An estimate of the lead isotopic compositions of upper mantle and upper crust and implications for the source of lead in the Jinding Pb-Zn deposit in Western Yunnan, China

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The Jinding Pb-Zn deposit occurs in the Tertiary red sedimentary formation of the Cenozoic continental fault depression basin at Lanping, western Yunnan. The orebodies are stratiform and stratoid in form and giant in size, with the associated Sr and Cd being of high grade. In the past thirty years the source of lead in this deposit has been a long-standing controversial problem. Some scholars considered that lead came from the upper mantle while others shed doubt on that viewpoint. However, no conclusive evidence has been obtained to support their respective viewpoints, and to find a more definite answer to the above question. We have re-examined the lead isotopic composition of the Jinding Pb-Zn deposit. The lead isotopic ratios of the striped ore are $^{206}\text{Pb}/^{204}\text{Pb} = 18.138\text{--}18.552$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.345\text{--}15.552$, and $^{208}\text{Pb}/^{204}\text{Pb} = 37.803\text{--}38.443$, and the lead isotopic ratios of the massive ore are $^{206}\text{Pb}/^{204}\text{Pb} = 18.394\text{--}18.600$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.583\text{--}15.767$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.266\text{--}39.046$. In terms of the lead isotopic composition of minerals and whole rock samples from basic-ultrabasic rocks and alkaline rockbodies in the region of western Yunnan, we have determined the lead isotopic composition of the upper mantle in this region at Meso- and Cenozoic times, as $^{206}\text{Pb}/^{204}\text{Pb} = 17.850\text{--}18.350$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.430\text{--}15.540$, and $^{208}\text{Pb}/^{204}\text{Pb} = 37.800\text{--}38.410$. Then in the light of the lead isotopic composition of metamorphic rocks and sedimentary rocks from Precambrian to Tertiary, which are exposed in the Lanping Basin and its adjacent areas, we have determined the lead isotopic composition of the upper crust, as $^{206}\text{Pb}/^{204}\text{Pb} = 18.420\text{--}19.200$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.500\text{--}16.010$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.450\text{--}39.500$, and several mineral samples from granulite and eclogite xenoliths yielded the lead isotopic information of the lower crust, as $^{206}\text{Pb}/^{204}\text{Pb} = 18.135\text{--}18.187$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.335\text{--}15.388$ and $^{208}\text{Pb}/^{204}\text{Pb} = 37.836\text{--}37.899$. A comparison has been made with the lead isotopic composition of the ore, and it is indicated that lead in the Jinding Pb-Zn deposit was not derived from the upper mantle, and there are two sources of lead: one is the upper crust and the other is the lower crust.

INTRODUCTION

The Jinding deposit is the largest-scale Pb-Zn ore deposit in China. It is characterized as being terrestrial redbed strata-bound (sedimentary metallogenesis in the terrestrial basin), young in metallogenic age (Himalayan metallogenesis) and associated with super-large Sr deposits. Since the early 1980's much beneficial work has been done on this deposit. In regard to the genesis of this

deposit, two hypotheses have been put forward, i.e., sedimentation-reworking origin according to the stratiform ore bodies and high ore-forming temperature (from 270°C to 350°C). Its ore-forming metal elements are considerably derived from the sedimentary rocks in the basin (Tu *et al.*, 1984; Bai *et al.*, 1985), and terrestrial exhalative-hydrothermal sedimentary origin as evidenced by the characteristics of the deposit similar to those of the SEDEX deposits, whose ore-forming metal

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elements are considerably derived from the upper mantle and/or the basement rocks of the basin (Li *et al.*, 1993). The lower isotopic ratios in most galena samples from this deposit indicated that the lead was derived from the upper mantle (Yin *et al.*, 1990; Luo *et al.*, 1992; Tu *et al.*, 2000). However, in their He-Ar isotopic tracing study, Hu *et al.* (1998) held that there is no mantle-source helium in this deposit. The isotopic compositions of S, O, C, H, and Sr provide reliable information to show that these elements were derived from the crust (Luo *et al.*, 1992; Tu *et al.*, 2000). No signs of magmatic activities of pyrolites on a large scale are noted within the mining district. So it has become questionable whether lead in the Jinding deposit comes from the upper mantle or not. For this reason, we have re-examined the origin of lead in the deposit. Our research thought is: (1) A direct approach to determining the source of ore-forming materials in Pb-Zn deposits is the lead isotopic composition; (2) On the basis of a better understanding of the lead isotopic composition of rocks from the upper mantle, the upper crust and the lower crust-derived xenoliths in the region of western Yunnan, a comparison will be made with the lead isotopic composition of the ore, in conjunction with its geochemical and geological characteristics, so as to constrain the origin of lead in this deposit.

GEOLOGICAL CHARACTERISTICS OF THE DEPOSIT

Stratigraphy and lithological character

With reference to the structural relations, the strata exposed in the mining district can be divided into two parts: the *in-situ* system and the exotic system. The exotic system includes the Upper Triassic Waigucun Formation, the Sanhedong Formation, the Maichuqing Formation and the Middle Jurassic Huakaizuo Formation, which have been thrust by large overthrust faults onto the Tertiary strata. Lithologically, shore- and shallow sea-facies sedimentary limestones, sandstones, siltstones and argillaceous siltstones are dominant, which are distributed mainly on both limbs of the

domes. The most significant visual difference between the exotic system and the *in-situ* system is that the former is dominated by grayish-white rocks and the latter by red and purple red rocks. The *in-situ* system consists of the Lower and Upper Tertiary series and the Quaternary system, with a total thickness of 689–940 m. The Cretaceous strata are distributed mainly in the periphery of the mining district, the Upper Tertiary strata are distributed in the northwestern part of the mining district and the Quaternary deposits are distributed along the river valley (Fig. 1). The Lower Tertiary Yunlong Formation strata comprise three lithological units (a, b, c). Ey^a stands for a suite of purple red argillaceous siltstones, measuring 300 m in thickness, at the foot wall of the ore beds. At the bottom, a 1.5–10 m thick layer of limestone breccias is developed. The sediments of Ey^a bed become coarse in grain size from west to east, and belong to arid, salt-lake facies. It has a transitional relationship with the overlying strata (Ey^b). In the Ey^b unit there are developed limestone breccia and slip-collapse breccia in the east, giving way to breccia, purple-red sandstone and purple-red to grayish-white muddy sandstone in the west. In going from east to west, the breccias tend to become smaller and smaller in scale while the bedding tends to become more and more distinct. In most cases the Ey^b strata, with a thickness of 400 m, are in fault contact with the overlying Ey^c strata. The Ey^c strata are made up of quartzose sandstone and breccia-bearing quartzose sandstone. At the bottom limestone breccia, marl breccia and dolomite breccia are developed, and at the top limestone lenses are occasionally developed. Horizontal bedding is recognized at the top and oblique bedding is seen in the middle part, in fault contact with the overlying exotic system, measuring <100 m in thickness.

Structure and magmatic activity

As the Jinding ore field is located in the Mesozoic Sanjiang folded zone (the name Sanjiang is referred to the Jinsha River, Lancang River and Nu River), in conjunction with the collision-compression of the Indian Plate, the fault

Fig. 1. Geological map of the Jinding Pb-Zn deposit. Q: Quaternary; N_{2s}: Sanying Formation of Upper Pliocene, Upper Tertiary; Ey: Yunlong Formation of Paleocene, Lower Tertiary; Ey^c: the upper member of the Yunlong Formation; Ey^b: the middle member of the Yunlong Formation; Ey^a: the lower member of the Yunlong Formation; Upper Cretaceous: K_{2h}: Hutoushi Formation; K_{2n}: Nanxing Formation; J_{2h}: Middle Jurassic Huakaizuo Formation; Upper Triassic: T_{3m}: Maichuqing Formation; T_{3s}: Sanhedong Formation; T_{3w}: Waigushu Formation. 1. Strata boundary; 2. Fault; 3. Orebody.

structures are well developed. The Lanping Basin is an inland fault depression basin controlled by a deep fault zone (Fig. 2). On the eastern side of the mining district the Bijiang fault zone extends from south to north with a total length of 120 km (Figs. 1 and 2). This fault zone is a long-term active synsedimentary fault which controls the sedimentary facies of the *in-situ* system strata. The Pb-Zn mineralization, pyritization and decolourization are recognizable along this fault

zone. So this fault zone may be an important ore-conduit structure.

Li (1994) investigated the reverse thrust nappe structure in the Lanping Basin. In the Jinding ore field the reverse thrusting of large-scale nappe faults (F₁, F₂, F₃, F₄) made the Mesozoic strata overlap the Tertiary red beds (Figs. 1 and 3). The reverse thrusting event took place after the sedimentation and diagenesis of the Lower Tertiary Yunlong Formation strata dated at about 65 to 50

Fig. 2. The geological map of the Lanping basin. 1. Yangtze plate; 2. Zhongdian minor plate; 3. Tibet-Yunnan plate; 4. Lanping basin; (1) Lancangjiang fault; (2) Cangshan fault; (3) Bijiang fault; (4) Jinshajiang fault; (5) Deqin-Zhongdian fault; (6) Lijiang fault; (7) Wuliangshan fault; (8) Mojiang fault.

Ma in age (Li, 1994). Based on our study on the regional geology, the time at which the reverse thrusting event took place is synchronous with that of orogenic uplifting of the basin in the Early Himalayan (Alpine) movement which started approximately 40 Ma in western Yunnan. Li *et al.* (2000) studied the thermal events of the Jinding deposit with the fission track method on phosphorite from the altered Tertiary (>40 Ma) and Jurassic wall rocks (sandstone) of the ore-bodies, and the results showed that a large thermal event took place from 25 Ma to 35 Ma in the ore field. This age probably represents a main ore-forming event.

In the mining district the Tertiary strata constitute a large-sized domal structure, in the middle part of which lies the lower member of the Yunlong Formation and in the periphery of which are the middle and upper members of the Yunlong Formation and Mesozoic strata. On the western and northern rims this dome is relatively steep and on the eastern and southern rims it is relatively gentle with respect to its attitude. The top part of the dome has been eroded, but if reverting to the original form (Fig. 3), it is apparent that the re-

verse thrusting and dome structures play an important role in mineralization, and mudstone and argillaceous siltstone (J_2h) form an effective confining bed for ore-forming fluid.

In the vast range of the mining district and its periphery there is not exposed any type of magmatic rocks.

Geology of the deposit

The Jinding Pb-Zn deposit occurs in the red sedimentary formation of the Lower Tertiary Yunlong Formation in the Lanping Cenozoic continental basin (Figs. 1 and 3). There are more than 380 orebodies, of which there are sixteen major ones, with a tonnage of Pb + Zn exceeding 20 Mt. The associated Sr content reaches the grade of a large-tonnage Sr deposit. The associated Cd has a tonnage of about 0.20 Mt.

According to the position of ore-host strata, the upper and lower ore-host beds are distinguished. Ey^c represents the upper ore-host bed. Stratiform and stratoid orebodies are predominating, which are controlled by the stratigraphic position and lithological character. The upper ore-

Fig. 3. The cross section of the Jinding Pb-Zn deposit. 1. Limestone; 2. Mudstone; 3. Argillaceous siltstone; 4. Sandstone; 5. Conglomerate; 6. Orebody; 7. Fault; 8. Strata boundary.

host bed is dominated by the sandstone-type ores and there is a transitional relation between the orebodies and the wall rocks. Orebody I₁, the largest in the upper ore-host bed, is 1450 m long, 1360 m obliquely deep, and 10–40 m thick. The orebodies extend in the E-W direction, dipping 10°–30° northwards, and contain on the average 1.51% Pb, 8.32% Zn, 13 ppm Ag and 230 ppm Cd.

Metallic minerals in the sandstone-type ores are usually present in the form of cements of detritus (e.g., quartz) in sandstone and, therefore, the ores often exhibit cement texture and disseminated and banded structures at the edges of the orebodies. But under microscope, it is observed that the coarse-grained metallic minerals (galena and sphalerite) have replaced the fine-grained metallic minerals and the cement in the sandstone. There exist massive coarse-grained ores within the orebodies. This probably indicates that the formation of the sandstone-type ores involves two stages: early synsedimentary mineralization and late hydrothermallymetasomatic mineralization.

The lower ore-host bed is situated within the Ey^b unit and contains lenticular, tubular and irregular orebodies in addition to stratiform and

stratoid ones (Fig. 3). The limestone-type or the limestone breccia-type ores are developed in the lower ore-host bed. It is commonly observed that mineralization is the result of replacement of limestone breccias in the rocks. The ores commonly exhibit a wide range of textures including metasomatic-resorption, milk-drop, concentric ring and granular textures, and massive, disseminated, brecciated, banded and comprising network structures, etc. Extensive metasomatism in the lower ore-hosted bed indicates that the ores are mainly formed from hydrothermal solutions in the late mineralizing stage. The typical tubular orebody VII in the lower ore-host bed occurs in the limestone breccia overlying the Ey^b strata, which is 580 m long, 215 m deep and 20 m–102 m thick and contains 2.42% Pb, 11% Zn and 130 ppm Cd. The celestite orebodies occur mainly in the limestone breccia of the Beichang ore run, some occurring as independent celestite orebodies and some as complex orebodies associated with Pb and Zn.

Different ore-host beds and different types of ores obtain almost similar metallic minerals, with galena, sphalerite and pyrite being dominant. Usually the minerals are fine in grain size and it is

commonly seen that galena and pyrite are cementing and framboidal in form at the edges of the ore-bodies in the western ore-field. The framboidal pyrite is sometimes found embracing granular galena. The minerals in the eastern ore-field are coarse in grain size and the massive ores are common. The gangue minerals are dominated by quartz, gypsum, barite and celestite. Wall-rock alterations are diverse in type though not so intensive, and silicification, calcitization, dolomitization and baritization are commonly seen.

The ore-forming temperature is relatively high, as is evidenced by the homogenization temperatures of the fluid inclusions in sphalerite of massive ores ranging from 270°C to 350°C. From east to west, the ore-forming temperature trends to decrease from 350°C to 270°C (Tu *et al.*, 1984; Chen *et al.*, 1996). This indicates that the ore-forming fluid moves in the direction from east to west.

SAMPLES AND ANALYTICAL PROCEDURE

Sampling

In order to reveal the isotopic composition of upper mantle lead in the region of western Yunnan, we collected samples of basic-ultrabasic rocks, alkaline rocks and deep-source inclusions from Beiya, Dali, Jinchang and Laowangzhai and picked out 13 mineral samples including plagioclase, garnet and olivine, and one serpentized peridotite. These rock samples are considered as mantle-source magmatic rocks (Deng *et al.*, 1998; Bian, 1998; Xu *et al.*, 1999). Four basalt samples and nine hydrothermal sulfide (pyrite and chalcopyrite) samples in the Yangla Cu deposit which occurs in basalts were collected from the northern margin of the Laping Basin. Of the four basalt samples, one shows obvious signs of alteration (e.g., silicification and sericitization). According to Pan *et al.* (2000, 2001), the origin of this deposit is related to basaltic magmatism and its ore-forming materials are derived from the mantle.

The lead isotopic composition of upper-crust

sedimentary rocks in the region of western Yunnan was modeled on the basis of that of the metamorphic rocks mainly including schist and gneiss from Early to Middle Proterozoic, whose primitive rocks are sedimentary rocks and were metamorphosed during the Jinning Movement (took place at 800 Ma) (Zhong *et al.*, 1998), and sedimentary rocks from Cambrian to Tertiary in the Laping Basin and its adjacent areas. Luo *et al.* (1992) analyzed 42 whole-rock samples from this region. Eight years later, we analyzed another 12 Mesozoic and Cenozoic whole-rock samples in an attempt to attest the consistency and reliability of the isotopic composition data obtained by different authors at different times.

Forty-three galena samples from the Jinding deposit were systematically analyzed for Pb isotopes by the Yunnan Provincial Bureau of Geology and Mineral Resources in 1980's and published by Luo *et al.* (1992). The conclusion that lead in the Jinding deposit stemmed from the upper mantle is based on this set of lead isotopic composition data. Additionally, eight massive coarse-grained galena samples were collected in this study from the limestone-hosted breccia-type and sandstone-type ores and four samples of galena embraced in framboid pyrite were collected from the margins of ore-bodies in the upper ore-host bed. Thus a total of 51 samples were collected in this study.

Analytical method

The sample pretreatment procedure was described by Robin *et al.* (1999). Galena sample (200 mg) was dissolved with HNO₃, and rinsed with water, followed by the loading of lead onto the Re filaments with a mixture of silica gel + H₃PO₄ for analysis. The whole-rock samples and feldspar, garnet and olivine samples (400 mg) were dissolved in the mixed solution of HF, HCl and HBr; chalcopyrite and pyrite (400 mg) were first washed with HCl to remove impurities coated on the surface of the minerals, then dissolved with aqua regia while heating, and finally converted to a HBr chromatographic solution. The Pb in the solution was eluted using an ion exchange resin with HBr-

HCl.

Of 51 samples, 28 samples were used for lead isotopic analysis on a VG-354 mass spectrometer at the Isotope Laboratory of the Institute of Geology, Chinese Academy of Sciences and 21 samples on a MAT-261 mass spectrometer at the Isotope Analysis Center of the Yichang Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences, respectively. Of the samples, 20% was repeatedly analyzed. The fractionation factor (0.1% per amu) is worked out in terms of the results of lead isotopic analyses of NBS-981 as the international standard samples so as to make correlations for the lead isotopic ratios of the samples. The measurements of the common-lead standard NBS-981 gave average values of $^{206}\text{Pb}/^{204}\text{Pb} = 16.923 \pm 3$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.467 \pm 3$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.733 \pm 6$ for MAT-354 and $^{206}\text{Pb}/^{204}\text{Pb} = 16.924 \pm 3$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.468 \pm 3$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.732 \pm 6$ for MAT-261 with uncertainties <0.1% at the 95% confidence level. The bulk lead blanks of the whole procedure are <1 ng and the analytical results for all the samples are corrected by this. The duplicate analysis indicates similar reproducibilities in all cases. The bulk error is <0.1% for all samples.

In order to understand the influence of U and Th in the whole-rock, feldspar, garnet and olivine samples on the lead isotopic composition, the ICP-MS techniques were employed to determine the contents of U, Th and Pb in these samples, with the detection limit being 1 ppm. The analytical results show that the four basalt samples contain 10–20 ppm Pb and 1–2 ppm U, Th; feldspar, garnet and olivine contain 18–28 ppm Pb and U, Th < 1 ppm; the 12 stratum samples contain 10–23 ppm Pb, 0.2–0.4 ppm U and 4–7 ppm Th. The ore-forming age of this deposit is 25 to 35 Ma (Li, 2000). The calculated radiogenic Pb composition from decay of radioactive elements after ore deposition is within the scope of the analytical errors, and their calculated radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ values are <0.006, $^{207}\text{Pb}/^{204}\text{Pb}$ values are <0.004 and $^{208}\text{Pb}/^{204}\text{Pb}$ values <0.008, implying that all the analytical results can be directly adopted in the discussion.

Pb ISOTOPIC COMPOSITION OF THE UPPER MANTLE IN WESTERN YUNNAN

Lu *et al.* (1993) and Deng *et al.* (1998) examined the lead isotopic composition of basic-ultrabasic rocks (gabbro, peridotite, anorthosite, etc.) and alkaline rocks (mainly quartz-syenite, quartz-orthophyre, aegirine syenite porphyry, cascadingite, syenite-porphyry, etc.) in the region of western Yunnan. From their detailed research on lithology, trace-element and isotopic geochemistry, Tu (1989), Deng *et al.* (1998), Bian (1998) and Xu *et al.* (1999) considered that these rocks are derived from the mantle of the region. Liu *et al.* (1999) projected the lead isotopic compositions of alkaline rocks (whole rock) ($^{206}\text{Pb}/^{204}\text{Pb} = 17.498\text{--}18.847$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.410\text{--}15.728$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.415\text{--}39.191$) into the plumbotectonics model of Zartman and Doe (1981), and found that some samples are located near the zero termination of the mantle lead evolution line. It follows that the alkali-rich porphyries are magmatic rocks probably of mantle derivation. Although the lead isotopic composition of the whole alkaline rocks bears some information about the mantle, the lead isotopic ratios vary over an apparent large scope and the largest value is noticed for radiogenic lead. There are two main aspects pertaining to lead isotopes in the rocks. One is radiogenic lead which generated from radioactive elements such as U and Th after the formation of the rocks, and the other is the contamination of crustal materials. That is to say, the whole-rock lead isotopic composition of these rock-bodies could by no means represent the lead isotopic composition of the upper mantle in the region studied.

The lead isotopic compositions of thirteen minerals including plagioclase, garnet and olivine and one serpentinized peridotite are shown in Table 1. The lead isotopic ratios are: $^{206}\text{Pb}/^{204}\text{Pb} = 17.877\text{--}18.460$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.465\text{--}15.543$, and $^{208}\text{Pb}/^{204}\text{Pb} = 37.797\text{--}38.520$, respectively. Lead isotopic ratios in the whole-rock samples of basalt from the Yangla Cu deposit on the northern margin of the basin are: $^{206}\text{Pb}/^{204}\text{Pb} = 18.056\text{--}$

Table 1. Isotopic composition of mantle lead in the region of western Yunnan

Location	Sample No.	Rock type	Mineral or rock	$^{206}\text{Pb}/^{234}\text{Pb}$ (2σ)	$^{207}\text{Pb}/^{234}\text{Pb}$ (2σ)	$^{206}\text{Pb}/^{238}\text{Pb}$ (2σ)
Deqin	83DX-1	Augite-peridotite	Plagioclase	18.167 (3)	15.498 (2)	38.366 (4)
	83DX-2	Augite-peridotite	Plagioclase	18.353 (2)	15.507 (2)	38.414 (5)
	83DX-3	Gabbro	Plagioclase	17.936 (3)	15.404 (3)	38.225 (4)
Jianchuan	JC-4	Gabbro xenolith in Syenite-porphry	Plagioclase	18.142 (3)	15.463 (3)	38.231 (4)
	JC-5	Anorthosite xenolith in Syenite-porphry	Plagioclase	17.977 (4)	15.398 (2)	38.183 (4)
Liuhe	83BY40	Garnet-pyroxenolite xenolith in Syenite-porphry	Garnet	17.977 (2)	15.465 (1)	37.797 (3)
	83BY41	Anorthosite xenolith in Syenite-porphry	Plagioclase	18.272 (4)	15.519 (3)	38.411 (6)
Beiya	83BY27	Garnet-pyroxenolite xenolith in Syenite-porphry	Garnet	18.133 (3)	15.476 (1)	38.268 (4)
	82RH43	Gabbro	Plagioclase	17.913 (2)	15.468 (2)	38.314 (5)
Tiechang	82RH44	Gabbro	Plagioclase	18.212 (4)	15.488 (2)	37.933 (5)
	82RH45	Gabbro	Plagioclase	18.109 (4)	15.492 (3)	38.095 (4)
Laowangzai	95AL-1	Lherzolite	Olivine	18.069 (3)	15.508 (2)	38.073 (6)
	95AL-3	Lherzolite	Olivine	18.131 (4)	15.491 (4)	38.156 (6)
Mojiang	95JC-1	Altered Peridotite	Olivine	17.990 (6)	15.467 (3)	38.005 (8)
	95JC-2	Altered Peridotite	Whole rock	18.460 (6)	15.543 (4)	38.520 (7)
Yao'an	82YA31	Syenite-porphry	Orthoclase	18.009 (3)	15.523 (1)	38.152 (5)
	83BY8	Syenite-porphry	Orthoclase	18.216 (2)	15.511 (2)	38.204 (4)
Yangla	yn133	Basalt	Whole rock	18.260 (4)	15.470 (2)	38.264 (6)
	yn129	Basalt	Whole rock	18.056 (5)	15.481 (3)	38.177 (6)
	yn127	Basalt	Whole rock	18.239 (4)	15.464 (2)	38.103 (5)
	yn124	Altered basalt	Whole rock	18.506 (5)	15.587 (3)	38.567 (8)
	yn-20	Basalt	Pyrite	18.256 (4)	15.490 (3)	38.334 (5)
	yn-21	Basalt	Pyrite	18.139 (3)	15.513 (2)	38.083 (4)
	yn-56	Basalt	Pyrite	18.023 (5)	15.436 (3)	37.833 (6)
	yn-37	Basalt	Chalcopyrite	18.112 (3)	15.450 (2)	37.998 (4)
	yn-47-1	Basalt	Chalcopyrite	18.149 (2)	15.505 (1)	38.177 (5)
	yn-47-2	Basalt	Chalcopyrite	18.113 (3)	15.498 (3)	38.037 (5)
	yn-58	Basalt	Chalcopyrite	18.205 (4)	15.541 (4)	38.178 (4)
	yn-65	Basalt	Chalcopyrite	17.985 (3)	15.430 (3)	38.358 (5)
	yn-71	Basalt	Chalcopyrite	18.221 (2)	15.519 (2)	38.189 (5)

Data in the brackets are analytical errors (2σ). All samples were analyzed in this study.

Fig. 4. Lead isotopic compositions of the upper mantle in western Yunnan and the upper crust in the Lanping Basin. Zartman's lead evolution model: M. upper mantle lead; O. orogenic belt lead; U. upper crustal lead; L. lower crustal lead. 1. Precambrian metamorphic rock; 2. Cambrian; 3. Permian; 4. Triassic; 5. Jurassic; 6. Cretaceous; 7. Tertiary; 8. Upper mantle lead in western Yunnan.

18.506, $^{207}\text{Pb}/^{204}\text{Pb} = 15.470\text{--}15.587$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.103\text{--}38.567$, respectively. Lead isotopic ratios of sulfide samples from the ores of the Yangla copper deposit are: $^{206}\text{Pb}/^{204}\text{Pb} = 17.985\text{--}18.256$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.434\text{--}15.519$, and $^{208}\text{Pb}/^{204}\text{Pb} = 37.833\text{--}38.358$, respectively. The lead isotopic composition of these samples mentioned above is significantly different from that of the whole rocks. The lead isotopic values are more homogeneous and are lower than those of the whole rocks. As observed in the plumbotectonics diagram of Zartman and Doe (1981) (Fig. 4), the data points of all samples fall on the mantle lead evolution line or are distributed in the extending direction along this evolution line. Along the long axis the variation range so defined is well consistent with the mantle lead evolution line. According to Pan *et al.* (2001), lead in the Yangla Cu deposit is believed to have stemmed from the upper mantle, with almost no contamination by

crustal materials. Our data for basaltic rocks at Yangla are consistent with this view and suggest that the data points falling within the areas defined by solid lines, as shown in Fig. 4, can represent the lead isotopic composition of the upper mantle since Late Paleozoic in the region of western Yunnan.

THE LEAD ISOTOPIC COMPOSITION OF UPPER CRUSTAL ROCKS IN THE LANPING BASIN

The upper crustal rocks exposed in the Lanping Basin and its periphery include the Precambrian Chongshan Group and Cangshan Group metamorphic rocks and the Cambrian to Tertiary sedimentary rocks. The lead isotopic compositions of 54 whole-rock samples are presented in Table 2. The results show that although the strata are different in geological age (from 1800 Ma to 60 Ma) and lithological character (migmatite, gneiss, schist,

Table 2. The Pb isotopic composition of the strata at different levels in the Lanping Basin

Stratigraphic	Location	Sequence No.	Sample No.	Rock type	$^{206}\text{Pb}/^{204}\text{Pb}$ (2 σ)	$^{207}\text{Pb}/^{204}\text{Pb}$ (2 σ)	$^{208}\text{Pb}/^{204}\text{Pb}$ (2 σ)
Precambrian	Cangshan	1	DXQ3	Schist	18.679	15.722	38.955
		2	DXQ4	Migmatite	18.906	15.754	39.373
		3	DXQ5	Migmatite	19.004	15.646	39.031
	Chongshan	4	DXQ33	Migmatite	19.380	15.808	39.209
		5	DXQ34	Granite	18.650	15.562	38.636
Cambrian	Deqing	6	NG4	Schist	18.750	15.417	37.878
	Sanjiacun	7	DZQ53	Dolomite	18.140	15.801	38.613
Permian	Yangla, Deqing	8	yn-26	Silicalite	18.397 (6)	15.575 (4)	38.602 (7)
		9	yn-120	Slate	19.014 (5)	15.754 (3)	39.348 (7)
		10	yn-141	Slate	18.911 (5)	15.625 (3)	39.149 (6)
		11	yn-122	Marble	18.423 (4)	15.554 (2)	38.555 (6)
		12	yn-117	Andesite	18.882 (6)	15.700 (3)	39.094 (8)
		13	NZB3	Tuff	18.657	15.633	38.430
	Nanzuo	14	NZB7	Tuff	18.626	15.633	38.624
		15	NZB8	Tuff	18.927	15.815	39.256
		16	NZB9	Limestone	18.928	15.756	39.337
		17	NZB10	Limestone	18.598	15.653	38.836
		18	NPTV-B19	Basalt	18.865	15.910	39.431
		19	NPD2-B4	Keratophyre	18.592	15.714	38.967
Triassic	Caizidi	20	CZK68TW1	Rhyolite	18.524	15.539	38.950
		21	PQTW1	Rhyolite	18.653	15.625	38.809
	Kedengjian	22	k-16	Altered andesite	19.268 (6)	15.634 (4)	38.914 (7)
		23	k-18	Altered andesite	18.809 (5)	15.888 (3)	38.914 (6)
		24	k-20	Altered basalt	18.553 (7)	15.587 (4)	38.431 (7)
	Weixi	25	DXQ51	Basalt	18.593	15.696	38.859
		26	DXQ52	Basalt	18.597	15.685	38.832
	West Xiaguan	27	DXQ9	Limestone	18.791	15.619	38.611
		28	DXQ10	Limestone	20.127	15.878	39.232
		29	DXQ11	Limestone	20.184	15.679	38.547
	Jinding	30	No. 3	Limestone	18.544	15.765	38.914
		31	No. 5	Limestone	18.888	15.988	39.464
		32	No. 6	Limestone	20.289	16.051	40.890
	Caizidi	33	DXQ49	Limestone	19.204	15.772	38.957
		34	DXQ50	Limestone	18.573	15.698	38.730
Jurassic	Jinman	35	97JM2	Silicalite	18.524 (5)	15.596 (2)	38.578 (6)
		36	jm-16	Silicalite	18.607 (5)	15.599 (3)	38.754 (7)
		37	97jm25	Sandstone	18.647 (4)	15.589 (2)	38.737 (5)
		38	jm23	Slate	18.725 (4)	15.593 (2)	38.911 (6)
	West Xiaguan	39	DXQ15	Limestone	18.595	15.807	39.259
	Jinding	40	JB308	Sandstone	18.592	15.742	39.306
	West Xiaguan	41	DXQ16	Sandstone	18.756	15.713	39.328
	West Xiaguan	42	DXQ18	Sandstone	18.645	15.710	38.912
Cretaceous	West Xiaguan	43	DXQ21	Sandstone	18.560	15.714	38.924
	Jinding	44	No. 1	Sandstone	18.517	15.705	38.889
	Jinding	45	No. 2	Sandstone	18.707	15.892	39.317
	Baiyangchang	46	TJY-14	Sandstone	18.746	15.779	39.198
	Xiaogela	47	J5B91	Sandstone	18.562	15.676	38.854
	West Xiaguan	48	DXQ22	Sandstone	18.523	15.574	38.749
	West Xiaguan	49	DXQ24	Sandstone	18.557	15.694	38.973
	Baiyangchang	50	TJY-15	Sandstone	18.606	15.768	39.068
Tertiary	Yunlong	51	DXQ26	Sandstone	18.706	15.736	38.934
	Yunlong	52	DXQ27	Sandstone	18.543	15.574	37.882
	Jinding	53	JB439	Sandstone	18.488	15.636	38.632
	Jinding	54	JB543-1	Sandstone	18.549	15.693	38.809

Sequence Nos. 8–12, 22–24, 35–38 samples were analyzed in this study, data for the others were published by Luo *et al.* (1992). All samples are whole rocks. Data in the brackets are analytical errors (2 σ). Except for the samples of this study, no analytical error values were given for the other samples.

sandstone, limestone, andesite, etc.), they have similar lead isotopic compositions. In Fig. 4 the data points of the samples fall within the area defined by $^{206}\text{Pb}/^{204}\text{Pb} = 18.100\text{--}20.300$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.200\text{--}16.050$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.255\text{--}40.890$, showing a significant difference from the isotopic composition of mantle-source lead. We consider that this range of isotopic variations can approximate the lead isotopic composition of modern upper crustal rocks in the region of western Yunnan (the dotted-line areas in Fig. 4).

ISOTOPIC COMPOSITION AND ORIGIN OF LEAD IN THE JINDING DEPOSIT

The lead isotopic composition data for the fifty-five galena, sphalerite and pyrite samples used in this study are presented in Table 3. These samples can be divided into two groups. The first group includes seventeen samples (Nos. 1–17 in Table 3). This group of samples is predominated by galena and minor sphalerite and pyrite which serve as sandstone detritus cements, and are separated from the sandstone-type ores in the ore-bodies I, II and X of the upper ore-host bed. In these ores, there is a few of the late hydrothermal replacement. All samples of this group were mainly collected from the disseminated and striped ores near the edges of the ore-bodies. Their lead isotopic ratios are: $^{206}\text{Pb}/^{204}\text{Pb} = 18.394\text{--}18.600$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.583\text{--}15.767$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.266\text{--}39.046$. The second group consists of thirty-eight samples (Nos. 18–55 in Table 3), including galena in the two types (sandstone- and limestone-type) of ores from orebodies I, II, VI, VII and X of the upper and lower ore-host beds in the Baichang, Nanchang and Xipo ore runs. The ore of this group exhibits massive ore texture. The lead isotopic ratios are: $^{206}\text{Pb}/^{204}\text{Pb} = 18.138\text{--}18.552$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.345\text{--}15.552$, and $^{208}\text{Pb}/^{204}\text{Pb} = 37.803\text{--}38.443$. Comparatively, lead isotopic ratios in the first group of samples are higher than those of the second group. The lead model ages of the two groups of samples calculated with the two-stage model by Stacey and Krammers (1975) show that the second group of samples are

dated at 29 to 40 Ma for 19 samples, similar to fission track ages (25 Ma to 35 Ma) by Li *et al.* (2000), and <15 Ma or negative ages for the other samples. The lead model ages of the first group of samples range from 98 Ma to 400 Ma, larger than those of the ore-hosted strata. The μ values calculated with the two-stage model are larger than 9.74 for the first group of samples and lower than 9.4 for the second group of samples. Differences in lead isotopic composition for the two groups of samples probably indicate the different sources of lead in the deposit.

Relationship between ore lead and upper mantle lead

It was previously considered that lead in the Jinding deposit had stemmed from the upper mantle mainly on the basis of its homogeneous lead isotopic composition and fairly primitive isotopic ratios (Yin *et al.*, 1990; Luo *et al.*, 1992; Tu *et al.*, 2000). We noticed that these authors over emphasized those samples with low lead isotopic ratios in their studies. Really, the samples of the second group described above have relatively low lead isotopic ratios and some data points fall directly within the area of mantle lead in the region of western Yunnan as in Fig. 5. However, the data points of most of the ore samples fall in the lower part of the mantle lead area. If it is assumed that the mantle lead area defined by the data from western Yunnan is reliable, there would be at least two inconsistencies with the ore lead data. The first one is: Why is the trend of ore lead inconsistent with the area of mantle lead? The second is: Where did the lead in the samples falling below the mantle lead area stem from? Following this, it may be concluded from Fig. 5 that the lead in the first group of samples did not originate directly from the mantle.

Relationship between ore lead and upper crustal lead

The isotopic comparisons of ore lead with sedimentary rock lead in the Lanping Basin show that the data points of the first group of 17 samples (solid circles in Fig. 5) fall within and/or near the

Table 3. The Pb isotopic composition of the Jinding Pb-Zn deposit

Seq. No.	Sample No.	Mineral	Occurrence	$^{206}\text{Pb}/^{204}\text{Pb}$ (2 σ)	$^{207}\text{Pb}/^{204}\text{Pb}$ (2 σ)	$^{208}\text{Pb}/^{204}\text{Pb}$ (2 σ)
1	82j-2	Galena	Sandstone-type ore cement from the upper ore-host bed	18.400 (4)	15.612 (2)	38.463 (5)
2	82j-5	Galena	Sandstone-type ore cement from the upper ore-host bed	18.441 (4)	15.632 (3)	38.660 (6)
3	82j-11	Galena	Sandstone-type ore cement from the upper ore-host bed	18.420 (2)	15.626 (2)	38.536 (5)
4	82j-27	Galena	Sandstone-type ore cement from the upper ore-host bed	18.506 (3)	15.640 (2)	38.557 (4)
5	BTW1	Galena	Orebody I ₁ in the upper ore-host bed	18.444	15.625	38.584
6	BTW2	Galena	Orebody I in the upper ore-host bed	18.394	15.583	38.470
7	BTW4	Galena	Orebody I in the upper ore-host bed	18.405	15.593	38.462
8	No4	Galena	Orebody I in the upper ore-host bed	18.534	15.754	39.000
9	BTW1	Sphalerite	Orebody I ₁ in the upper ore-host bed	18.566	15.627	38.675
10	BTW2	Sphalerite	Orebody I in the upper ore-host bed	18.543	15.767	39.046
11	BTW3	Sphalerite	Orebody I ₁ in the upper ore-host bed	18.484	15.628	38.598
12	BTW3	Pyrite	Orebody I in the upper ore-host bed	18.413	15.597	38.483
13	82j-31	Galena	Coexisting with framboid pyrite from the striped ore of orebody II	18.588 (3)	15.617 (2)	38.321 (5)
14	82j-33	Galena	Coexisting with framboid pyrite from the striped ore of orebody II	18.600 (3)	15.622 (3)	38.359 (4)
15	82j-35	Galena	Disseminated ore from orebody II of the lower ore-host bed	18.493 (4)	15.619 (3)	38.488 (5)
16	BTW7	Galena	Orebody XII in the lower ore-host bed	18.443	15.628	38.516
17	Ding-3	Galena	Lower ore-host bed	18.523	15.634	38.481
18	82j-7	Galena	Coarse-grained, sandstone-type ore from the upper ore-hosted bed	18.285 (3)	15.491 (3)	38.300 (4)
19	82j-9	Galena	Coarse-grained, sandstone-type ore from the upper ore-hosted bed	18.303 (2)	15.501 (2)	38.290 (3)
20	Yn10-1	Galena	Orebody I ₁ in the upper ore-host bed	18.172	15.345	37.803
21	Yn10-2	Galena	Orebody I ₁ in the upper ore-host bed	18.173	15.345	37.803
22	Yn13-1	Galena	Orebody I ₁ in the upper ore-host bed	18.312	15.474	38.136
23	TY37	Galena	Orebody I ₁ in the upper ore-host bed	18.283	15.463	38.297
24	TY38	Galena	Orebody I ₁ in the upper ore-host bed	18.222	15.423	38.093
25	TY39	Galena	Orebody I ₁ in the upper ore-host bed	18.207	15.377	38.007
26	TY41	Galena	Orebody I ₁ in the upper ore-host bed	18.138	15.352	37.921
27	TY42	Galena	Orebody I ₁ in the upper ore-host bed	18.169	15.362	38.042
28	Yn41	Galena	Orebody I ₁ in the upper ore-host bed	18.290	15.450	37.993
29	Yn41-1	Galena	Orebody I ₁ in the upper ore-host bed	18.402	15.549	38.357
30	Yn42-2	Galena	Orebody I ₁ in the upper ore-host bed	18.346	15.527	38.286
31	Yn45	Galena	Orebody I ₁ in the upper ore-host bed	18.351	15.517	38.168
32	Yn46-2	Galena	Orebody I ₁ in the upper ore-host bed	18.313	15.485	38.158
33	Yn59	Galena	Orebody I ₁ in the upper ore-host bed	18.188	15.391	37.889
34	Yn61	Galena	Orebody I ₁ in the upper ore-host bed	18.325	15.495	38.169
35	BTW8	Galena	Orebody I ₁ in the upper ore-host bed	18.552	15.552	38.334
36	Ding-1	Galena	Orebody I ₁ in the upper ore-host bed	18.195	15.396	38.113
37	TY40	Galena	Orebody II ₂ in the lower ore-host bed	18.212	15.399	38.046
38	TY46	Galena	Orebody II ₂ in the lower ore-host bed	18.220	15.407	38.155
39	Yn55	Galena	Orebody II ₂ in the lower ore-host bed	18.346	15.513	38.204
40	Yn87	Galena	Orebody II ₂ in the lower ore-host bed	18.333	15.488	38.146
41	Yn16-1	Galena	Orebody X ₁ in the lower ore-host bed	18.293	15.499	38.215
42	Yn25	Galena	Orebody X ₁ in the lower ore-host bed	18.238	15.404	37.900
43	Yn30	Galena	Orebody X ₁ in the lower ore-host bed	18.322	15.497	38.178
44	Yn31-1	Galena	Orebody X ₁ in the lower ore-host bed	18.282	15.452	38.041
45	Yn31	Galena	Orebody X ₁ in the lower ore-host bed	18.347	15.521	38.281
46	TY45	Galena	Orebody X ₁ in the lower ore-host bed	18.286	15.453	38.443
47	Yn23	Galena	Orebody X ₂ in the lower ore-host bed	18.267	15.437	38.033
48	Yn16	Galena	Orebody VI ₁ in the lower ore-host bed	18.267	15.466	38.118
49	Yn16-2	Galena	Orebody VI ₁ in the lower ore-host bed	18.213	15.374	37.928
50	82j-18	Galena	The massive ore from orebody VII of the lower ore-hosted bed	18.232 (1)	15.476 (1)	38.174 (4)
51	82j-19	Galena	The massive ore from orebody VII of the lower ore-hosted bed	18.283 (3)	15.493 (2)	38.295 (5)
52	82j-26	Galena	The massive ore from orebody VII of the lower ore-hosted bed	18.321 (2)	15.450 (1)	38.235 (4)
53	BTW5	Galena	Orebody VII ₂ in the lower ore-host bed	18.374	15.504	38.243
54	TY43	Galena	Orebody VII ₂ in the lower ore-host bed	18.247	15.410	38.226

Samples 1 to 4, 13 to 15, 18 to 19 and 50 to 52 by this paper, the other samples were published by Luo *et al.* (1992) and detailed occurrence information is not presented. Data in the brackets are analytical errors (2 σ). Except for the samples of this study, no analytical error values were given for the other samples.

Fig. 5. Comparison of the Pb isotopic composition of the Jinding deposit with that of the mantle lead and upper crust lead in western Yunnan. Zartman's lead evolution model: M. Upper mantle lead; O. Orogenic belt lead; U. Upper crust lead; L. Lower crust lead. 1. Samples from disseminated and fine-grained ores; 2. Samples from massive ore in the center of orebody; 3. Lower crustal lead from the minerals in granulite and eclogite xenoliths. The solid-line area: upper mantle lead in the region of western Yunnan; the dotted-line area: upper crust lead in the Laping Basin.

area of sedimentary rock lead, while those of the second group with a few exceptions fall below the area of sedimentary rock lead.

Li *et al.* (1993) considered that the Jinding deposit is a terrestrial exhalative-hydrothermal sedimentary deposit (terrestrial SEDEX deposit). We noticed that near the edges of the ore-bodies, especially in the upper ore-hosted bed and the western area of the ore-field, there exist bedded, laminated and disseminated ores, and spheroidal, spherulitic and framboidal pyrite. At the center of orebodies, especially in the lower ore-hosted bed, metasomatic mineralization is common. These characteristics indicate that the Jinding deposit is of exhalative-hydrothermal mineralization origin. The lead isotope data of the first group of sam-

ples represent this stage of mineralization. Metasomatic mineralization postdated the sedimentary mineralization, which probably has the lead isotopic characteristics of the second group of samples.

Leaching seems to be the main mechanism by which lead in the regional upper crustal strata found its way into hydrothermal solutions and were incorporated in ore of the first-group samples. The results of leaching experiments by Lin and Guo (1985) and Andrew *et al.* (1990) demonstrated that in the process of leaching of the rock lead the radiogenic lead would preferentially enter the solution, resulting in higher lead isotopic ratios in the leaching solution than those in the whole-rock samples. It can therefore be deduced

Fig. 6. $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ diagram of the Jinding Pb-Zn deposit. Zartman's lead evolution model: M. Upper mantle lead; O. Orogenic belt lead; U. Upper crust lead; L. Lower crust lead. 1. Samples from disseminated and fine-grained ore; 2. Samples from massive ore in the center of orebody; 3. Lower crustal lead from the minerals in granulite and eclogite xenoliths. The solid-line area: upper mantle lead in the region of western Yunnan; the dotted-line area: upper crust lead in the Laping Basin.

that lead isotopic ratios in minerals formed from hydrothermal solutions which have assimilated lead by rock leaching should be higher, or at least should not be lower, than those in the original leached rocks. It thus can be claimed with confidence that lead in the second group of samples did not stem mainly from the upper crustal strata. By analogue, if the lead in the first group of samples was derived completely from leaching of these strata, their lead isotopic ratios should be much higher. Clearly, the lead in this deposit is not of a single source origin.

A possible source of ore lead: a possible model

The source of lead: the mixing model of upper and lower crust lead As can be seen in Fig. 5, the data points of all the ore samples are arranged linearly. Especially in the $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ diagram, the linearity is more conspicuous, but of no isochronity. Based on the relationship between the ore lead and the upper crustal strata, we may consider that lead in the first group of samples, which was formed in the process of terrestrial exhalative-sedimentary mineralization, is mainly derived from upper crustal rocks in the region.

In Fig. 5a, lead in those isotopically lowest samples may have been contaminated by regionally available upper crustal lead and their isotopic signature can be approximately regarded

as the lead isotopic composition of the source region for the isotopically primitive components of the second group of samples. As viewed from the data available, neither the magmatic and Precambrian metamorphic rocks and the Phanerozoic sedimentary strata (from Cambrian to Tertiary), exposed in the region of western Yunnan, nor the matle rocks in the region possess such kind of lead isotopic composition. We guess such lead is possibly derived from the lower crust.

There is no exposure of lower crustal rocks in the wesrtern Yunnan. Fortunately, we discovered granulite and eclogite xenoliths in the aegirine syenite porphyry at Liuhe. These xenoliths may be derived from the lower crust of the region. The lead isotopic ratios in two garnet and one hornblende minerals range from 18.135 to 18.187 for $^{206}\text{Pb}/^{204}\text{Pb}$, 15.335 to 15.388 for $^{207}\text{Pb}/^{204}\text{Pb}$ and 37.836 to 37.899 for $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. These data are the same as those of the isotopically lowest lead samples of ore (see Fig. 5).

Zhang (1992) considered that the evolution line of the lower crust lead in $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ diagram by Zartman and Doe (1981) is not suitable for the situation of the Chinese continent. Really, even if the typical rocks of the lower crust in China are taken into consideration, the lead isotopic plots are far away from the lower crustal lead line. Therefore, we present the $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$

^{204}Pb diagram (Fig. 6) to make a further discussion. As can be seen in Fig. 6, sample data follow two patterns of distribution. Samples of the first group and some samples of the second group are distributed along the straight line AC, with $r = 0.9458$. The other samples of the second group are distributed along the straight line BC and developed near the evolution line of the lower crust lead, with $r = 0.8233$. The data points of xenoliths are also plotted into the lowest part of lines AC and BC. Thus it can be seen the conclusion that lead in the second group of samples is primarily derived from the lower crust of western Yunnan is believable.

In Figs. 5 and 6, the linear distributions of sample points may be the result of mixing of lead of two sources. Because lead of the lower crustal source is involved in mineralization on the basis of hydrothermal sedimentary ore-deposition, and the mixing of lead of two sources is inevitable. Mixing in different proportions resulted in such a lead isotopic compositional pattern in the deposit.

Other lines of geochemical evidence contradicting a predominant mantle lead involvement during the ore-forming process No exposure of mantle rocks is known from the Jinding mining district and this is another piece of geological evidence to show that ore lead was not derived from the upper mantle. Various pieces of isotopic evidence are also in favor of a non-mantle origin for the Jinding deposit. For instance, no mantle-source helium has been detected in the deposit (Hu *et al.*, 1998). Moreover, the $\delta^{34}\text{S}$ values of framboidal and fine-grained pyrite, sphalerite and galena at the edges of orebodies range from -12‰ to -30‰ , those of sulfide from massive ores range from -2‰ to -24‰ , those of celestite vary between $+11.2\text{‰}$ and $+18.8\text{‰}$ (Zhang, 1991), and the $\delta^{13}\text{C}$ values of calcite are within the range of -6‰ to -25‰ (Luo *et al.*, 1992). All these data display the isotopic characteristics of crust-derived components.

Sr ($^{87}\text{Sr}/^{86}\text{Sr}$) isotopic ratios of celestite and gypsum in the ore are 0.71039–0.71185 (Luo *et al.*, 1992). Recently we analyzed the Sr isotopic composition of sphalerite from orebody I₁ of the

Baichang ore run. The results show $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in disseminated sphalerite from the edge of the orebody are from 0.71463 to 0.72358 and those of massive sphalerite from the center of the orebody are from 0.70982 to 0.71271. Apparently, the two types of ore have different Sr isotopic compositions.

To make a comparison with ore, some of Sr isotopic data for different geological units in western Yunnan are collected. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in gabbro and basalt range from 0.7036 to 0.7083, those of alkaline igneous rocks range from 0.7045 to 0.7080, those of the Mesozoic S-type granite and rhyolite are from 0.7090 to 0.7139, those of the Early and Middle Proterozoic migmatite, gneiss and schist are from 0.7159 to 0.7249, and those of the sedimentary rocks (mainly limestone and shale) from Permian to Triassic range from 0.7191 to 0.7335 (Zhou and Liu, 1988; Lu *et al.*, 1993; Zhong *et al.*, 1998). We have obtained the Sr isotopic compositions of the granulite and eclogite xenoliths from the aegirine syenite porphyry, and their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are from 0.7098 to 0.7116 (three samples). These data indicate that the different geological units in western Yunnan are different from Sr isotopic composition.

According to the Sr isotope data above, it is found that in the Jinding deposit, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of terrestrial exhalative-sedimentary sphalerite from the edge of the orebody are similar to those of the Early and Middle Proterozoic migmatite, gneiss and schist, and those of the sedimentary rocks from Permian to Triassic. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of massive sphalerite from the center of the orebody are larger than those of gabbro, basalt and ankline igneous rocks, but similar to those of xenoliths, S-type granite and rhyolite. Such similarities suggest that strontium at the early ore-forming stage (terrestrial exhalative-sedimentary mineralization stage) was probably derived from the upper crustal rocks and that at the late stage (hydrothermal metasomatic mineralization stage) from the lower crustal rocks. This conclusion is the same as what is drawn on the basis of lead isotope data.

CONCLUSIONS

(1) The Jinding Pb-Zn deposit occurs in the Lower Tertiary red sedimentary formation in the middle part of the Lanping Basin in western Yunnan. The involvement of mantle-source lead in metallogenesis is a hypothesis that has occupied an important position for long. Nevertheless, no exposure of mantle-source magmatic rocks in the vast mining area has launched a great challenge to this hypothesis.

(2) In the region of western Yunnan the isotopic ratios of upper mantle-source lead since Meso- and Cenozoic times are approximated to: $^{206}\text{Pb}/^{204}\text{Pb} = 17.850\text{--}18.350$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.430\text{--}15.540$, and $^{208}\text{Pb}/^{204}\text{Pb} = 37.800\text{--}38.410$; lead isotopic ratios of the upper crust sedimentary rocks in the basin are: $^{206}\text{Pb}/^{204}\text{Pb} = 18.420\text{--}19.200$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.500\text{--}16.010$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.450\text{--}39.500$; lead isotopic ratios of several garnet and hornblende samples from lower crust-derived granulite and eclogite xenoliths range from 18.135 to 18.187 for $^{206}\text{Pb}/^{204}\text{Pb}$, 15.335 to 15.388 for $^{207}\text{Pb}/^{204}\text{Pb}$ and 37.836 to 37.899 for $^{208}\text{Pb}/^{204}\text{Pb}$.

(3) There are two different types of the ore lead isotopes in the Jinding deposit. The lead isotopic ratios of the massive ore are from 18.138 to 18.552 for $^{206}\text{Pb}/^{204}\text{Pb}$, 15.345 to 15.552 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 37.803 to 38.443 for $^{208}\text{Pb}/^{204}\text{Pb}$, and the lead isotopic ratios of the striped ore are from 18.394 to 18.600 for $^{206}\text{Pb}/^{204}\text{Pb}$, 15.583 to 15.767 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 38.266 to 39.046 for $^{208}\text{Pb}/^{204}\text{Pb}$. Based on a comparison with the lead isotopic compositions, lead in the deposit was not derived from the upper mantle. Instead, it may stem from the two geological units: one is the upper crust and the other is probably the lower crust. The upper crustal source lead is incorporated into ore during the early sedimentary mineralization stage, and the lower crustal source lead is incorporated into ore during the late hydrothermal metasomatic mineralization stage.

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