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In situ Pb and bulk Sr isotope analysis of the Yinchanggou Pb-Zn deposit in Sichuan Province (SW China): Constraints on the origin and evolution of hydrothermal fluids

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ABSTRACT

The Yinchanggou Pb-Zn deposit, located in southwestern Sichuan Province, western Yangtze Block, is stratigraphically controlled by late Ediacaran Dengying Formation and contains > 0.3 Mt of metal reserves with 11 wt % Pb + Zn. A principal feature is that this deposit is structurally controlled by normal faults, whereas other typical deposits nearby (e.g. Maozu) are controlled by reverse faults. The origin of the Yinchanggou deposit is still controversial. Ore genetic models, based on conventional whole-rock isotope tracers, favor either sedimentary basin brine, magmatic water or metamorphic fluid sources. Here we use in situ Pb and bulk Sr isotope features of sulfide minerals to constrain the origin and evolution of hydrothermal fluids. The Pb isotope compositions of galena determined by femtosecond LA-MC-ICPMS are as follows: $^{206}Pb/^{204}Pb$ = 18.17–18.24, $^{207}Pb/^{204}Pb$ = 15.69–15.71, $^{208}Pb/^{204}Pb$ = 38.51–38.63. These in situ Pb isotope data overlap with bulk-chemistry Pb isotope compositions of sulfide minerals ($^{206}Pb/^{204}Pb$ = 18.11–18.40, $^{207}Pb/^{204}Pb$ = 15.66–15.76, $^{208}Pb/^{204}Pb$ = 38.25–38.88), and both sets of data plotting above the Pb evolution curve of average upper continental crust. Such Pb isotope signatures suggest an upper crustal source of Pb. In addition, the coarse-grained galena in massive ore collected from the deep part has higher $^{206}Pb/^{204}Pb$ ratios (18.18–18.24) than the fine-grained galena in stockwork ore sampled from the shallow part ($^{206}Pb/^{204}Pb$ = 18.17–18.19), whereas the latter has higher $^{208}Pb/^{204}Pb$ ratios (38.59–38.63) than the former ($^{208}Pb/^{204}Pb$ = 38.51–38.59). However, both types of galena have the same $^{207}Pb/^{204}Pb$ ratios (15.69–15.71). This implies two independent Pb sources, and the metal Pb derived from the basement metamorphic rocks was dominant during the early phase of ore formation in the deep part, whereas the ore-hosting sedimentary rocks supplied the majority of metal Pb at the late phase in the shallow part. In addition, sphalerite separated from different levels has initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7101 to 0.7130, which are higher than the ore formation age-corrected $^{87}Sr/^{86}Sr$ ratios of country sedimentary rocks ($^{87}Sr/^{86}Sr_{200\ Ma}$ = 0.7083–0.7096), but are significantly lower than those of the ore formation age-corrected basement rocks ($^{87}Sr/^{86}Sr_{200\ Ma}$ = 0.7243–0.7288). Again, such Sr isotope signatures suggest that the above two Pb sources were involved in ore formation. Hence, the gradually mixing process of mineralizing elements and associated fluids plays a key role in the precipitation of sulfide minerals at the Yinchanggou ore district. Integrating all the evidence, we interpret the Yinchanggou deposit as a strata-bound, normal fault-controlled epigenetic deposit that formed during the late Indosinian. We also propose that the massive ore is formed earlier than the stockwork ore, and the temporal-spatial variations of Pb and Sr isotopes suggest a certain potential of ore prospecting in the deep mining area.

1. Introduction

Hydrothermal ore deposits hosted by sedimentary rocks supply the majority of the world's Pb and Zn, as well as a significant proportion of Cu. Generally speaking, sediment-hosted Pb-Zn deposits that contain Pb and/or Zn (rather than e.g. Cu) as their primary commodity have no

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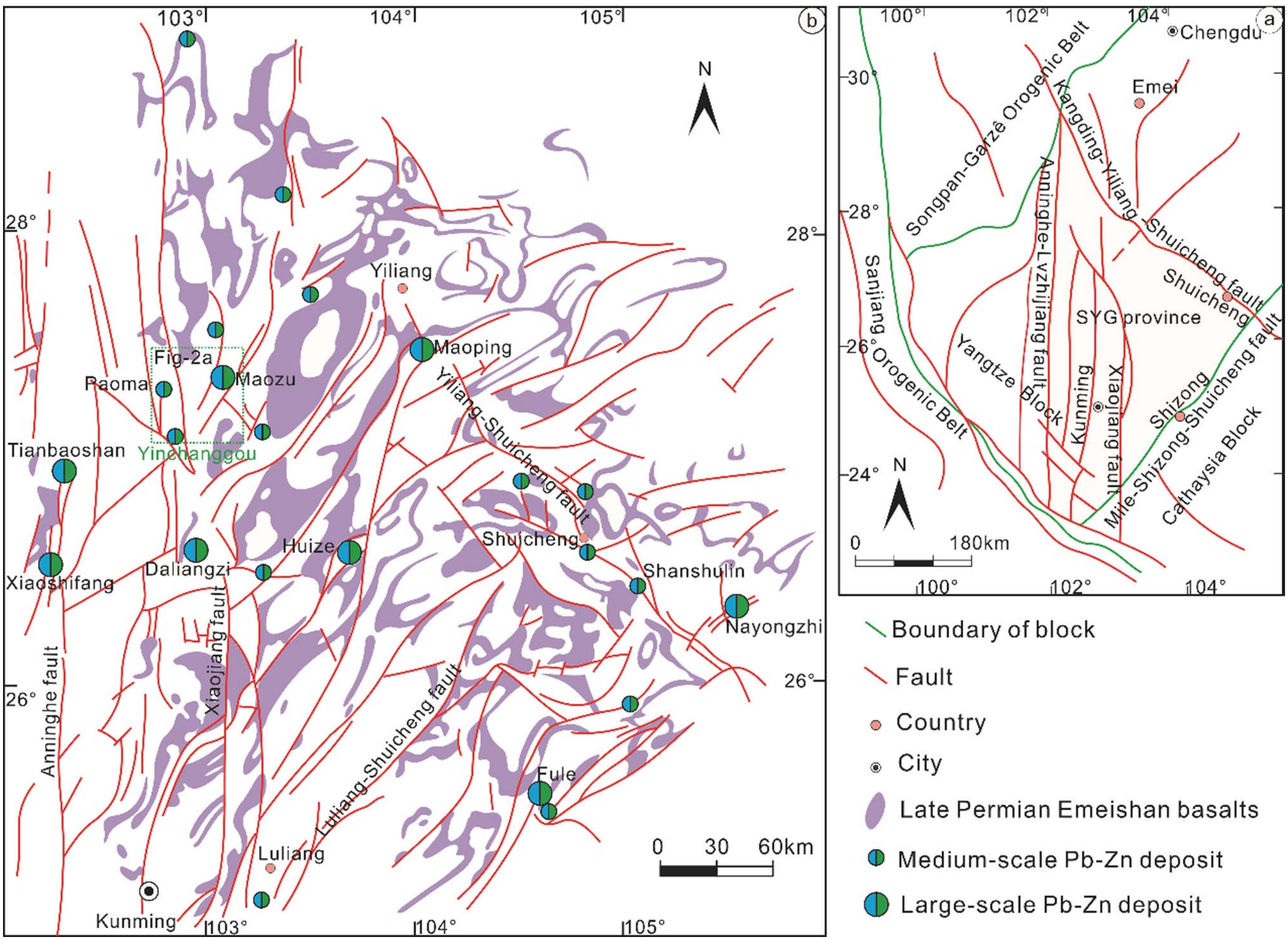

Fig. 1. a: Regional geological setting of Southwest China, highlighting the general study area (modified from Huang et al., 2004); b: Geological sketch map of the Sichuan-Yunnan-Guizhou (SYG) Pb-Zn metallogenic province (modified from Liu and Lin, 1999), which shows the distribution of Pb-Zn ore deposits, Emeishan basalts and faults.

obvious temporal and spatial association with igneous activities (Leach et al., 2005). Such a type of Pb-Zn deposits represents the world's most important source of Pb and Zn, and widely occurs around the world (Heijlen et al., 2003; Leach et al., 2010; Wang et al., 2014). Carbonate-hosted Pb-Zn deposits, a key subtype of sediment-hosted hydrothermal sulfide deposits, are strictly hosted in carbonate platforms (Leach et al., 2005; Wilkinson et al., 2005). The best known carbonate-hosted Pb-Zn deposits occur in the central and western region in the United States, Pine Point in Canada, Upper Silesia in Poland, and Sichuan, Yunnan and Guizhou (SYG) triangular area in China (Heijlen et al., 2003; Leach et al., 2005; Zaw et al., 2007; Zhou et al., 2013a). For example, more than 400 Pb-Zn deposits have been found in the western Yangtze Block (Fig. 1a and b), which form the SYG Pb-Zn metallogenic province (Zhou et al., 2014a). Such a province is an important part of the giant South China low-temperature metallogenic domain (Zhou et al., 2014b; Hu et al., 2017), accounting for 27% of total Zn + Pb resources in China (Zhang et al., 2015). Although extensive research on these Pb-Zn deposits has contributed greatly to our understanding of the metallogeny, the sources of mineralizing elements and associated fluids remain controversial (Zheng and Wang, 1991; Zhou et al., 2001; Xu et al., 2014; Zhou et al., 2014b; Wei et al., 2015; Zhu et al., 2017).

The Yinchanggou deposit, a medium-scale (> 0.3 Mt metal reserves with 11 wt% Pb + Zn) carbonate-hosted Pb-Zn deposit, is located in the central part of the SYG Pb-Zn metallogenic province (Fig. 1b). Unlike other well-studied reverse fault-controlled Pb-Zn deposits (e.g. Maozu, Maoping, Huize and Tianqiao) in the SYG province (Huang et al., 2010; Bai et al., 2013; Zhou et al., 2013a; Wei et al., 2015), this deposit is structurally controlled by normal faults (Figs. 2 and 3). Therefore, the Yinchanggou deposit provides a good opportunity to deepen the understanding of the Pb-Zn mineralization in the SYG province. Although a lot of studies have been carried out on this deposit (Yang, 2009; Zhou, 2009; Yan et al., 2010; Li, 2011; Li et al., 2016), its origin is currently subject to some debates. For example, some studies interpreted it as a distal hydrothermal deposit associated with magmatic water (Yang, 2009; Li, 2011), whereas other investigations considered it to be an example of Mississippi Valley-type (MVT) mineralization (Lin et al., 2010; Wang et al., 2010). In addition, more recent literatures proposed an epigenetic SYG-type model, whereby mineralizing elements and associated fluids were considered to be derived from a mixed source of Emeishan continental flood basalts, ore-hosting marine sedimentary rocks and basement metamorphic rocks (Zhou et al., 2013a; Li et al., 2016).

Radiogenic isotopes are a powerful tool for tracing the origin of mineralizing elements and associated fluids, among which, Pb and Sr isotopes have been widely used for determining the source and evolution of hydrothermal fluids (Carr et al., 1995; Zhou et al., 2001; Wilkinson et al., 2005; Zhou et al., 2016; Li et al., 2015). Microbeam analytical techniques have the potential to provide crucial microscale chemical and isotopic information to reveal the ore formation process and depositional environment of hydrothermal systems (Ikehata et al., 2008; Barker et al., 2009; Ye et al., 2011; Yuan et al., 2015; Jin et al., 2016; Deng et al., 2017). Such information is essential for understanding the genesis of hydrothermal ore deposits. Laser-ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) is a technique that can efficiently determine in situ isotope compositions of sulfide minerals in hydrothermal systems (Woodhead

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