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The mechanisms and time scale of alteration halos in vein-type tungsten deposits in southern China

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ABSTRACT

Alteration halos are the fingerprints left by hydrothermal flow in rocks and indicative of ore forming processes. The Nanling Range in southern China is a world-class tungsten province. However, it is poorly understood why alteration halos normal to veins in many tungsten deposits in the area decrease with increasing depth, and the time it takes to form the halos. Finite element based numerical experiments were conducted to investigate hydrothermal flow and species diffusion processes from fractures to adjacent wallrock in the tungsten deposits. The vertical distribution of alteration halos is influenced by wallrock porosity, fracture permeability, and the duration of hydrothermal flow in fractures. When hydrothermal fluids flow upwards, wider alteration halos are formed at deeper levels, when the wallrock has a constant porosity for a depth of around one kilometre. This is inconsistent with the characteristics of alteration halos in the tungsten deposits in southern China. Alteration halos in the tungsten deposits could be formed when the wallrock porosity decreases with increasing depth. The silicification and greisenization of the tungsten deposits could form over a period from tens of years to a few thousand years. Such a period is much shorter than the uncertainties of existing isochronal ages and may represent the duration of mineralizing pulses rather than all the geological events associated with tungsten mineralization. Tungsten diffusion from fractures to adjacent wallrock cannot produce large-scale disseminated tungsten mineralization during such a short period of time.

1. Introduction

Hydrothermal alteration results from the interaction between hot aqueous fluids and rocks (Pirajno, 2009). An understanding of hydrothermal alteration is valuable because it provides an insight into ore forming processes and aids in exploration (e.g. Barnes and Lavery, 1977; Geiger et al., 2002). The tungsten deposits located in the Nanling Range in southern China contribute a great part to the world's tungsten resources (e.g. Mao et al., 2013a). It has been discovered among these tungsten deposits that the hydrothermal alteration width decreases with increasing depth, which is independent of the alteration types (e.g. Chen et al., 1989; Que and Xia, 1988). However, the mechanisms for forming such hydrothermal alteration are still enigmatic. These tungsten deposits form by fracture filling in short geological periods (e.g. Zhu et al., 2014), but accurate timescales are poorly understood.

Theoretical and numerical studies suggest that alteration halos normal to fractures often decreases along the flow direction as reactive fluids flow through fractures (e.g. Cathles and Shannon, 2007; Steefel and Lichtner, 1998; Wang et al., 2013a). Therefore, it is assumed that some unknown variables may control the formation of the hydrothermal alteration in the tungsten deposits in the Nanling Range. Previous numerical modelling used the diffusion rate of silica to compare the width of silicification at different depths (Liu et al., 2016). A few improvements on the previous numerical model were made to put a better constraint on the mechanisms and time scale of alteration halos in the tungsten deposits. In addition to silicification, the width of greisenization and tungsten halos in the tungsten deposits is estimated in the numerical experiments. Hydraulic parameters of fractures and adjacent wallrock are also varied to find the key variables controlling species diffusion.

2. Geological background of the tungsten deposits

The tungsten deposits in the Nanling Range are ca. 160–150 Ma, and are interpreted to be associated with re-melted granitic rocks in a continental crust during the Jurassic to Cretaceous (Hua et al., 2003;

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Mao et al., 2013a; Zhou et al., 2006). The vein-type tungsten deposits in the region are located near the roof zone of buried alkali-feldspar granites. Mineralized veins of these deposits contain wolframite, quartz, feldspar, muscovite, calcite, and tourmaline, and extend to depths of 1000 m (Zhu et al., 2014).

Hydrogen, oxygen, carbon, and sulfur isotopic data indicate that the ore fluids responsible for tungsten mineralization have a magmatic origin and later mixed with meteoric fluid (c.f. Chen et al., 1989; Zhu et al., 2014). Numerous fluid inclusion studies indicate that the ore fluids contained NaCl-H_2O ± CO_2 with a small amount of CO, CH_4, N_2, and H_2. The fluid inclusions trapped by ore and minerals are two-phase aqueous at room temperature and have homogenization temperatures ranging from 160° to 390° C. The fluid inclusions have salinities in the range 1–10 wt% NaCl eqv. The mineralization pressure ranges from 20 to 160 MPa with a maximum range of 75–160 MPa (e.g. Gong et al., 2015; Liu et al., 2011; Ni et al., 2015; Wang et al., 2011, 2007, 2013b; Wei et al., 2012; Xi et al., 2008; Xiong et al., 2017; Zhu et al., 2015).

3. Alteration halos of the tungsten deposits in the Nanling Range

The vein-type tungsten deposits in the Nanling Range are hosted by low-grade metamorphosed sandstone and granite (Gu, 1984; Zhu et al., 1981). Alteration of these deposits is characterized by the mineral assemblage of silica-pyrite-biotite-muscovite in sandstone and silica-muscovite-topaz-fluorite in granite (Liu and Ma, 1993; Zhu et al., 1981). The alteration halos are commonly in < 1 m wide selvages adjacent to the mineralized veins (Fig. 1) and generally decrease in width with increasing depth, which does not depend on the wallrock lithology or specific alteration (Chen et al., 1989; Que and Xia, 1988; Zhu et al., 2014).

Disseminated tungsten mineralization is found to be close to the tungsten mineralization in quartz veins in some tungsten deposits in southern China (e.g. Mao et al., 2013b). No one has yet studied whether the disseminated tungsten mineralization can be formed by tungsten diffusion from fractures to adjacent wallrock. The silicification, greisenization, and tungsten halos on two sides of mineralized veins were investigated using finite element-based numerical experiments.

4. Numerical modelling of hydrothermal flow of the tungsten deposits

4.1. Mathematical theories

Fractures control hydrothermal flow in the tungsten deposits in the Nanling Range (e.g. Liu et al., 2014; Yu, 2004). Fractured rocks in these deposits were considered as an equivalent porous medium (cf. Long et al., 1982; Oda, 1985; Snow, 1969). Assuming that this is the case, hydrothermal flow can be mathematically expressed with the continuity equation and Darcy's equation and heat transfer, which are controlled by both heat conduction and convection (see Appendix A and Appendix B). These equations are solved by an in-house finite element based supercomputer simulator PANDAS. PANDAS can simulate the coupled hydraulic-thermal-mechanical processes in active fault systems and geothermal reservoirs (Li and Xing, 2015; Liu et al., 2015, 2017; Xing, 2014; Xing et al., 2015, 2007; Xing and Makinouchi, 2002). This simulator was employed to investigate the hydrothermal fluid flow of the tungsten deposits in the Nanling Range.

Alteration halos commonly form after a volume of reactive fluids flow through fractures or pores and alter the adjacent rocks (Cathles and Shannon, 2007; Wang et al., 2015, 2012). The width of alteration halos is controlled by the physical and chemical properties of fluids and rocks, the diffusion rate, and duration of fluid flow (e.g. Cathles and Shannon, 2007; Geiger et al., 2002; Steefel and Lichtner, 1998). The density model of Batzle and Wang (1992) and the viscosity model developed for this study based on that from Phillips et al. (1981) were used to estimate these variables (see Liu et al., 2016).

Diffusion cannot proceed in a porous media as fast as in water because ions must follow longer pathways as they move around mineral grains. An effective diffusion coefficient is a key parameter for describing diffusion in porous media (Fetter, 2001). The alteration halo width Z is a nonlinear function of the effective diffusion coefficient D_e and equates to:

$$Z(t) = 2\sqrt{\frac{D_e t}{\phi + 2G}} \tag{1}$$

where t is the time and G is a dimensionless parameter that equals the volume (m^3) of the fluid required to alter 1 m^3 volume of rock (Cathles and Shannon, 2007). From Eq. (1), the alteration halo width is positively correlated with the time-integrated effective diffusion coefficient of species.

The effective diffusion coefficient of a chemical species in porous media depends on the porosity ϕ and its diffusion coefficient D_s in aqueous solutions:

$$D_e = D_s\phi^2 \tag{2}$$

This is an empirical function derived from diffusion experiments on low-porosity rocks (cf. Boving and Grathwohl, 2001; Rimstidt, 2014; Van Loon and Mibus, 2015). The diffusion coefficient D_s follows the Stokes-Einstein equation (Cussler, 2009; Li and Gregory, 1974; Rimstidt, 2014).

The formation of alteration halos is often caused by diffusion of chemical species (Cathles and Shannon, 2007; Reed, 1997). The relative

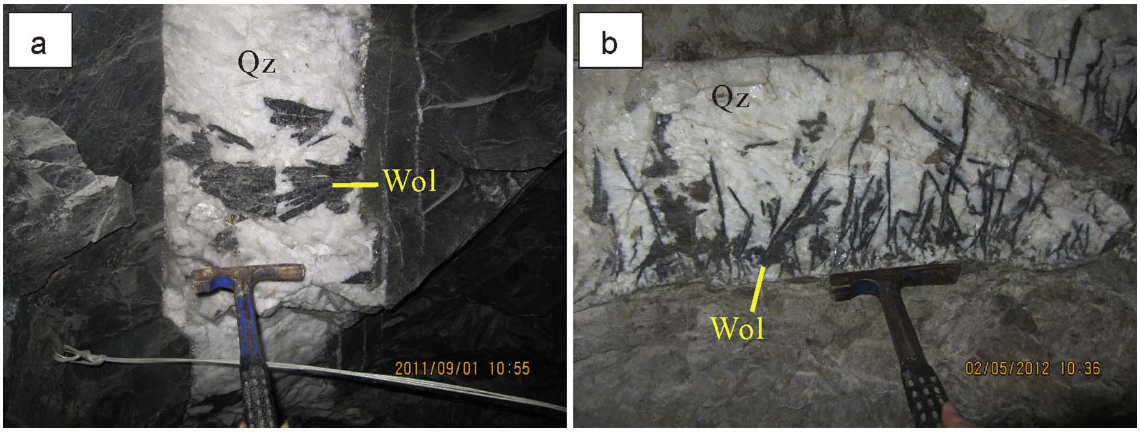

Fig. 1. Photos of typical veins in two tungsten deposits in the Nanling Range: (a) a thick vein at deeper parts of vein sets in the Dajishan deposit (Liu et al., 2014). Viewed upwards; (b) a thick vein at deeper parts of vein sets in the Piaotang deposit (Liu et al., 2017). Viewed upwards. Both two veins show a sharp contact relation to weakly altered sandstone. Abbreviations: Qz, quartz; Wol, wolframite.