rocks are littoral to neritic carbonates interbedded with bathyal facies beds, alternating with marine-continental clastics. They are the most favorable wall rocks to host Cu- and Fe–Cu-skarn deposits (Figs. 2 and 3).

The Yueshan diorite intrusion forms the core of the Anqing orefield (Fig. 3). All Cu and Fe orebodies occur strictly in the vicinity of the contact zone between the Yueshan intrusion and the Triassic sedimentary carbonates. The Yueshan diorite is mainly composed of 67.9% plagioclase, 6.1% K-feldspar, 2.2% quartz, 18.1% hornblende and 1% biotite (Anhui 326 Geological Team, 1992). This intrusion is also the largest copper mineralizing intrusion in the district with a surface area of about 3 km^2 (Figs. 1, 3 and 4). The exposed part of the intrusion is uniquely cross-shaped (Fig. 3a). In a 3D view, the distinct feature of the intrusion is that the southern boundary is much more complex in shape than the northern, but the 3D outline of the intrusion (Fig. 4) does not look like a cross as the 2D outline in a surface plane (Fig. 3a). The SHRIMP U–Pb zircon age of the Yueshan intrusion is 138.7 ± 0.5 Ma (Zhang et al., 2008). The Re–Os age of molybdenite in the ores is 134.7 to 142.6 Ma (Mao et al., 2006). The Yueshan intrusion and associated mineralization were emplaced in the late Jurassic to early Cretaceous, when the crustal regime in the YRMB changed from compression to extension (Dong and Qiu, 1993; Mao et al., 2006; Zhang et al., 2008).

In the Anqing orefield, there are five main structures: (1) a NW-trending fold with parallel faults along the limbs in the southwestern sector of the field; (2) NS-trending folds with almost parallel faults along the limbs in the southeastern sector of the field; (3) NE-trending folds with parallel faults along the limbs in the northeastern sector of the field; (4) approximately EW-trending faults in the center of the field and (5) NNW- and NNE-trending faults scattered in almost the whole field (Fig. 3). The NW- and NS-trending folds might have been formed immediately after the early Triassic, because the youngest folded strata are of an early Triassic age. The NE-trending folds might have formed immediately after the middle Jurassic, because the youngest folded beds are of a middle Jurassic age. The approximate EW-trending faults consist mainly of normal faults and cut through the NE-trending fold and the Yueshan intrusion. This indicates that there was an extensional event after the Jurassic folding and the magmatic intrusion. The NNW- and NNE-trending faults are certainly the latest, as they cut through all other structures and orebodies. A major approximately EW-trending normal fault is parallel to and immediately nearby the orebodies (Fig. 3). Major orebodies are all located in the approximately EW-trending tensile fractures, while orebody No. 3 is an EW-trending vein in the intrusion. This implies that the extensional event after the Jurassic folding could be related to mineralization.