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Origin and evolution of ore-forming fluids in the Hemushan magnetite–apatite deposit, Anhui Province, Eastern China, and their metallogenic significance

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ABSTRACT

The Middle–Lower Yangtze River Metallogenic Belt in the northern Yangtze Block is one of the most important economic mineral districts in China. The Hemushan deposit is a medium-class Fe deposit located in the southern part of the Ningwu iron ore district of the Middle–Lower Yangtze River Metallogenic Belt. The Fe-orebodies are mainly hosted in the contact zone between diorite and Triassic marble. The actinolite–phlogopite–apatite–magnetite ore shows metasomatic/filling textures and disseminated/mesh–vein structures. Based on evidences and petrographic observations, the ore-forming process can be divided into three distinct periods—the early metallogenic period (albite–diopside stage), the middle metallogenic period (magnetite stage and hematite stage), and the late metallogenic period (quartz–pyrite stage and carbonate stage). Fluid inclusion studies show four types of inclusions: type I daughter mineral-bearing three-phase inclusions (L + V + S), type II vapor-rich two-phase inclusions (L + V), type III liquid-rich two phase inclusions (L + V), and minor type IV liquid-phase inclusions (L). Apatites from the magnetite stage contain type I, type II and type III inclusions; anhydrites from the hematite stage mainly contain abundant type II inclusions and relatively less type I inclusions; quartz and calcite from the late metallogenic stage are mainly characterized by type III inclusions. Laser Raman spectroscopy and microthermometry of fluid inclusions show that the ore-forming fluids broadly correspond to unsaturated NaCl–H_2O system. From the magnetite stage to the carbonate stage, the ore-forming fluids evolved from moderate-high temperature (average 414 °C), moderate salinity (average 25.01 wt.% NaCl equiv.) conditions to low temperature (average 168 °C), low salinity (average 6.18 wt.% NaCl equiv.) conditions. Hydrogen and oxygen isotopic studies indicate that the ore-forming fluid during the early stage of middle metallogenic period was mainly of magmatic water, and mixing of the ore fluids with meteoric water took place during the late phase. During this evolution, water–rock interaction, and boiling and mixing of the ore fluids with meteoric water occurred. The boiling of fluids was a potential mechanism for the formation of magnetite.

1. Introduction

The Middle–Lower Yangtze River Belt (MLYRB) is one of the most important metallogenic belts in China, hosting numerous Fe–Cu–Au deposits (Fig. 1a, e.g., Goldfarb et al., 2014; Zhu et al., 2014; Yang et al., 2014). These deposits are clustered in several mining districts, such as Edong (southeastern Hubei province), Jiurui (Jiujiang–Ruichang), Anqing–Guichi, Tongling, Luzong, Ningwu, and Ningzhen districts (Fig. 1b, e.g., Mao et al., 2006; Pan and Dong, 1999; Chang et al., 1991). The Ningwu mining district occurs in the eastern section of the MLYRB, and is an important district for magnetite–apatite deposits with large scale Fe mineralization associated with Mesozoic dioritic plutons (e.g., Mao et al., 2011; Duan et al., 2012; Wang et al., 2001; Zhai et al., 1992; Chang et al., 1991). Many world-class apatite-bearing magnetite and/or hematite mineral systems (e.g., Meishan, Washan, and Gushan iron deposits) have been studied in the Ningwu area (e.g., Zhou et al., 2013; Yu et al., 2011). The Fe deposits occur either in the upper portions of plutons, at the contact between the plutons and overlying volcanic-sedimentary strata, or occur within the volcanic rocks adjacent to the plutons. Although previous workers from China classified the Ningwu Fe deposits as "porphyritic iron deposits" (e.g., Zhou et al., 2013; Mao et al., 2006; Ningwu Research Group, 1978), they correspond to the magnetite–apatite deposits of IOCG type and are comparable with the Kiruna type Fe deposits

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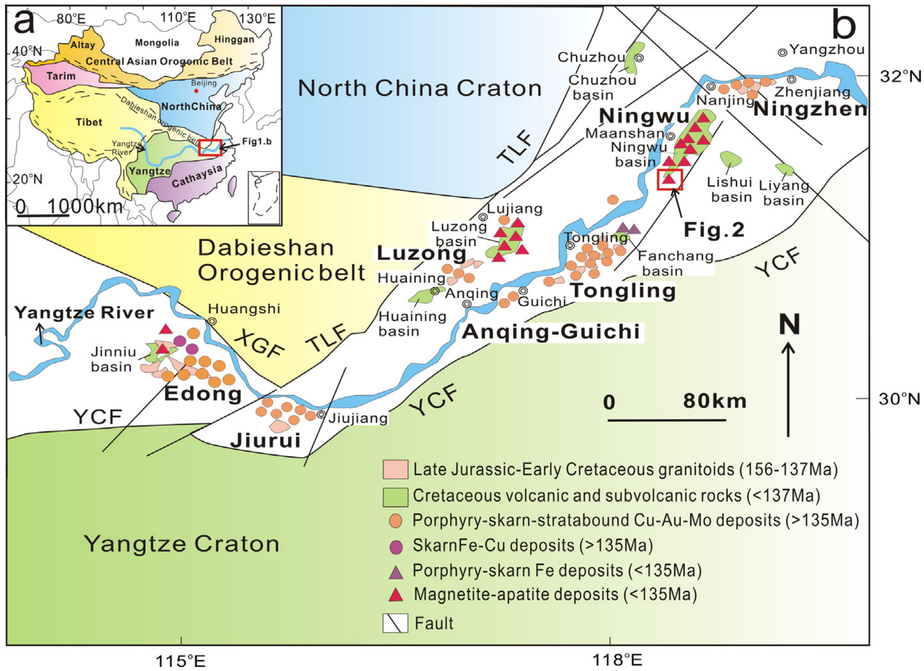

Fig. 1. (a) Location map of the Middle–Lower Yangtze River Belt in China. (Modified from Tang et al. (2012); Zhai et al. (1992)). (b) Sketch map of the Middle–Lower Yangtze river belt, East China. The inset is a simplified structural map of China. TLF—Tancheng-Lujiang fault, XGF—Xiangfan-Guangji fault, YCF—Yangxing–Changzhou fault. (Modified from Mao et al. (2011); Zhai et al. (1992); Chang et al. (1991)).

(e.g., Williams et al., 2005; Hildebrand, 1986; Frietsch and Perdahl, 1995 and references there in). A total reserve of 500 million tons of iron is estimated for the iron deposits and occurrences in the Ningwu mining district, and is a major contributor of iron ore for the Chinese steel industry (Wu et al., 2011; Guo et al., 2000; Gao and Zhao, 2008).

Fluid inclusion studies have been used as a useful tool to constrain the physicochemical parameters of metal-bearing fluids in these magnetite–apatite deposits (Ningwu Research Group, 1978). However, apart from a few studies published in Chinese journals (Fan et al., 2012; Ma et al., 2006; Wei, 1986; Lu and Hu, 1990; Chu et al., 1986; Li et al., 1978), no detailed work has been carried out as yet on the ore-forming fluids of Ningwu mining district.

The Hemushan iron deposit, one of the important magnetite–apatite deposits in the MLYRB (Ningwu Research Group, 1978), is located in the southern part of the Ningwu mining district (Fig. 2). The Fe-orebodies are mainly hosted at the contact zone between diorite and sedimentary strata, and the mineral assemblages in the iron ores mainly include magnetite, actinolite, phlogopite and apatite. The geologic features of this deposit represent of the typical Ningwu-type iron ores. The mineral assemblages in iron ores indicate that the iron mineralization is closely related to the ore-forming fluids. Previous studies have addressed the geological features for the area (Hong and Sun, 2006; Chen et al., 1982), diagenetic event (Yuan et al., 2010; Fan et al., 2010; Hou et al., 2010a,b), and metallogenic features of the deposit (Zhou et al., 2013; Fan et al., 2011). However, there is lack of detailed work on the ore-forming fluids of Hemushan deposit. Hence the Hemushan iron deposit provides a window for the study of these magnetite–apatite deposits of the Ningwu mining district.

In this paper, we present fluid inclusion petrography, laser Raman spectroscopy, and microthermometry, as well as the stable isotope compositions from the Hemushan iron deposit. We discuss the characteristics and evolution of the ore-forming fluids, as well as metallogenic mechanism and ore genesis, aiming to enrich and deepen the understanding of metallogenic model of "porphyritic iron deposits".

2. Regional geology

The MLYRB occurs along the northeastern part of the Yangtze Block in central eastern China and extends along the southeastern margin of the North China Block and Dabieshan orogenic belt. The belt is bounded by the Xiangfan–Guangji fault (XGF) to the northwest, the Tangcheng–Lujiang regional strike-slip fault (TLF) to the northeast, and the Yangxing–Changzhou fault (YCF) to the south (Fig. 1b). Basement rocks of the MLYRB consist of trondhjemite–tonalite–granodiorite (TTG) gneisses and supracrustal rocks (felsic gneiss and muscovite quartz schist with intercalated amphibolites) that range in age from 2900 to 990 Ma (Zhai et al., 1992; Chang et al., 1991). The metamorphosed basement is unconformably overlain by a thick cover sequence consisting of Neoproterozoic clastic rocks, carbonate, and chert; Cambrian chert nodules, mudstone, and argillaceous limestone; Ordovician limestone and dolomitic limestone; Silurian clastic rocks; Devonian sandstone; Carboniferous siltstone and limestone; Permian shale, siliceous rocks, and limestone; and Triassic limestone and argillaceous clastic rocks (Zhai et al., 1992; Chang et al., 1991). Magmatic activity in this region mainly took place between 145 Ma and 120 Ma (Zhou et al., 2008), resulting in the emplacement of high-*K* calc-alkaline to alkaline intrusions and extrusion of shoshonitic volcanic rocks.

As one of seven mining districts in the Lower Yangtze River Valley metallogenic belt in East China, the Ningwu basin is situated at the eastern part of MLYRB (Fig. 1b). The Cretaceous Ningwu basin is a NNE-trending rhomboid-shaped faulted basin (Zhigang, 1990; Ningwu Research Group, 1978), bounded by the Fangshan–Xiaodanyang Fault in the east, the Yangtze River (Changjiang) fault zone in the west, the Nanjing–Hushu Fault in the north and the Sanshanjie–Xuancheng Fault in the south. The basin extends for approximately 80 km from the Meishan in Jiangsu Province in the north to the Zhonggu orefield of the Anhui Province in the south, forming a NNE-trending rhomboid-shaped rift basin structure (Hou et al., 2010a,b). The basin is partially filled by continental volcanic rocks intruded by cogenetic subvolcanic and plutonic rocks. The stratigraphy is dominated by a cover sequence of