Ore Geology Reviews 67 (2015) 264–278

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

The role of evaporites in the formation of magnetite–apatite deposits along the Middle and Lower Yangtze River, China: Evidence from LA-ICP-MS analysis of fluid inclusions

Wanting Li [a,b,c,*], Andreas Audétat [b,**], Jun Zhang [a]

[a] Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, China
[b] Bayerisches Geoinstitut, University of Bayreuth, Bayreuth 95440, Germany
[c] Geological Survey of China University of Geosciences, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form 21 November 2014
Accepted 3 December 2014
Available online 9 December 2014

Keywords:
Magnetite–apatite deposits
Yangtze
Evaporites
LA-ICP-MS
Fluid inclusions
IOCG deposits

ABSTRACT

Numerous magnetite–apatite deposits occur in the Ningwu and Luzong sedimentary basins along the Middle and Lower Yangtze River, China. These deposits are located in the contact zone of (gabbro)-dioritic porphyries with surrounding volcanic or sedimentary rocks and are characterized by massive, vein and disseminated magnetite–apatite ± anhydrite mineralization associated with voluminous sodic–calcic alteration. Petrologic and microthermometric studies on multiphase inclusions in pre- to syn-mineralization pyroxene and garnet from the deposits at Meishan (Ningwu basin), Luohe and Nihe (both in Luzong basin) demonstrate that they represent extremely saline brines (~90 wt.% $NaCl_{equiv}$) that were trapped at temperatures of about 780 °C. Laser ablation ICP-MS analyses and Raman spectroscopic studies on the natural fluid inclusions and synthetic fluid inclusions manufactured at similar P–T conditions reveal that the brines are composed mainly of Na (13–24 wt.%), K (7–11 wt.%), Ca (~7 wt.%), Fe (~2 wt.%), Cl (19–47 wt.%) and variable amounts of SO_4 (3–39 wt.%). Their Cl/Br, Na/K and Na/B ratios are markedly different from those of seawater evaporation brines and lie between those of magmatic fluids and sedimentary halite, suggesting a significant contribution from halite-bearing evaporites. High S/B and Ca/Na ratios in the fluid inclusions and heavy sulfur isotopic signatures of syn- to post-mineralization anhydrite ($\delta^{34}S_{Anh} = +15.2$ to $+16.9$‰) and pyrite ($\delta^{34}S_{Py} = +4.6$‰ to $+12.1$‰) further suggest a significant contribution from sedimentary anhydrite. These interpretations are in line with the presence of evaporite sequences in the lower parts of the sedimentary basins.

The combined evidence thus suggests that the magnetite–apatite deposits along the Middle and Lower Yangtze River formed by fluids that exsolved from magmas that assimilated substantial amounts of Triassic evaporites during their ascent. Due to their Fe-oxide dominated mineralogy, their association with large-scale sodic–calcic alteration and their spatial and temporal associations with subvolcanic intrusions we interpret them as a special type of IOCG deposits that is characterized by unusually high contents of Na, Ca, Cl and SO_4 in the ore-forming fluids. Evaporite assimilation apparently led to the production of large amounts of high-salinity brine and thus to an enhanced capacity to extract iron from the (gabbro)-dioritic intrusions and to concentrate it in the form of ore bodies. Hence, we believe that evaporite-bearing sedimentary basins are more prospective for magnetite–apatite deposits than evaporite-free basins.

1. Introduction

The Middle and Lower Yangtze River metallogenic belt is one of the most important polymetallic resource areas in China, famous for abundant Fe, Cu, Au, Pb, Zn (±Mo, Ag) and sulfur deposits occurring within seven rift basins (e.g., Chen et al., 2007; Pan and Dong, 1999). Among these deposits, magnetite–apatite deposit, mainly distributed in the Ningwu and Luzong volcanic basins, is a distinct type of deposits that has been found only in this region of China so far. Due to their close temporal and spatial relationships with Mesozoic dioritic porphyries, these deposits have been referred to as "porphyry/porphyrite iron deposits" in the Chinese literature. Intrusions of monzonitic to granitic composition are typically associated with vein-type Cu–Au and Pb–Zn deposits (Zhao et al., 1999). Generally speaking, the basins host an unusually high density of ore deposits, with about 50% of the shallowly exposed intrusions being economically mineralized (Fig. 1). Most of the magnetite–apatite deposits are situated in the top of the dioritic intrusions and/or

* Correspondence to: W. T. Li, Faculty of Earth Resources, China University of Geosciences, No. 388 Lumo Road, Hongshan District, Wuhan, Hubei Province 430074, China. Tel.: +86 18388052502.
** Correspondence to: A. Audétat, Bayerisches Geoinstitut, University of Bayreuth, Bayreuth 95440, Germany. Tel.: +49 921 55 3713.
E-mail addresses: liwanting0930@foxmail.com (W. T. Li), andreas.audetat@uni-bayreuth.de (A. Audétat).

http://dx.doi.org/10.1016/j.oregeorev.2014.12.003
0169-1368/

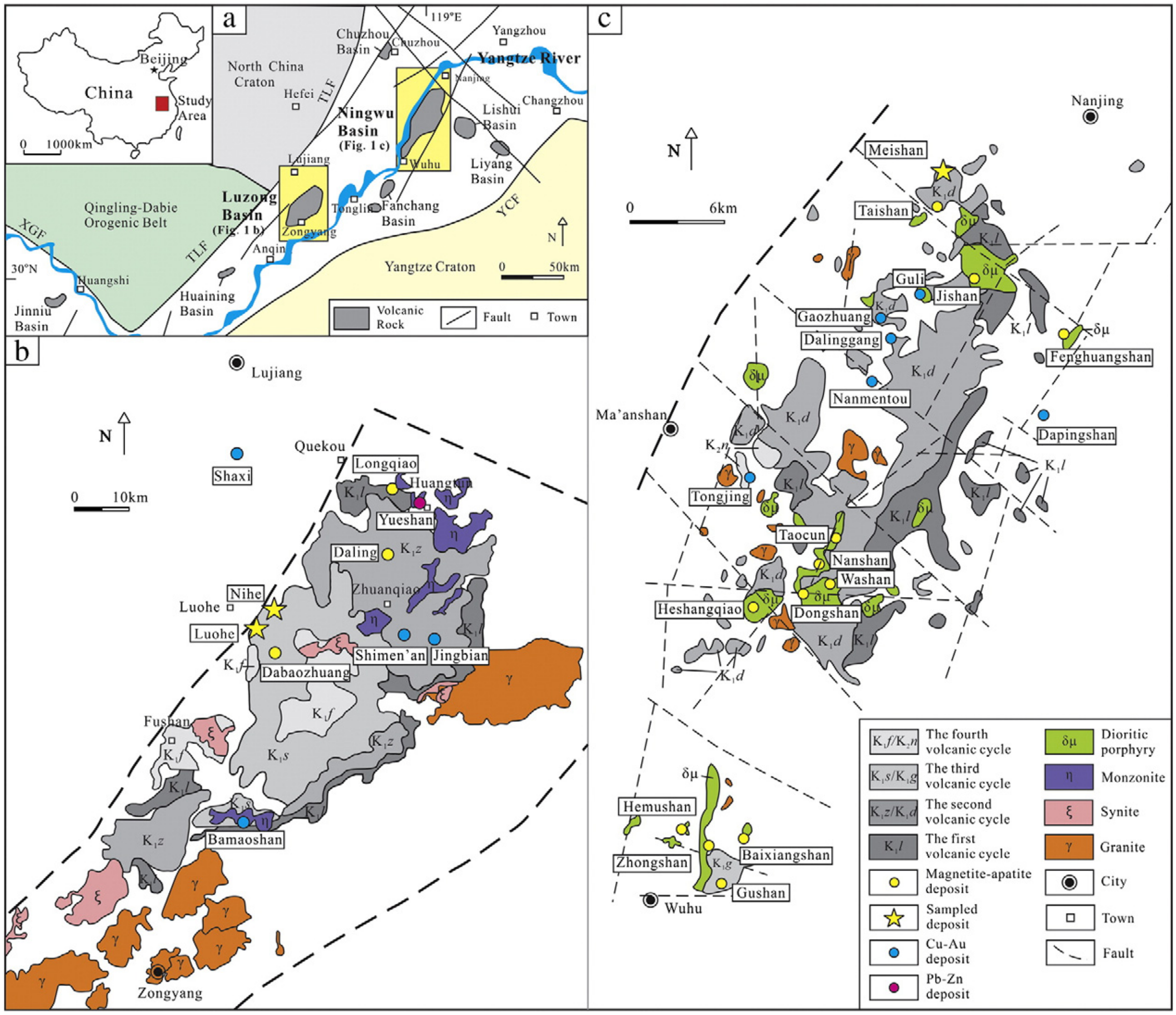

Fig. 1. (a) Regional geology and locations of the Ningwu and Luzong basins in the Middle and Lower Yangtze River Valley, China (modified from Chang et al., 1991; Mao et al., 2011; Zhai et al., 1992). (b) Geological map of the Luzong volcanic basin (modified from Zhou et al., 2010). (c) Geological map of the Ningwu volcanic basin (modified from Ningwu Research Group, 1978; Liu et al., 2014). XGF = Xiangfan–Guangji fault; TLF = Tangcheng–Lujiang fault; YCF = Yangxing–Changzhou fault.

their contact zones with contemporaneous to slightly older volcanic rocks, whereas some deeper intrusions were emplaced within sedimentary rocks. Well-known examples of the former type include Meishan, Washan, Jishan, Taocun and Hemushan (in the Ningwu basin) and Luohe, Nihe and Dabaozhuang (in the Luzong basin). Individual deposits contain proven resources of 120–500 Mt iron ore grading at 25–60% Fe, 0.01–1.0% P_2O_5 and 0.04–8.2% S (Fang et al., 1989; Gushan Mining Co. Ltd. of Masteel Group Corporation, 2006; Huang and Yin, 1989; Nanshan Mining Co., Ltd. of Masteel Group Corporation, 2007; Wu et al., 1996; Zhang, 2012). Although a large number of petrologic and geochemical studies have been undertaken on these deposits, their origin still remains controversial. Two main models have been proposed: (1) an orthomagmatic origin via emplacement of iron-rich oxide melts (Chang et al., 1991; Ding, 1992; Hou et al., 2009, 2010a, 2010b, 2011; Li et al., 2014; Song et al., 1981; Yuan et al., 1997; Zhu, 1987); and (2) a hydrothermal origin involving fluids of the following sources: (2a) dominantly magmatic fluids (Lin et al., 1983; Ma et al., 2006; Zhang and Lin, 1984; Zhang et al., 2011; Zhou et al., 2011a), (2b) major involvement of basinal brines (Hu and Hu, 1991), and (2c) major involvement of an evaporite source (Cai, 1980; Cao, 1977; Chu et al., 1986; Fan et al., 1995; Huang and Yin, 1989; Zhang, 1986).

In the orthomagmatic model the iron-apatite ores are believed to have crystallized directly from iron-rich oxide melts that were generated through silicate melt immiscibility (e.g., Lester et al., 2013; Philpotts, 1967). An orthomagmatic origin has been suggested mainly for the Meishan and Gushan deposits because their ore bodies display structures similar to those described from Kiruna-type ore deposits (e.g., Frietsch, 1978; Naslund et al., 2000, 2002) such as vesicles, amygdaloidal structures, skeletal textures, infill structures, flow structures and breccias with relatively minor metasomatism (e.g., Chang et al., 1991; Hou et al., 2010b, 2011). The widespread hydrothermal alterations in these deposits are regarded subordinate and late. Further evidence for an orthomagmatic origin of these two deposits was considered to be found in the oxygen isotopic composition of magnetite and hematite in the ore ($\delta^{18}O = 0.4$–4.0‰, Chang et al., 1991; Yuan et al., 1997), which is similar to that of iron oxides in magmatic rocks, and in the presence of multisolid inclusions in pyroxene, garnet and apatite, which look similar to crystallized melt inclusions and could be homogenized and quenched to glass after heating to up to 1075 °C (Li and Xie, 1984; Li et al., 1983; Liu, 2012).

However, defenders of the hydrothermal model have challenged some of these interpretations. They interpreted the vesicular and amygdaloidal structures as hydrothermal features (Lu et al., 1990), and the skeletal and porphyritic textures were considered as growth textures of hydrothermal hematite by Gu and Ruan (1988). Lu et al. (1990) demonstrated that the contact relationships between rich (massive) ore and lean ore (disseminated, porphyritic and "bamboo leaf" ore) or wall rocks are mostly transitional rather than sharp. Furthermore, the