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Cretaceous Cu–Au, pyrite, and Fe-oxide–apatite deposits in the Ningwu basin, Lower Yangtze Area, Eastern China

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ABSTRACT

The Cretaceous Ningwu volcanic basin of the Middle and Lower Yangtze River Valley metallogenic belt of eastern China hosts numerous Fe-oxide–apatite, Cu–Au, and pyrite deposits. The mineralization in the Ningwu basin is associated with subvolcanic rocks, consisting of gabbro–diorite porphyry and/or pyroxene diorite. However, the mineralization is associated with subvolcanic and volcanic rock suite belonging to the Niangniangshan Formation in the Tongjing Cu–Au deposit, including nosean-bearing aegirine–augite syenites, quartz syenites, and quartz monzonites. The zoning displayed by the alteration and mineralization comprises: (1) an upper light-colored zone of argillic, carbonate, and pyrite alteration and silicification that is locally associated with pyrite and gold mineralization, (2) a central dark-colored zone of diopside, fluorapatite–magnetite, phlogopite, and garnet alteration associated with fluorapatite–magnetite mineralization, and (3) a lowermost light-colored zone of extensive albite alteration. The Cu–Au and pyrite orebodies are peripheral to the Fe-oxide–apatite deposits in this area and overlie the iron orebodies, including the Meishan Cu–Au deposit in the northern Ningwu basin and the pyrite deposits in the central Ningwu basin. The $\delta^{34}S$ values of sulfides from the Fe-oxide–apatite, Cu–Au, and pyrite deposits in the Ningwu basin show large variation, with a mixed sulfur source, including magmatic sulfur and/or a mixture of sulfur derived from a magmatic component, country rock, and thermochemical reduction of sulfate at 200–300 °C. The ore-forming fluids associated with iron mineralization were derived mainly from magmatic fluids, and the late-stage ore-forming fluids related to Cu–Au and pyrite mineralization may have formed by the introduction of cooler meteoric water to the system. The Fe-oxide–apatite, Cu–Au, and pyrite deposits of the Ningwu basin formed in an extensional environment and are associated with a large-scale magmatic–hydrothermal system.

1. Introduction

The Ningwu volcanic basin in eastern China hosts three types of ore deposits: Fe-oxide–apatite, Cu–Au, and pyrite. These deposits were systematically explored by the Bureau of Geology and Minerals Resources of Anhui and Jiangsu Provinces and the Bureau of Geology and Exploration for Nonferrous Metal Deposits of Anhui and Jiangsu Provinces between the 1950s and the 1980s. The exploration led to the discovery of more than 30 Fe-oxide–apatite deposits within the Ningwu volcanic basin, containing a total resource of about 2700 million tons (Mt) iron (Zhou et al., 2013). The Meishan Cu–Au deposit was recently discovered by the No. 1 Geological Team of the Bureau of Geology and Minerals Resources of Jiangsu Province, with an estimated reserve of ca. 6 t Au (Meishan Mining Co. Ltd., 2011). The further exploration in this area is underway.

Previous studies on Fe-oxide–apatite deposits and related volcanic and subvolcanic rocks were mainly focused on the geology, alteration zoning and geochemistry of these deposits and associated rocks (Ningwu Research Group, 1978; Zhang, 1979; Chen et al., 1981; Li and Xie, 1984; Ishihara et al., 1986; Institute of Geochemistry, Chinese Academy of Sciences, 1987; Lu et al., 1990; Xu, 1990; Chang et al., 1991; Zhai et al., 1992; Tang et al., 1998; Lin, 1999; Hou et al., 2009, 2010, 2011, 2012; Mao et al., 2012) in an attempt to constrain the type, origin, and source of ore-forming fluids, and to evaluate the petrogenesis of associated volcanic and subvolcanic rocks in this area. These Fe-oxide–apatite deposits, which are designated as porphyry iron deposits in the Chinese literature, are temporally, spatially, and genetically associated with

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subvolcanic plutons, consisting of gabbro–diorite porphyry and/or pyroxene diorite. The timing of Fe-oxide–apatite ore formation and the intrusion of associated subvolcanic plutons has been the focus of previous studies (e.g., Yu and Mao, 2004; Mao et al., 2006; Hou and Yuan, 2010; Hu and Jiang, 2010; Xue et al., 2010; Yuan et al., 2010; Duan et al., 2011; Hou et al., 2012; Zhou et al., 2013). Most of the results from these studies were published in Chinese. Exceptions include the works by Yu and Mao (2004), Mao et al. (2006, 2011b), Yu et al. (2011), and Zhou et al. (2013), who reported albite and phlogopite ^{40}Ar–^{39}Ar and zircon LA–ICP–MS ages for mineralization and associated subvolcanic plutons in this area, and further discussed the tectonic implications of these ages. Hou et al. (2009, 2010, 2011, 2012) also described the geology and geochemistry of the Gushan and Washan deposits, and based on the geochemistry of mineralization-associated subvolcanic plutons, proposed potential models for the origin of the Gushan and Washan deposits. In addition, Yu et al. (2011) suggested that the Fe-oxide–apatite deposits of the Ningwu basin are genetically similar and may have formed in a tectonic environment identical to the Kiruna-type deposits in northern Sweden. However, the majority of the previous research has been undertaken on Fe-oxide–apatite deposits in the Ningwu basin, and little attention was focused on the Cu–Au and pyrite deposits of this area. The relationship between the Fe-oxide–apatite, Cu–Au, and pyrite deposits in the Ningwu basin therefore remains unclear, including the question whether all of these deposits formed in a large-scale magmatic–hydrothermal system.

The objectives of the present study include: (1) characterizing the occurrence of the Fe-oxide–apatite, Cu–Au, and pyrite deposits, particularly focusing on the latter two types of deposits; (2) presenting new fluid inclusion and sulfur isotope data for the Cu–Au deposits; (3) exploring the relationship of the Fe-oxide–apatite and associated Cu–Au and pyrite deposits as part of the same magmatic–hydrothermal system; and (4) comparing the Fe-oxide–apatite and Cu–Au deposits of the Cretaceous Ningwu basin with the Norrbotten Fe-oxide–Cu–Au district of northern Sweden.

2. Geological setting

2.1. The Middle–Lower Yangtze River Valley metallogenic belt

The Middle–Lower Yangtze River Valley (MLYRV) metallogenic belt is located on the northern margin of the Yangtze Craton, adjacent to the Dabie orogenic belt and to the south of the North China Craton (Goldfarb et al., 2014; Mao et al., 2014 and references therein). The belt is bounded by the Yangxing–Changzhou Fault to the southeast, the Tanlu Fault to the northwest, and is cut by the Xiangfan–Guangji Fault to the south (Fig. 1). The MLYRV metallogenic belt contains a series of well-developed NE–SW trending structures that controlled both Mesozoic magmatic activity and the spatial distribution of ore deposits, with the latter particularly focused at the intersections between structures (Zhai et al., 1992). The metamorphic basement rocks of the Yangtze Craton include amphibolite and granulite facies rocks including biotite–hornblende gneisses, tonalites, trondhjemites, granodiorites and supracrustal rocks, all of which have undergone pervasive migmatization (Chang et al., 1991; Zhai et al., 1992; Gao et al., 1999). Zircon U–Pb and whole-rock Sm–Nd geochronological data indicate that these basement rocks formed during Mesoarchean–Paleoproterozoic (2900–1895 Ma; Chang et al., 1991). The metamorphosed basement is unconformably overlain by Neoproterozoic clastic rocks, dolomite and siliceous rocks, Cambrian to Early Triassic sedimentary rocks and Jurassic to Cretaceous intercalated continental volcanic and clastic rocks. The Cretaceous volcanic rocks, and Permian and Triassic carbonate sediments are the main hosts for polymetallic Cu–Fe–Au mineralization in the MLYRV metallogenic belt.

The MLYRV metallogenic belt witnessed Neoproterozoic (1000–850 Ma), and Cambrian to Early Triassic sedimentation as well as Mesozoic intra-plate deformation induced by two major tectonic domains (Tethys and paleo-Pacific) with deep crust–mantle interaction (Chang et al., 1991; Zhai et al., 1992; Pan and Dong, 1999; Mao et al., 2006).

The extensive Mesozoic magmatic suites have been divided into three types (Tang et al., 1998; Mao et al., 2006, 2011b; Xie et al., 2011). Type 1 comprises 156–137 Ma K-rich calc-alkaline granitoids associated with porphyry–skarn–stratabound Cu–Au–Mo–Fe mineralization, consisting of diorite, quartz diorite, granodiorite and granodiorite porphyry within uplifted blocks (Mao et al., 2011a, 2011b). Type 2 is composed of 135–127 Ma Na-rich calc-alkaline subvolcanic rocks and their corresponding volcanic rocks. The volcanic and subvolcanic rocks occur in seven Late Mesozoic subaerial basins; from west to east, these are the Jinniu basin, the Huaining basin, the Luzong basin, the Ningwu basin, the Lishui basin, the Liyang basin and the Chuzhou basin, covering a total area of about 5000 km^2 (Pan and Dong, 1999; Fig. 1). The subvolcanic rocks host magnetite–apatite deposits (Mao et al., 2006, 2011b). The type 2 volcanic and subvolcanic rocks are considered to have been derived from an enriched mantle metasomatized by subducted oceanic sediments (Wang et al., 2001, 2006). The type 3 is made up of A-type granitoids associated with minor gold mineralization. These granitoids can be subdivided into quartz syenite, syenite, quartz monzonite, and alkaline granite phases, and their corresponding volcanic rocks are represented by the 127–125 Ma phonolites (Tang et al., 1998; Fan et al., 2008). It is possible that the type 2 and 3 rocks formed contemporaneously (Mao et al., 2011b), or that the type 3 A-type granitoids formed slightly later than the type 2 igneous rocks (Fan et al., 2008). Type 2 volcanic and subvolcanic rocks and type 3 A-type granitoids appear to have formed in an intra-continental extensional setting and their genesis was probably controlled by lithospheric thinning and upwelling of hot asthenosphere along NE–SW striking fault zones (e.g., the Tanlu and Yangtze River fault zones) in eastern China (Wang et al., 2001, 2006; Mao et al., 2006; Fan et al., 2008; Zhou et al., 2013).

2.2. Ningwu volcanic basin

The Cretaceous Ningwu volcanic basin is located in the eastern part of the MLYRV metallogenic belt (Fig. 1), in the area between Nanjing City (Ning) in Jiangsu province and Wuhu City (Wu) in Anhui Province, eastern China. It is a NNE-trending rhomb-shaped faulted volcanic basin (Ningwu Research Group, 1978; Fig. 2) that is bounded to the east by the Fangshan–Xiaodanyang Fault, to the west by the Yangtze River (Changjiang) Fault Zone, and to the north and south by the Nanjing–Hushu and Sanshanjie–Xuancheng Faults (outside the limits of Fig. 2).

The basement of the Ningwu volcanic basin consists of, from bottom to top, the Lower–Middle Triassic Qinglong Group, the Upper Triassic Huangmaqing Formation, the Lower–Middle Jurassic Xiangshan Group, and the Upper Jurassic Xihengshan Formation (Ningwu Research Group, 1978). The Qinglong Group is >500 m thick and contains limestones and intercalated calcareous shales, dolomitic limestones, and lagoonal gypsum and anhydrite layers. The gypsum and anhydrite layers are well exposed in the uppermost Qinglong Group and are <90 m thick in the Ningwu area. The Upper Triassic marine and continental Huangmaqing Formation is 500–800 m thick, consists of calcareous siltstones, silty shales, and shales, with local intercalations of thinly layered limestones and coal seams. Overlying the Huangmaqing Formation is the 1500 m-thick continental Lower–Middle Jurassic Xiangshan Group, which contains grayish–white quartz sandstone, feldspathic sandstones and locally intercalated siltstone and shale in