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Computational simulation of iron ore-forming processes in the Caiyuanzi siderite ore district, Guizhou, China

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ABSTRACT

By means of 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 in the Caiyuanzi siderite ore district, Guizhou. The effect of pore-fluid pressure on the equilibrium concentration of siderite has been considered. The main purposes of this paper are: (1) to illustrate some simulation results for the possibility of hydrothermal mineralization of siderite in a sedimentary environment; (2) to get a better understanding of the processes and mechanism of siderite orebody formation in the sedimentary environment; (3) to analyze the influence of the concentration of carbon dioxide on the siderite mineralization; and (4) to compare the simulation results with the actual situation, so as to demonstrate that this simulation method is effective and feasible for understanding the mineralization mechanism of iron ore in the Caiyuanzi siderite ore district.

1. Introduction

With the significant advancements of computational science and computer technology, the computational simulation method, as a new method for dealing with a lot of complex problems in the field of mineral exploration, has attracted increasing interest of research. From the existing extensive studies carried out by Zhao et al. (1998, 2008a,b, 2009) and others (Ju et al., 2011; Lin et al., 2003, 2009; Liu et al., 2005, 2010b, 2011; Ord et al., 2002, 2008a; Xing and Makinouchi, 2008; Yan et al., 2003; Zhao, 2009, 2015), 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 rock deformation (Hobbs et al., 2006, 2007; Phillips, 1991; Zhao et al., 1998, 2008b); (2) numerical simulation and theoretical analyses of convective and advective heat transfer in geological systems (Gow et al., 2002; Hobbs et al., 2000, 2004; Ord et al., 2008b, 2010; Zhao et al., 2012, 2013); (3) theoretical study of chemical dissolution and mineral precipitation instability problems (Hobbs et al., 2008, 2010a,b; Hornby et al., 2006a,b, 2008; Poulet and Regenauer-Lieb, 2015a,b; Zhao, 2014; Zhao et al., 2015a,b); and (4) application of numerical simulation to different ore-forming systems in different geological regions (Gessner et al., 2009; Schaubs and Zhao, 2002; Sorjonen-Ward and Zhang, 2002; Yang et al., 2010; Zhang et al., 2003, 2008, 2011) and to various types of geoscience problems (Alt-Epping and Zhao, 2010; Garven et al., 1993; Lei et al., 2013; Lin et al., 2006, 2008; Poulet et al., 2013; Zhao et al., 2010).

Among the above-mentioned research achievements, Zhao et al. (1998, 2008a,b, 2009) have conducted primitive and pioneering work on reactive fluid mixing and mineralization in pore-fluid saturated hydrothermal systems. In particular, Zhao et al. (2002, 2008a, 2009) proposed, for the first time, the mineralization rate concept and modern mineralization theory, which were successfully applied to the finite element simulation of mineralization patterns in hydrothermal systems, and excellent results have been obtained (Hobbs et al., 2000, 2006; Ohmoto and Lasage, 1982; Reid et al., 2012a,b; Zhao et al., 1998, 2008b). In this paper, we will add the function of Zhao's modern mineralization theory (Zhao et al., 2002, 2008a) in the FLAC code through using the FISH language, and then apply this theory to predict the mineralization patterns in the Caiyuanzi iron district.

The Caiyuanzi iron deposit is a large siderite ore deposit in Guizhou province, which has the characters of high-grade and large-scale (Lin et al., 1986). Because of both economic and scientific importance, the Caiyuanzi ore district has been widely exploited, and investigated intensively by many researchers (Lin et al., 1986; Nie, 1986). These researchers concluded that the siderite ore in the Caiyuanzi district was formed by sedimentary deformation. In recent years, other studies

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(Zhang et al., 2014) have shown that the siderite ore may be precipitated by hydrothermal transformation. This new view on the mineralization of the siderite gives us a chance to get better understanding of ore formation and mineralization in the Caiyuanzi ore district, but the preliminary research results (Yang et al., 2011) still provide some useful information about the Caiyuanzi iron deposit. We can briefly summarize the preliminary research results (Yang et al., 2011) as follows: (1) the storage situation and distribution characters of siderite resources in the Caiyuanzi iron district have been investigated; (2) the strata and the structure in the Caiyuanzi district have been determined; and (3) the siderite ore are controlled by stratum obviously. In addition, the new research results (Zhai, 2008) also give some valuable messages. They can be summarized as follows: (1) the metallogenetic resource comes from the hydrothermal fluids which are carrying the iron ion; (2) the hydrothermal intrusions was caused by the surrounding rock crack; and (3) the common way of ore forming is through the hydrothermal fluids penetrating a carbonate layer, where a chemical reaction should take place.

However, the ore-forming process in the Caiyuanzi ore district is very complex. There are still several key factors that have been ignored. For example, (1) the effects of temperature and pressure gradient on the siderite ore deposits have not been analyzed in this district; (2) the control of structures on the localization of orebodies is emphasized, but the processes of ore migration are seldom considered; (3) the research of related chemical reactions for siderite precipitation is still not deep enough; (4) many studies are restricted to the traditional methods, and the new approach of computational simulation (Liu and Dai, 2014; Zhao et al., 2009) has not been tried in the Caiyuanzi iron deposit; and (5) the influence of the concentration of carbon dioxide on the siderite mineralization has seldom been analyzed. 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 processes in the Caiyuanzi ore district.

In this study, we use the numerical simulation method (Liu and Dai, 2014) and the modern mineralization theory (Zhao et al., 2002) to investigate the iron ore-forming mechanism of the Caiyuanzi iron deposit. The outcome of this study will not only enrich the contents of the emerging computational geoscience discipline (Hobbs et al., 2011; Ord et al., 2012, 2013a,b; Peng et al., 2008, 2011; Zhao et al., 2009), the methodology of which has been used to solve many geoscience problems (e.g., Reid et al., 2012a,b; Schmidt Mumm et al., 2010; Turcotte and Schubert, 2002; Walshe et al., 2001; Zhao, 2009, 2014; Zhao et al., 2014, 2015a, 2015b), but also give us a better understanding of the ore-formation processes in this region.

2. Geological setting

2.1. The Caiyuanzi iron district

The Caiyuanzi iron district in Guizhou province, located in the Northwest of China, is an important district of siderite deposits and has the following features: (1) the ore reserve is substantial; (2) the iron orebodies were well preserved; and (3) the iron orebodies in this district are of high-grade and large-scale, so that this district has great potential prospect for exploitation (Zhang et al., 2014). The main disputes of ore-forming genesis in this district fall into two categories: hydrothermal transformation and sedimentary deformation. Currently, most iron bodies are located in the first lithologic segment of the Dushan formation, and the local siderite is presented in the Shujiaping formation and the Longshuidong formation. The reservoir rocks are mainly composed of the Lower and the Middle Devonian carbonate, while the main ore mineral is siderite in this region. In addition, due to the excellent geographical environment and convenient traffic condition, this district has become one of the important siderite exploitation regions in China (Lin et al., 1986; Liu and Nie, 1985).

2.1.1. Strata

In the Caiyuanzi iron district, the main strata comprise the Late Silurian strata and the Devonian strata (Yan et al., 2012; Zhang et al., 2014). Among them the Middle Devonian strata and the Late Devonian strata are the main ore-bearing strata with the lithologies dominated by carbonate (Zhang et al., 2014). The sequence of the strata is shown in Table 1, where the Late Devonian Yaosuo formation and Wangchengpo formation are mainly composed of Shaly sandstone; the Middle Devonian Dushan formation with dolomite is the major metallogenic region of siderite; the main material in the Middle Devonian Dahekou formation is quartz sandstone; the Middle Devonian Longdongshui formation and the Early Devonian Shujiaping formation are dominated by muddy dolomite with a small amount of siderite deposits; the Early Devonian Danlin formation contains the quartz sandstone as the main component; and the Late Silurian Hanjiadian formation is filled by silica classic rock.

2.1.2. Structure

The fault structure is commonly developed in the Caiyuanzi field. The main structure is the NW–SE fault with seldom fold, and the width of fault crush belt is between 30 and 50 m. The rocks are mainly made up of limestone, dolomite and quartz sandstone. The rock structure of limestone is not complex. Most of them are worm-like and banded structures and located within the Middle Ordovician Dushan formation and the Early Ordovician Shujiaping formation. The dolomite, which is located within the Middle Ordovician and the Early Ordovician carbonate layer, has three main rock structures: layered structure, blocky texture and brecciated structure. The rock structure of quartz sandstone is of simple and massive texture feature, which is mainly distributed within the Middle Ordovician Dahegou formation and the Early Ordovician Danlin formation. The geological map is shown in Fig. 1.

2.1.3. Mineralization

The main ore deposit is the siderite ore in the Caiyuanzi district. There are two previous statements about the mineralization of siderite. Some researchers (Hu, 1985; Liao et al., 1980) believed that the siderite ore was formed by sedimentary deformation, because the main structure in Caiyuanzi district is the multi-layer structure, and the location of the siderite ore was controlled by the certain strata strictly. Other studies, such as the geochemical anomaly investigation (Yan et al., 2012), the enclosure parameter analysis (Zhang et al., 2014) and rock alteration research, suggested that the siderite ore could be precipitated by hydrothermal transformation.

2.2. The deposit character of the Caiyuanzi iron district

The siderite in the Caiyuanzi district is located on the south of Yangzi landmass. This district is characterized by complex geological structures, developed multi-layer strata, strong fault actions, predominant metallogenic condition and rich siderite ore resources. Thus, it formed a centralized zone of mineralization and also constituted one of the important large siderite ore deposits. This is why the geological research on this deposit is of great significance (Guizhou Bureau and of Geology and Mineral Resources, 1987).

The major siderite ore was located in the Middle Devonian Dushan formation (D_2d^1) carbonate layer, and the fewer deposit was hosted in the Middle Devonian Longdongshui formation (D_2l) and Shujiaping formation (D_2s) carbonate layers. The distributions of the four larger orebodies are from northwest to southeast, which belong to the completely-concealed ore deposit. The dip angles of the deposit are about 5–35°. The ore deposit is extended about 1000–1600 m in the NW direction, while the width of the ore deposit is between 150 m and 300 m. There is little impurity in the ore samples, so that the siderite content can reach about 90%. The mineralization temperature measured from the 10 siderite ore samples is about 195–260 °C, with an average mineralization temperature of 217 °C.