Journal of Geochemical Exploration 144 (2014) 115–127

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

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

Numerical modeling of pore-fluid flow and heat transfer in the Fushan iron ore district, Hebei, China: Implications for hydrothermal mineralization

Yao Liu [a,*], Tagen Dai [a,b]

[a] Computational Geosciences Research Center, Central South University, Changsha 410083, China
[b] The Key Laboratory of Chinese Education Ministry for Non-ferrous Metal Metallogenic Prediction, Central South University, Changsha 410083, China

ARTICLE INFO

Article history:
Received 17 September 2013
Received in revised form 28 January 2014
Accepted 23 February 2014
Available online 1 March 2014

Keywords:
Numerical modeling
Fushan iron ore district
Mineralization rate
Hydrothermal system
Equilibrium concentration

ABSTRACT

This paper uses the numerical method to simulate pore-fluid flow and heat transfer associated with iron ore-forming processes in the Fushan iron ore district, Hebei, China. Since mineralization may last a long period of time in a hydrothermal system, it is commonly assumed, in geochemistry, that the solutions and minerals are in an equilibrium state or near an equilibrium state. The relationship between the equilibrium concentration of iron and temperature has been considered to determine the mineralization rate of iron ore. Using the FISH language in the FLAC code, the coupled pore-fluid flow, heat transfer and mineralization have been simulated first with a generic model, and then with an actual geological model of the Fushan iron ore district. Since the equilibrium concentration of iron ion (Fe^{2+}) in magnetite (in the *NaCl* buffer) has been calculated using the TOUGHREACT software in geochemistry, it can be used to analyze the precipitation pattern of magnetite. The results of hydrothermal studies of coupled heat transfer and pore fluid flow with considering the mineralization rate can enhance our understanding of the ore formation processes in the Fushan district, and can be used directly or indirectly for mineral exploration.

1. Introduction

With the significant development of computer technologies and numerical methods, computational simulation has become a useful tool for dealing with a lot of complex problems, especially in the mineral exploration field. From the existing extensive studies carried out by Zhao et al. (2008a, 2009 and the references therein included) and others (Candela et al., 2005; Ju et al., 2011; Lin et al., 2003, 2006, 2008, 2009; Liu and Zhao, 2010; Liu et al., 2005, 2008; Ord et al., 2002; Xing and Makinouchi, 2008; Yan et al., 2003; Zhao, 2009), it has been well known that an ore-forming system commonly involves several processes, such as rock deformation, pore-fluid flow, heat transfer, mass transport and chemical reactions. The published papers in this research field can be briefly classified into the following categories: (1) numerical simulation and theoretical analyses of coupled heat transfer and pore fluid flow processes without considering the mechanical deformation (Phillips, 1991; Zhao et al., 2008a and the references therein included); (2) numerical simulation and theoretical analyses of convective and advective heat transfer in geological systems (Gow et al., 2002; Hobbs et al., 2000); (3) theoretical study of chemical dissolution and mineral precipitation instability problems (Zhao et al., 2008a, 2010); and (4) application of numerical simulation to different ore-forming systems in different geological regions (Fu et al., 2010; Gessner et al., 2009; Sorjonen-Ward and Zhang, 2002; Yang et al., 2010; Zhang et al., 2003, 2008, 2011) and to various types of geoscience problems (Barnes, 1997; Bethke, 1985, 1986; Cathles, 1981, 1983; Garven and Freeze, 1984; Garven et al., 1993; Norton and Cathles, 1973; Norton and Cathles, 1979; Taylor, 1974).

Among the above-mentioned research achievements, Zhao et al. (2008a, 2009 and the references therein included) have conducted the pioneering and primitive work on reactive fluid mixing and mineralization in pore-fluid saturated hydrothermal systems. In particular, Zhao et al. (2002, 2008a, 2009 and the references therein included) proposed, for the first time, the mineralization rate concept, which was successfully applied to the finite element simulation of mineralization patterns in hydrothermal systems, and good results have been obtained (Hobbs et al., 2000; Ohmoto and Lasage, 1982; Zhao et al., 2008a, 2009 and the references therein included). In this paper, we will first add the function of this theory in the FLAC code through using the FISH language, and then apply this theory to predict the mineralization patterns in the Fushan iron ore district.

The Fushan ore district is a skarn-type iron deposit in the Handan–Xingtai district, and the iron orebodies in this district are of high-grade and large-scale (Shen et al., 1979, 1981; Xu and Gao, 1990). Because of both economic and scientific importance, the Fushan ore district has been widely exploited, and investigated intensively by many

* Corresponding author. Tel.: +86 18608405455.
E-mail address: liuyao168@163.com (Y. Liu).

http://dx.doi.org/10.1016/j.gexplo.2014.02.023
0375-6742/

researchers (e.g., Chen et al., 2003; Mao et al., 2005; Niu et al., 1995; Zheng et al., 2007a, 2007b). These studies are useful for the understanding of ore formation processes in the Fushan ore district, the preliminary research results available can be briefly summarized as follows: (1) the storage situation and distribution characters of magnetite resources in the Fushan ore district have been investigated; (2) the pluton emplacement mechanism has been determined; (3) the periods of intrusions have been detected; and (4) the chemical constituents of iron migration have been experimentally verified.

However, the ore-forming process in the Fushan ore district is very complex. There are still several controversies including that: (1) the effect of temperature and pressure gradient on the iron ore deposits have not been analyzed in this district; (2) the control of structures on the localization of orebodies is emphasized, but the driving force and process of migration are seldom considered; (3) the research of related chemical reactions for magnetite precipitation is still not deep enough; and (4) many studies are restricted to the traditional methods, and the new approach of numerical computation (Zhao et al., 2009) has not been tried in the Fushan iron deposit. Therefore, it is necessary to develop innovative knowledge models for understanding ore-forming processes in detail, so as to facilitate the understanding of ore formation process in the Fushan ore district.

In this study, we use the numerical simulation method and the modern mineralization rate concept to investigate the iron ore-forming mechanism of the Fushan iron deposit. The outcome of this study will not only enrich the contents of the emerging computational geoscience discipline (Zhao et al., 2009), the methodology of which has been used to solve many geoscience problems (e.g. Turcotte, 1997; Turcotte and Schubert, 2002; Zhao et al., 2008a, 2009 and the references therein included), but also give us a better understanding of the ore-formation processes in this region. In addition, since the Fushan iron deposit is a crisis mine of ore reserves, the modeling result can be used to better predict the location of orebodies, so that the exploration risk can be greatly reduced.

2. Geological setting

2.1. The Handan–Xingtai district

The Handan–Xingtai district in Hebei province, located in the center of the North China platform (North China Craton), is an important district of skarn iron deposits. The iron orebodies in this district are of high-grade and large-scale, and the reserves of iron ore are substantial (Zheng, 2007). Currently, more than 100 iron deposits have been found and more than 10 million tons of magnetite ore have been mined, the most iron bodies are located in the contact zone between the Middle Ordovician carbonate and the Mesozoic intrusions, the main ore mineral is magnetite in this region. In addition, due to the excellent geographical environment and convenient traffic condition, this district has become one of the important mineral exploitation regions in China (Mao et al., 2005).

2.1.2. Strata

In the Handan–Xingtai district, the main strata comprise the sedimentary sequences mainly consisting of the Middle Ordovician carbonate layer and the Majiagou Formation limestone layer, the Carboniferous strata, the Permian strata and the Cambrian–Upper Ordovician strata (Mao et al., 2005; Zheng, 2007). Among them the Middle Ordovician strata are the main ore-bearing strata with the lithologies dominated by carbonate (Liu et al., 1982; Shen et al., 1977, 1981; Zhao et al., 1990; Zheng et al., 2007a, 2007b). The sequence of strata is shown in Table 1, and the statistic thickness of the strata is almost 6 km.

2.1.3. Igneous rock

The rocks in this district include hornblende diorite, syenite, and diorite–monzonite (Fig. 1). The isotopic dating data (Luo et al., 1997; Niu et al., 1995; Zheng, 2007) showed that the main intrusions were divided into three periods: the early period is before 140 Ma, the middle period is between 140 Ma and 120 Ma, and the late period is after 120 Ma. The Cambrian–Upper Ordovician strata are consisted of hornblende diorite.

The Yanshanian intrusions formed the core of the Handan–Xingtai ore-field. All Fe orebodies occur strictly in the vicinity of the contact zone between the Yanshanian intrusion and the Middle Ordovician sedimentary carbonates. The lithologies of the Yanshanian intrusions are dominated by diorite–monzonite, alkali-syenite, and gabbro diorite (Li et al., 2010; Shen et al., 1979, 1981; Wang et al., 2003a, 2003b; Xu and Gao, 1990; Xu et al., 2009). The SHRIMP U–Pb zircon age of the Fushan intrusion is 132.0 ± 2 Ma and 126.7 ± 1.1 Ma (Chen et al., 2003, 2005; Dong et al., 2003; Peng et al., 2004). The $^{40}Ar–^{39}Ar$ age of phlogopite associated with magnetite in the ores is 133.1 ± 1.3 Ma (Liao et al., 2003; Xie et al., 2007; Zheng, 2007), indicating that the Yanshanian intrusion and associated mineralization were emplaced in the late Jurassic to early Cretaceous, when the tectonic setting was characterized by substantial lithospheric thinning (Niu et al., 1995; Wang, 1992; Zhai, 2008). This means that the iron mineralization took place

Table 1
Stratigraphy and thickness of stratum in the Fushan district.
From Zheng et al., 2007a, 2007b.

Period	Epoch	Series	Lithostratigraphic unit	Code	Thickness (m)
Cenozoic	Quaternary			Q	220–330
	Tertiary	Miocene	Zhangwu Formation	N1z	>109
Mesozoic	Cretaceous	Early	Louli Formation	K1	>744
	Triassic	Middle	Liuquan Formation	T2	106–255
		Early	Liujiagou Formation	T1	760
Late Paleozoic	Permian	Late	Shangshihezi Formation	P2s	670–750
		Early	Xiashihezi Formation	P1x	120–220
	Carboniferous	Late	Taiyuan Formation	C3t	100–140
		Middle	Benxi Formation	C2b	10–35
Early Paleozoic	Ordovician	Middle	Fengfeng Formation	O2f	170–315
			Majiagou Formation	O2m	366–467
		Early	Liangjiashan Formation	O1l	42–72
			Yeli Formation	O1y	12–34
	Cambrian	Late	Fengshan Formation	∈3f	112–160
		Middle	Zhangxia Formation	∈2z	232–307
		Early	Maozhuang Formation	∈1 m	69–101
Proterozoic	Changchengian		Changzhouguo Formation	Chc	300–450
Archean	Under Zanhuang Group		Beisai Formation	Arb	35–300
			Fangjiapu Formation	Arf	>533