Modeling of fluid pressure evolution related to sediment loading and thrust faulting in the Lanping basin: Implications for the formation of the Jinding Zn–Pb deposit, Yunnan, China

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Abstract

The Jinding Zn–Pb deposit occurs in Cretaceous and Paleocene siliciclastic rocks (mainly sandstones) in the Meso-Cenozoic Lanping basin, western Yunnan, China. With a reserve of approximately 200 Mt of ore containing 6.1% Zn and 1.3% Pb, Jinding is the largest sandstone-hosted Zn–Pb deposit in the world. Most previous studies assumed that the mineralizing fluids were derived from within the basin (including meteoric recharge), and the fluid flow was driven by topographic relief under a hydrostatic regime. In contrast, we propose that the mineralizing system was strongly overpressured based on observations of hydraulic fractures and fluid inclusion data. Numerical modeling results indicate that the overpressures could not have been produced by normal sediment compaction. Thrust faulting and input of mantle-derived fluids are likely responsible for the building-up of the high overpressures. The special hydrodynamic regime and potential contribution of mantle-derived fluids to the mineralizing system distinguish Jinding from other known sedimentary basin-related Pb–Zn deposits.

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1. Introduction

The Jinding Zn–Pb deposit is located in the Meso-Cenozoic Lanping basin in western Yunnan, China (Fig. 1). Hosted in siliciclastic rocks (mainly sandstones) and having a reserve of approximately 200 Mt of ore containing 6.1% Zn and 1.3% Pb (i.e., a metal reserve of about 15 Mt), Jinding is the largest sandstone-hosted Zn–Pb deposit in the world (Xue et al., in press). Since its discovery in the 1960s, a large number of geological and geochemical studies have been carried out, and various genetic models have been proposed, including a syngenetic or SEDEX-type, a syngenetic + overprinting epigenetic type, and an epigenetic type (see Xue et al., in press for a review). In terms of fluid flow mechanisms, previous studies generally assumed a hydrostatic, intrabasinal (including meteoric recharge) fluid flow system driven by topographic relief (Sun and Xu, 1989; Hu et al., 1998; Xu and Li, 2003). However, based on observations of hydraulic fractures and fluid pressures estimated from fluid inclusion data, Chi et al. (2005) proposed that the mineralizing fluid system was strongly overpressured. The present study aims to evaluate the
potential mechanisms of overpressure development through numerical modeling and to discuss the implications on hydrodynamics and fluid sources of the mineralizing system.

2. Regional and local geology

The regional and local geology of the Jinding Zn–Pb deposit have been described in various papers (Yin et al., 1990; Zhu et al., 2000; Kyle and Li, 2002; Xue et al., 2002a,b, in press), and only the salient points are summarized here. The Lanping–Simao basin (or Lanping basin for the northern part) is a narrow (about 50–150 km wide, >400 km long), NNW-trending intracontinental basin filled with Late Triassic to Neogene sediments up to more than 10 km thick (Fig. 1). The basin is separated from the Tibet–Yunnan plate to the west by the Lancang Jiang fault, and from the Yangtze plate to the east by the Jinsha Jiang fault (Fig. 1). Following the collision of the Tibet–Yunnan and Yangtze plates and a micro-plate between them in mid-Triassic, the Lanping–Simao basin evolved from a rift basin in Late Triassic, through a continental depression in Jurassic and Cretaceous, to a continental pull-apart basin in Tertiary, accompanied and followed by compression and thrusting associated with the Indian–Eurasian plate collision. Except for some Upper Triassic limestones, the basin is characterized by siliciclastic rocks with evaporitic intervals. The strata have been strongly folded and faulted during the Himalayan orogeny, and intruded by some alkaline magmatic intrusions.

The Jinding deposit occurs as tabular ore bodies in sandstones of the Jingxing Formation (K1j) and sandstones and carbonate breccias of the Yunlong Formation (E1y) near a NS-trending, high-angle normal fault, the Pijiang fault (Fig. 1). K1j was thrust over E1y along a flat-lying fault (F2), and both allochthonous and autochthonous strata as well as the thrust plane are domed (the Jinding dome). The deposit consists of more than 100 ore bodies that are distributed mainly around the dome. These relationships suggest that thrust faulting occurred after deposition of the Yunlong Formation (55.8 Ma), doming took place during or after thrusting, and mineralization accompanied or postdated doming. The mineralization is characterized mainly by fine-grained sulfides disseminated in sandstones and breccias, with some open-space filling in cavities and veins. Colloform texture of sphalerite and frambooidal texture of pyrite are locally present. Hydraulic fractures filled by calcite and sulfides are locally observed. Ore minerals are sphalerite and galena, and gangue minerals include pyrite, marcasite, barite, celestite, gypsum, anhydrite, and minor quartz. Bitumen is found locally in veins and pore space.

3. Modeling of fluid pressures related to sediment loading and thrust faulting

The evolution of fluid pressures in the Lanping basin was simulated using the Basin2™ version 5.0 program (Bethke et al., 1993). The objective was to evaluate how much overpressure can be generated by sediment compaction and by nappe thrusting. The conceptual model of the basin (Fig. 2) consists of continuous T3 to K1 strata (228–99.6 Ma) with constant thicknesses across the 60 km wide basin, followed by a basin-wide hiatus during K2 (99.6–65.5 Ma), then localized sedimentation along two depocenters in E1 (65.5–55.8 Ma), thrusting of a nappe over one of the depocenters (55.8–52.8 Ma), and finally sedimentation along a flat-lying fault (F2), and both allochthonous and autochthonous strata as well as the thrust plane are domed (the Jinding dome). The deposit consists of more than 100 ore bodies that are distributed mainly around the dome. These relationships suggest that thrust faulting occurred after deposition of the Yunlong Formation (55.8 Ma), doming took place during or after thrusting, and mineralization accompanied or postdated doming. The mineralization is characterized mainly by fine-grained sulfides disseminated in sandstones and breccias, with some open-space filling in cavities and veins. Colloform texture of sphalerite and frambooidal texture of pyrite are locally present. Hydraulic fractures filled by calcite and sulfides are locally observed. Ore minerals are sphalerite and galena, and gangue minerals include pyrite, marcasite, barite, celestite, gypsum, anhydrite, and minor quartz. Bitumen is found locally in veins and pore space.

![Fig. 1. Geological map of part of the Lanping basin showing the location of the Jinding Zn–Pb deposit in western Yunnan, China (after Kyle and Li, 2002).](image1)

![Fig. 2. Conceptual model of the Lanping basin used in the numerical modeling.](image2)
in a new depocenter in E2–3 (52.8–23 Ma). The lithologic components and thicknesses of the strata, based on the data from the Third Geological Team (1990) and Zhu et al. (2000), are listed in Fig. 2. The bottom and two sides of the basin are closed to fluid flow, and the top boundary is open to fluid flow. A heat flux of 83.6 mW/m² (2 HFU) is supplied evenly across the bottom. The porosity and permeability parameters for sandstone, shale and carbonate are the default values of Basin2™ (Bethke et al., 1993), i.e., ϕ₀=0.4, ϕ₁=0.05, bpor=0.5 (km⁻¹), A_perm=15, B_perm=−3 (log darcy), p_kxxz=2.5 for sandstone, ϕ₀=0.55, ϕ₁=0.05, bpor=0.85 (km⁻¹), A_perm=8, B_perm=−7 (log darcy), p_kxxz=10 for shale, and ϕ₀=0.4, ϕ₁=0.05, bpor=0.55 (km⁻¹), A_perm=6, B_perm=−4 (log darcy), p_kxxz=2.5 for limestone. The parameters for evaporites are from Kaufman (1994) except a p_kxxz value of 20 is used instead of 100: ϕ₀=0.5, ϕ₁=0.05, bpor=10 (km⁻¹), A_perm=8, B_perm=−8 (log darcy). The thrusting of the nappe is modeled by adding a 2 km thick unit of lithified sedimentary rocks on top of a depocenter over a period of 3 Ma. The porosity and permeability parameters for the lithified sandstone, shale, carbonate and evaporite are modified from those of nonsolidified sediments, with initial porosity (ϕ₀) being equal to final porosity, i.e., no compaction within the nappe.

The modeling results indicate that minor amounts of overpressures were developed from T₃ to K₁ and were dissipated during K₂ (hiatus). Negligible fluid overpressures were developed during E₁ deposition in the two depocenters (Fig. 3, line a). Significant fluid overpressures were developed within and below the nappe during thrusting (Fig. 3, line b), with the maximum values (up to 170 bars) being confined immediately below the thrust plane (Fig. 4). The overpressures were gradually dissipated after the emplacement of the nappe and slight underpressures were developed by the end of E₃ deposition (Fig. 3, line c).

4. Discussion and conclusions

Some previous studies have noted the difference between Jinding and other sandstone-hosted Pb–Zn deposits in terms of tectonic environments and Zn/Pb ratios (Kyle and Li, 2002), potential fluid and metal contribution from the mantle (Xue et al., 2000, in press), and hydrodynamic regime (Chi et al., 2005). In particular the occurrence of CO₂-rich inclusions (Xue et al., 2002c; Chi et al., 2005), the high CO₂/H₂O ratios of bulk fluid inclusions (around 1, 1.57–4.07, Wang and Li, 1991; 0.02 to 13.65, Wen et al., 1995), and high fluid pressures estimated from CO₂ inclusions (up to 1364 bars; Chi et al., 2005) are unusual for sedimentary basin-related Zn–Pb deposits. Our numerical modeling results indicate that significant fluid overpressures can be produced by thrusting of nappes, but the magnitudes do not appear to be as high as indicated by fluid inclusions. Although higher overpressures can be achieved by increasing the thickness of the nappe or changing the porosity and permeability parameters in the numerical model, we postulate that the extra overpressures (in addition to those related to thrusting and compaction) were due to input of CO₂ from a deep source into the basin. The effect of CO₂ on the pressure regime is similar to intrabasinal fluid production (e.g., hydrocarbon...
generation and mineral dehydration), which is represented by a source term in the fluid flow equation. The hydrodynamic regime of the Jinding mineralizing system is significantly different from conventional models of base metal mineralization in sedimentary basins, in which the fluids were intrabasinal (including meteoric recharge) and the driving forces were topographic relief or overpressures caused by factors within the basin (e.g., sediment compaction). The peculiar features of the Jinding deposit, including active tectonic setting, mantle signature, CO2 enrichment and overpressured regime are interrelated, and collectively set Jinding apart from other sedimentary basin-related base metal deposits.

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