



# Geological and isotopic constraints on the origin of the Anle carbonate-hosted Zn–Pb deposit in northwestern Yunnan Province, SW China



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## ABSTRACT

The Anle Zn–Pb deposit, hosted by Upper Cambrian dolostone, is located in the southern Songpan–Ganzi Block in southwest China. In this deposit, ore bodies occur as stratiform lenses and consist of galena, sphalerite and pyrite as ore minerals, and quartz, dolomite and calcite as gangue minerals. The mineralization shows mainly vein, banded and brecciated structures. Four ore bodies have been found in the Anle deposit, with a combined 2.0 million tonnes (Mt) of sulfide ores at average grades of 1.64 wt.% Pb, 6.64 wt.% Zn and 45 g/t Ag. Brown, brownish-yellow and yellow sphalerite samples have  $\delta^{66}\text{Zn}$  values ranging from +0.08 to +0.10‰ (average +0.09‰,  $n = 3$ ), +0.12 to +0.38‰ (average +0.24‰,  $n = 8$ ) and +0.40 to +0.50‰ (average +0.46‰,  $n = 3$ ), respectively. We interpret the progressively heavier Zn isotopes from brown to yellow sphalerite as being led by kinetic Raleigh fractional crystallization. Calcite samples have  $\delta^{13}\text{C}_{\text{PDB}}$  and  $\delta^{18}\text{O}_{\text{SMOW}}$  values ranging from −4.8 to −0.2‰ (average −1.7‰,  $n = 7$ ) and +17.9 to +21.4‰ (average +19.6‰,  $n = 7$ ), respectively. Whole-rock  $\delta^{13}\text{C}_{\text{PDB}}$  and  $\delta^{18}\text{O}_{\text{SMOW}}$  values of the Cambrian ore-hosting dolostone range from +0.1 to +1.1‰ (average +0.6‰,  $n = 3$ ) and +23.2 to +24.1‰ (average +23.6‰,  $n = 3$ ), respectively. This suggests that carbon in the ore-forming fluids was provided by the host dolostone through carbonate dissolution.  $\delta^{34}\text{S}_{\text{CDT}}$  values of sulfide samples range between −1.3‰ and +17.8‰ with an average value of +6.3‰ ( $n = 25$ ), lower than evaporites (such as barite +19.8‰) in the overlying Lower Ordovician sedimentary strata. The data suggest that sulfur in the hydrothermal fluids were derived from evaporites by thermo-chemical sulfate reduction (TSR).  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios for sulfide minerals range from 17.63 to 17.86, 15.58 to 15.69 and 37.62 to 37.95, respectively. The data are similar to those of the age-corrected Cambrian ore-hosting dolostone ( $^{206}\text{Pb}/^{204}\text{Pb} = 17.70\text{--}17.98$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.58\text{--}15.65$  and  $^{208}\text{Pb}/^{204}\text{Pb} = 37.67\text{--}38.06$ ), but lower than those of age-corrected Ordovician sandstone and slate ( $^{206}\text{Pb}/^{204}\text{Pb} = 18.54\text{--}19.58$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.73\text{--}15.81$  and  $^{208}\text{Pb}/^{204}\text{Pb} = 38.44\text{--}39.60$ ). This indicates that ore Pb was most likely to be derived from the Cambrian ore-hosting dolostone. Therefore, our new geological and isotopic evidence suggests that the Anle Zn–Pb deposit is best classified to be an epigenetic carbonate-hosted Mississippi Valley-type (MVT) deposit.

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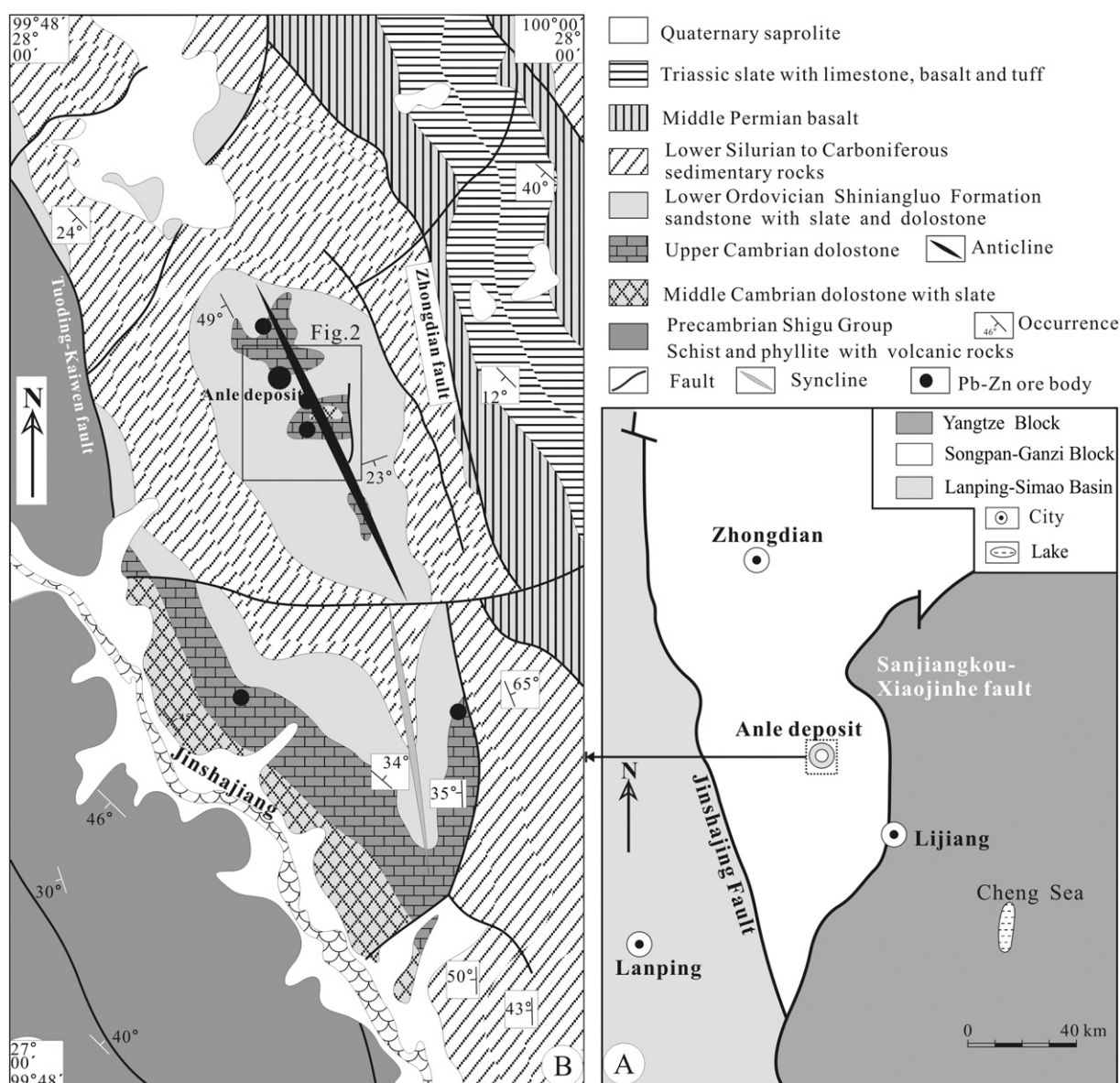
## 1. Introduction

The Sanjiang (three rivers in Chinese: Jinshajiang, Lancangjiang and Nujiang) tectonic belt in southwestern China, extending for more than 1500 km, is an important polymetallic metallogenic belt with abundant Cu–Mo–(Au) and Pb–Zn–Ag deposits in the Eastern India–Eurasia collision zone (e.g., Hou et al., 2007; Hou and Cook, 2009). The Anle Zn–Pb deposit is located in the eastern section of the Songpan–Ganzi Block, in the mid-northern part of the Sanjiang metallogenic belt (Fig. 1A). The Songpan–Ganzi Block is situated between the Yangtze Block to the east and the Lanping–Simao basin to the west (Fig. 1A). Studies

indicate that the main deformation process of the Songpan–Ganzi fold belt occurred during the Late Triassic (e.g., Chang, 2000; Xu et al., 1992). More than 400 carbonate-hosted Pb–Zn deposits have been found in the western Yangtze Block (Liu and Lin, 1999), and they constitute the famous Sichuan–Yunnan–Guizhou (SYG) Pb–Zn metallogenic province (Huang et al., 2010; Zhou et al., 2013a, 2014a, 2015). Among these deposits, there are many large scale (>1 Mt Pb + Zn metal reserves) Pb–Zn deposits, such as the Huize Zn–Pb–Ge (Han et al., 2007; Huang et al., 2010; Zhou et al., 2001), Daliangzi Zn–Pb–Cd (Zheng and Wang, 1991) and Tianbaoshan Zn–Pb deposits (Zhou et al., 2013b). There are also many famous sediment-hosted Pb–Zn deposits in the Lanping–Simao basin, including the world-class (>10 Mt Pb + Zn) Jinding Pb–Zn deposit (Tang et al., 2014; Xue et al., 2007) and the large scale Baiyangping Pb–Zn deposit (Zhang et al., 2013). However,

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**Fig. 1.** A: Map showing the tectonic setting of the Anle Zn–Pb deposit district; B: Regional map of the Anle Zn–Pb deposit showing faults, folds, lithologies and deposits. Modified from Wang et al. (2011).

in the southern part of the Songpan–Ganzi Block, no large scale sediment-hosted Pb–Zn deposits were reported (Wang et al., 2011).

The Anle Zn–Pb deposit has been mined since 1736 AD (the Qing dynasty Qianlong Period), and by then extraction of Ag was given priority over other metals. This deposit contains more than 2.0 Mt of sulfide ores with an average grade of 1.64 wt.% Pb, 6.64 wt.% Zn and 45 g/t Ag (Wang et al., 2011). Ore deposit geology and fluid inclusion geochemistry indicate that the Anle Pb–Zn deposit is different from many Zn–Pb deposits in the western Yangtze Block (SYG-type, Li et al., 2015; Zhou et al., 2013c, 2014b) and the Lanping–Simaobasin (Jinding-type, Tang et al., 2014; Wang et al., 2014; Xue et al., 2007), but similar to other carbonate-hosted Pb–Zn deposits (Mississippi Valley-type) in the southern Songpan–Ganzi Block (Wang et al., 2011), as evidenced by: (i) ore bodies are hosted in Upper Cambrian dolostone, (ii) Zn–Pb mineralization occurs within the Anle anticline, (iii) simple mineral assemblage and wall rock alteration, (iv) evaporites are common in Lower Ordovician Shiniangluo Formation sandstone, (v) organic matter is abundant in Middle Cambrian shale, and (vi) ore-forming fluids have medium–high temperatures (130–370 °C) and low salinities (3.0–12.8 wt.% eq. NaCl). However, despite the fluid inclusion

geochemical work done by Wang et al. (2011), there are still many unknown aspects regarding the source of ore-forming fluids and metals, ore genesis and geodynamic setting of the Anle Zn–Pb deposit.

C–O and S isotopes have been widely used to constrain the source of the ore-forming fluids (e.g., Basuki et al., 2008; Huang et al., 2003, 2010; Ohmoto and Goldhaber, 1997; Palinkaš et al., 2013; Pašava et al., 2014; Zhou et al., 2013d, 2014b), and Pb isotopes are useful for tracing the origin of the ore-forming metals for carbonate-hosted sulfide deposits (e.g., Carr et al., 1995; Gromek et al., 2012; Mirnejad et al., 2011; Pass et al., 2014; Xue et al., 2007; Zhou et al., 2013e, 2016). In addition, Zn isotopes have recently been used for understanding the geochemical process of Zn extraction, transportation and deposition in hydrothermal systems (e.g., Chen et al., 2013; Fujii et al., 2011; Gagnevin et al., 2012; John et al., 2008; Kelley et al., 2009; Mason et al., 2005; Pašava et al., 2014; Toutain et al., 2008; Wilkinson et al., 2005; Zhou et al., 2014a, 2014b). In this paper, we describe the Anle Zn–Pb ore deposit geology and report new C–O isotopic data of hydrothermal calcite and the ore-hosting dolostone whole-rock, S- and Zn isotopic data of sulfide minerals, and Pb isotopic data of wall rocks and sulfides. This new dataset, together with the previously published data of fluid inclusions in

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