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Lead isotope composition and constraints on origin of Dafulou ore deposit, Guangxi, China

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Abstract: To discuss the material source and tectonic setting, the lead isotope composition was analyzed based on the samples from the latest tunnel of the Dafulou deposit. The lead isotope values are 17.478−18.431, 15.440−15.717, and 37.556−38.839 for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, respectively. The values of Φ, μ, and Th/U are 0.592−0.638, 9.26−9.69 and 3.74−3.97. By comparing the lead isotope composition of the different ore belts, it indicates that the lead source of the west belt may be more single than the other ore belts. The lead isotope value in the middle and east belts are the maximum and minimum, respectively. In the Dachang ore district, the lead sources are comprised of the upper crust lead, the mixed crust and mantle subduction zone lead and the orogenic lead. The tectonic distinguish model suggests that the ore lead derived from both the mantle and crust. And, the upper crust and magmatism played an important role during the mineralization. The orogenesis also supplied a minority of ore lead. The ore deposit should be the result of the crust-mantle interaction and maybe had been formed in the orogenic environment.

Key words: Pb isotope; ore source; tectonic setting; Dafulou; Dachang ore field

1 Introduction

The Dachang ore field in Guangxi province, which is also one of the largest tin-polymetallic ore fields in this world with 15 km in length and 9 km in width, is an important tin-polymetallic mining industry base in China [1]. It is regarded as the best natural laboratory for investigating tin-polymetallic ore deposits because of with several super large scale tin-polymetallic ore deposits such as two super large deposits and six large deposits [2]. In contrast, in the west ore belt, there are more large scale deposits and mineral reserves, higher research degree [3]. Yet, in the east ore belt, the deposits are characterized by the smaller scale and reserve, lower research degree. Being located at both sides of the Longxianggai concealed rock body and with the similar geological conditions, there are rather significant differences in the mineralization between the west and east ore belt, which has attracted more thought about the theoretical study for the east ore belt. In 1978, the findings of two bedded tin-polymetallic ore bodies made the Dafulou deposit with large scale. Afterwards, the relevant research is scarce, and about the report of the genesis for the Dafulou deposit is more even less. For a long time, the genetic model of the Dafulou tin deposit habits with reference to the west ore belt, which restricts the exploration of mineral resources in the east ore belt. Around the Longxianggai concealed rock body, the tin-polymetallic ores occurring in the east and the west ore belt exist obvious difference such as the ore-forming elements, ore-bearing layer [4]. In the west ore belt, the ore-bearing layer is the middle and upper Devonian and the main mineralized elements consist of Sn, Pb, Zn, Sb and Ag. Yet, in the east ore belt, the Dafulou ore deposit, whose main mineralized elements consist of Sn and Zn, is hosted in the lower Devonian [5]. Obviously, the different mineralized elements exist in both of the ore belts. In the Dafulou tin deposit, the main mineralized elements are significantly less than the east ore belt and

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the orebodies are hosted by the different strata. So, it is necessary to carry out specialized research for establishing the genesis and improving the ore theory, based on the characteristics of the Dafulou ore deposit.

About the ore genesis, a lot of researches have been done [6−12], mainly involving the isotope geochemistry, the fluid inclusions, the trace element geochemistry and the REE geochemistry. In recent years, the high-precision geochronology has been adopted [13−17], such as SHRIMP zircon U-Pb dating, Rb-Sr dating. And, some analyses to reveal the deep mineralization played an important role, such as helium−argon isotope, $^{87}Sr/^{86}Sr$, $^{3}He/^{4}He$ and laser Raman spectroscopy, which supplied the new data for the ore genesis and the deep crust-mantle metallogeny. Yet, it still exists debate on the ore-forming mechanism, especially on the material source, the metallogenic epoch and the deep dynamics mechanism. Based on the above purposes, in this study the lead isotope composition is analyzed, the material source and metallogenetic geodynamical setting are discussed, for supplying new data to the ore theory.

2 Regional and deposit geology

The world-famous Danchi ore belt locates at the southern border from the Proterozoic to the early Paleozoic, and it lies in the second rifting basin of the Youjiang basin [18]. The Dachang ore field is located at the junction of the Guangxi platform and the Jiangnan uplift in Northwest Guangxi [19,20]. A partially restricted sea basin formed in this area during late Paleozoic as a result of depression along the NW-striking basement fault, with the fast-depressing sector developing in the Middle–Late Devonian Nandan-type basin in Guangxi (Fig. 1). In the Danchi metallogenic belt, the magmatic rock is characterized by small size and extreme depth; the wall rock alteration occurs in large scope and hosts several kinds of endogenic metal deposits. The host rocks are typically banded, consisting mainly of siliceous rock and limestone, with lesser but significant amounts of alternating thin beds of sulfides and K-feldspar-rich rocks.

The Dafulou tin-polymetallic ore deposit is located at the east ore belt and in the eastern flank of the NNW–SSE-trending Danchi anticlinorium. In the Dafulou ore district, the NW-trending faults are the most important tectonic system [1,4]. The strata are mainly the upper Devonian (Liujiang formation), the middle Devonian (Luofu formation and Nabiao formation), the lower Devonian (Tangding formation), among which the Tangding formation of the lower Devonian is the main host rock of the bedded ore. The ore mainly consists of vein ore and bedded ore such as Nos. 0, 21 and 22. The bedded tin-polymetallic mineralization formed

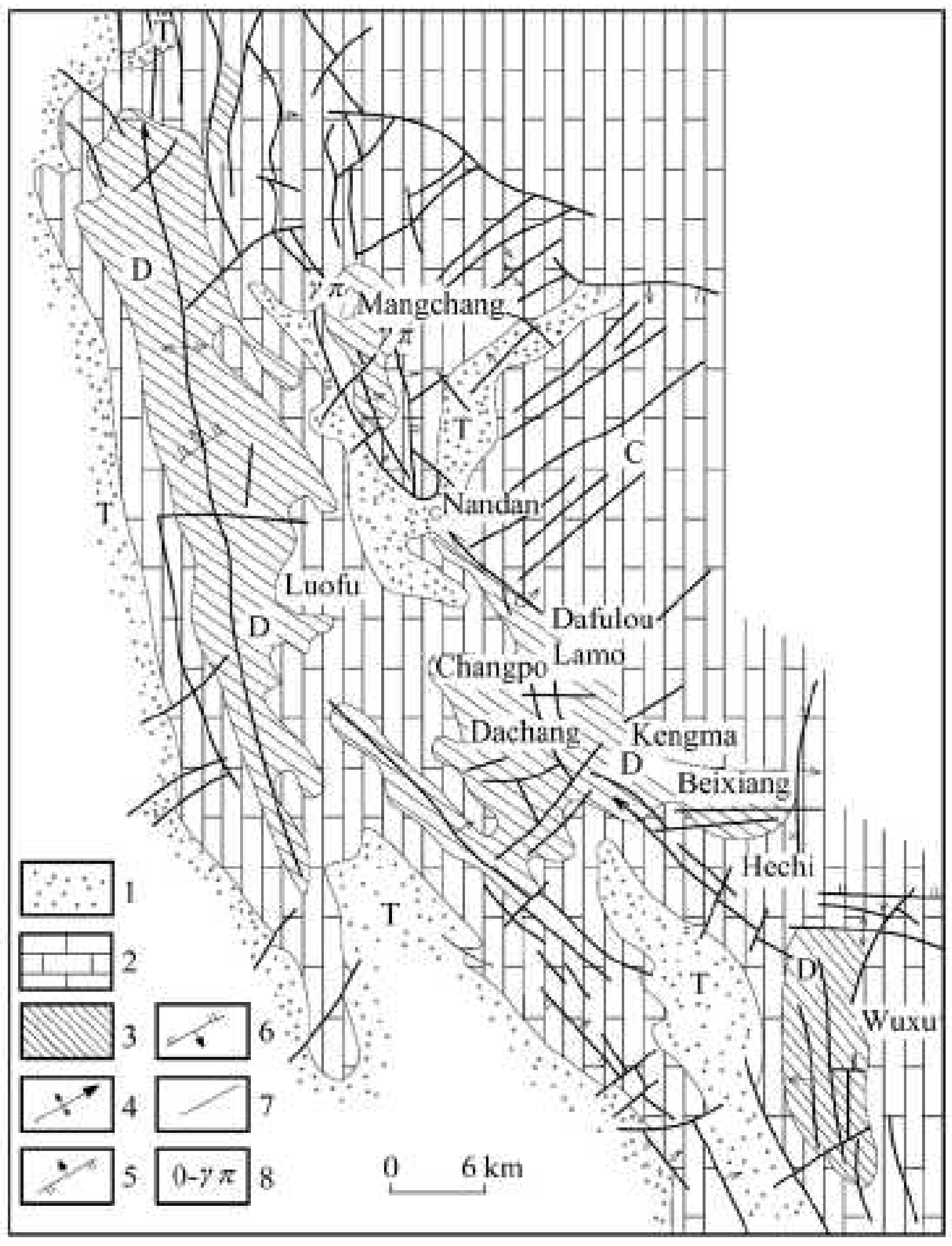

Fig. 1 Simplified geological map of Dachang ore field, Guangxi, China: 1—Triassic; 2—Carboniferous–Permian; 3—Devonian; 4—Anticline axis; 5—Normal fault; 6—Thrust fault; 7 — Faults; 8 — Granite porphyry (modified from China nonferrous metals industry corporation)

concordantly in the Tangding formation shale of the lower Devonian (Fig. 2). Nos. 21 and 22 ores are roughly parallel to each other. No. 21 ore, situating 60−80 m above No. 22 ore body, is approximately 450 m in length and 2.5 mm thickness, with an average of 1.14% Sn content. The ore textures are mainly metasomatic texture, euhedral-subhedral granular texture and solid solution texture, and ore structures are mainly massive, disseminate, veinlet, stockwork and breccia. The ore types consist of disseminated ore, compact massive ore, fine-vein ore and brecciated ore. The mineralization types of ores are of bedded mineralization, strata penetration mineralization and stockwork mineralization. The wall rock alteration types are dominated by silicification, carbonation, sericitization, pyritization and pyrrhotitezation.

3 Lead isotope studies

3.1 Sampling and analysis

The lead isotope composition is a very useful geochemical tracer system. It indicates not only the crust evolution, but also the ore genesis and the material sources. Especially, the characteristics of the stability, variability and directivity have direct significance for the ore genesis, material sources, the mineralization process, the ore-forming environment and exploration [21,22].

The eight lead isotope samples (consisting of one galena, three pyrrhotite and four pyrite samples) were collected from the latest tunnel, which can satisfy the experimental precision and supply some new isotope data for this study of the ore deposit genesis. The lead isotope analysis was carried out in the Isotope Geology Laboratory of Wuhan Institute of Geology and Minerals Resources, Chinese Ministry of Land Resources. The main instrument is MAT-262 mass spectrometer using the international standards 16.937 ($^{206}Pb/^{204}Pb$), 15.491 ($^{207}Pb/^{204}Pb$), and 36.722 ($^{208}Pb/^{204}Pb$). The accuracy of analysis is ±0.05%. The experimental results can assurance the precision and meet the theory research.

3.2 Results and discussion

Table 1 shows the compositions and relevant parameters of the lead isotope in the Dafulou tin-polymetallic deposit from this study. It shows that the $^{206}Pb/^{204}Pb$ of sulfide ore value ranges from 17.478 to18.431, with an average of 17.991 and a maximum difference of 0.953. The $^{207}Pb/^{204}Pb$ value ranges from 15.440 to 15.717, with an average of 15.582 and a maximum difference of 0.277. The $^{208}Pb/^{204}Pb$ value ranges from 37.556 to 38.839, with an average of 38.233 and a maximum difference of 1.283. The values of Φ, μ and Th/U vary from 0.592 to 0.638, 9.26 to 9.69, and 3.74 to 3.97, respectively. ZHANG et al [23] measured 13 lead isotope samples from the Dachang ore field. It suggested that the value of $^{206}Pb/^{204}Pb$ ranges from 18.35 to 18.98, with an average value of 18.54, the value of $^{207}Pb/^{204}Pb$ ranges from 15.59 to 15.96, with an average value of 15.76, the value of $^{208}Pb/^{204}Pb$ ranges from 37.74 to 39.32, with an average value of 38.64. YE et al [24] measured the lead and sulfur isotope of the Dachang ore field. The results suggested that the values of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ range from 18.3 to 18.7, 15.55 to 15.67, 38.38 to 38.29, respectively. So, YE et al [24] thought that the lead source of Dachang ore field is derived from stratum and magma.

According to Table 1, the value of $^{206}Pb/^{204}Pb$ is

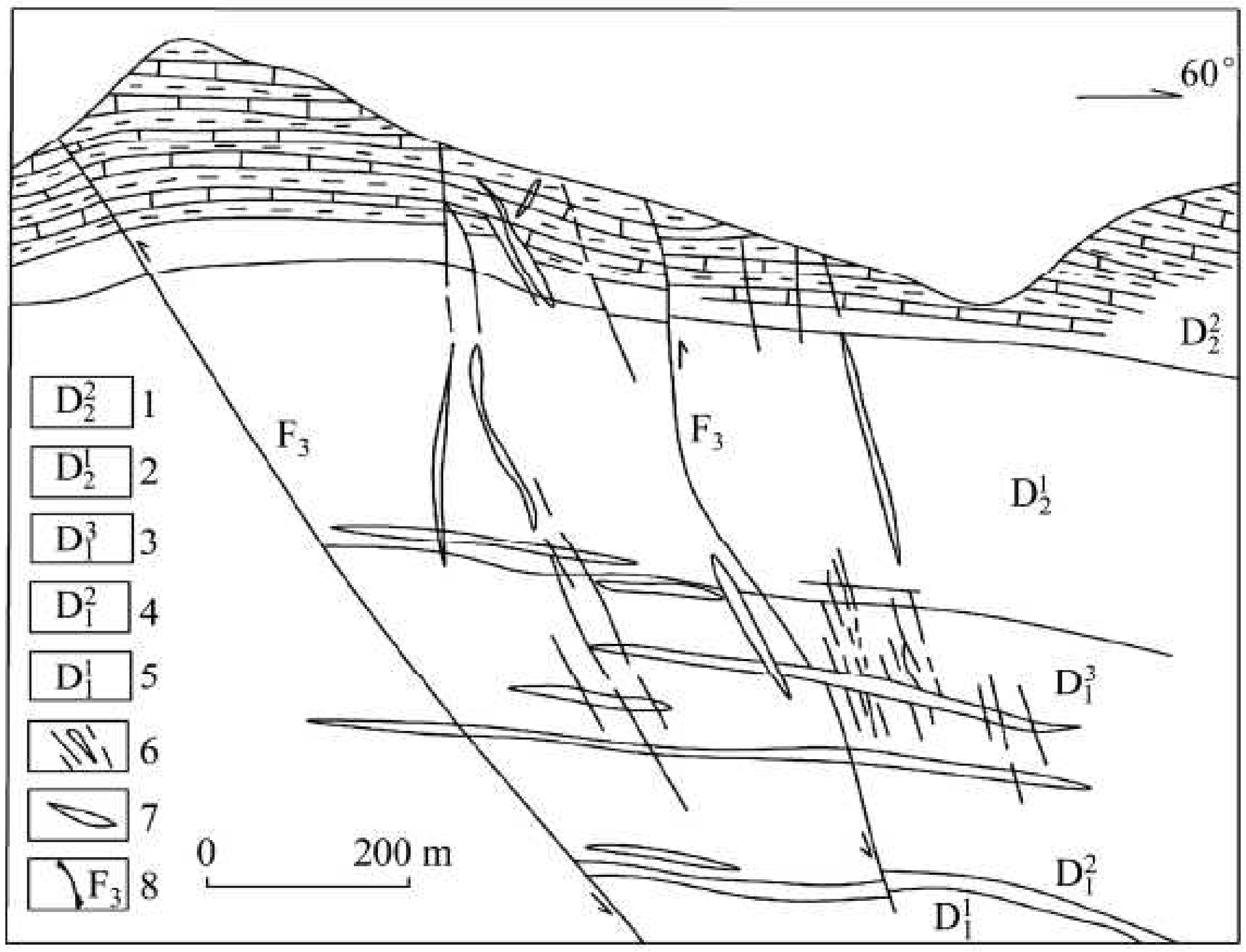

Fig. 2 Geological section of exploration line No. 5 at Dafulou ore deposit (modified from China Nonferrous Metals Industry Corporation, 1987): 1—Mudstone and limestone; 2—Black shale; 3—Mudstone with siltstone layer; 4—Siltstone; 5—Sandstone; 6—Vein-type orebody; 7—Stratiform orebody; 8—Faults

Table 1 Lead isotopic compositions in Dafulou deposit

Sample	Mineral	Isotope ratio			Parameter		
		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Φ	μ	Th/U
Y11-3	Galena	18.431±0.016	15.717±0.010	38.839±0.040	0.594	9.69	3.91
Y29-2-1	Pyrite	18.369±0.003	15.667±0.002	38.678±0.006	0.593	9.60	3.87
Y03-1	Pyrite	17.478±0.006	15.510±0.005	37.849±0.017	0.638	9.41	3.97
Y01-3	Pyrrhotite	18.269±0.011	15.647±0.008	38.515±0.026	0.597	9.57	3.85
Y21-1	Pyrrhotite	17.566±0.008	15.468±0.007	37.687±0.015	0.626	9.31	3.84
Y30-2	Pyrrhotite	17.517±0.007	15.440±0.006	37.556±0.016	0.627	9.26	3.80
Y29-4	Pyrite	18.304±0.001	15.624±0.001	38.505±0.002	0.592	9.52	3.82
Y03-2	Pyrite	18.044±0.007	15.525±0.006	38.026±0.014	0.599	9.36	3.74

characterized by the large scope and dispersion, mainly ranging from 17.4 to 17.6 and from 18.2 to 18.4, respectively. In order to compare the lead isotope composition, the ore lead isotope values are listed from the different ore belts in the Dachang ore field [25−29] (see Table 2). From the diagram of $^{207}Pb/^{204}Pb$−$^{206}Pb/^{204}Pb$ (Fig. 3), in the west belt, the projection points are concentrated in a very narrow range, being characterized by overlapping each other. Yet, the projection points of the east belt and the middle belt are dispersed in a wider range. In the east belt, the values are lower than the other two ore belts. And, the projection points of the middle belt are the maximum among the three ore belts (see Fig. 3).

Table 2 Lead isotope composition of Dachang ore field, in Guangxi, China [25−29]

Sample	Ore belt	Deposit	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$\Delta\gamma$	$\Delta\beta$	Data source
Y01-3	East belt	Dafulou	18.269	15.647	38.515	42.13	21.86	This study
Y03-1	East belt	Dafulou	17.478	15.51	37.849	42.30	15.44	This study
Y03-2	East belt	Dafulou	18.044	15.525	38.026	29.57	13.97	This study
Y11-3	East belt	Dafulou	18.431	15.717	38.839	49.48	26.27	This study
Y21-1	East belt	Dafulou	17.566	15.468	37.687	32.80	11.90	This study
Y29-2-1	East belt	Dafulou	18.369	15.667	38.678	44.42	22.93	This study
Y29-4	East belt	Dafulou	18.304	15.624	38.505	39.51	20.10	This study
Y30-2	East belt	Dafulou	17.517	15.44	37.556	29.35	10.09	This study
	East belt		18.680	15.789	38.822	45.04	30.55	XU et al [25]
	East belt		18.450	15.753	38.969	54.31	28.77	XU et al [25]
	East belt		18.049	15.397	37.757	15.14	4.83	XU et al [25]
L57	Middle belt	Lamo	18.461	15.699	38.818	47	24.89	LEI [26]
L58	Middle belt	Lamo	18.52	15.701	38.925	48.12	24.84	LEI [26]
L61	Middle belt	Lamo	18.51	15.611	38.73	38.28	18.51	LEI [26]
L62	Middle belt	Lamo	18.429	15.67	38.749	44.6	22.94	LEI [26]
L8	Middle belt	Lamo	18.432	15.731	38.718	46.92	27.27	LEI [26]
L67	Middle belt	Lamo	18.458	15.608	38.566	35.38	18.46	LEI [26]
L-66	Middle belt	Lamo	18.467	15.683	38.855	46.95	23.73	ZHAO et al [27]
L-71	Middle belt	Lamo	18.546	15.709	38.976	49.11	25.32	ZHAO et al [27]
L-72	Middle belt	Lamo	18.548	15.698	38.933	47.29	24.53	ZHAO et al [27]
L-73	Middle belt	Lamo	18.533	15.705	38.95	48.6	25.08	ZHAO et al [27]
LM-1	Middle belt	Lamo	19.462	15.755	39.076	42.84	27.48	LIANG et al [27]
LM-2	Middle belt	Lamo	19.106	15.75	39.241	47.25	27.15	LIANG et al [27]
LM-3	Middle belt	Lamo	20.02	15.788	39.124	44.12	29.63	LIANG et al [27]
LM560-2	Middle belt	Lamo	18.5152	15.7022	38.9385	48.71	24.94	LIANG et al [27]
LM560-3	Middle belt	Lamo	18.5052	15.7056	38.9509	49.54	25.21	LIANG et al [27]
DC9030	West belt	Changpo	18.508	15.709	38.906	48.42	25.44	HAN et al [28]
C925	West belt	Changpo	18.527	15.721	38.827	46.34	26.23	HAN et al [28]
DC9019	West belt	Changpo	18.5	15.718	38.881	48.48	26.11	HAN et al [28]
C8834	West belt	Changpo	18.503	15.706	38.844	46.75	25.25	HAN et al [28]
C15	West belt	Changpo	18.494	15.703	38.755	44.47	25.06	HAN et al [29]
DC92-1	West belt	Changpo	18.528	15.727	38.858	47.46	26.65	HAN et al [29]
C9214	West belt	Changpo	18.552	15.711	38.843	45.44	25.44	HAN et al [29]
T-43	West belt	Changpo	18.616	15.711	38.902	45.01	25.24	ZHAO et al [27]
T-44b	West belt	Changpo	18.505	15.715	38.939	49.73	25.88	ZHAO et al [27]
T-45a	West belt	Changpo	18.522	15.724	38.938	49.65	26.46	ZHAO et al [27]
T-47	West belt	Changpo	18.421	15.701	38.734	46.11	25.17	ZHAO et al [27]
T-36C	West belt	Changpo	18.472	15.726	38.839	48.66	26.77	ZHAO et al [27]
T-38	West belt	Changpo	18.457	15.702	38.768	45.94	25.12	ZHAO et al [27]
T-33	West belt	Changpo	18.479	15.698	38.793	45.71	24.76	ZHAO et al [27]
T-57	West belt	Changpo	18.596	15.735	38.947	48.15	27	ZHAO et al [27]
DTK355-2	West belt	Changpo	18.4966	15.7146	38.9173	49.39	25.88	LIANG et al [28]
TK455-26	West belt	Changpo	18.537	15.7269	38.8616	47.27	26.61	LIANG et al [28]
DTK305-1	West belt	Changpo	18.7503	15.7188	39.1192	47.02	25.38	LIANG et al [28]

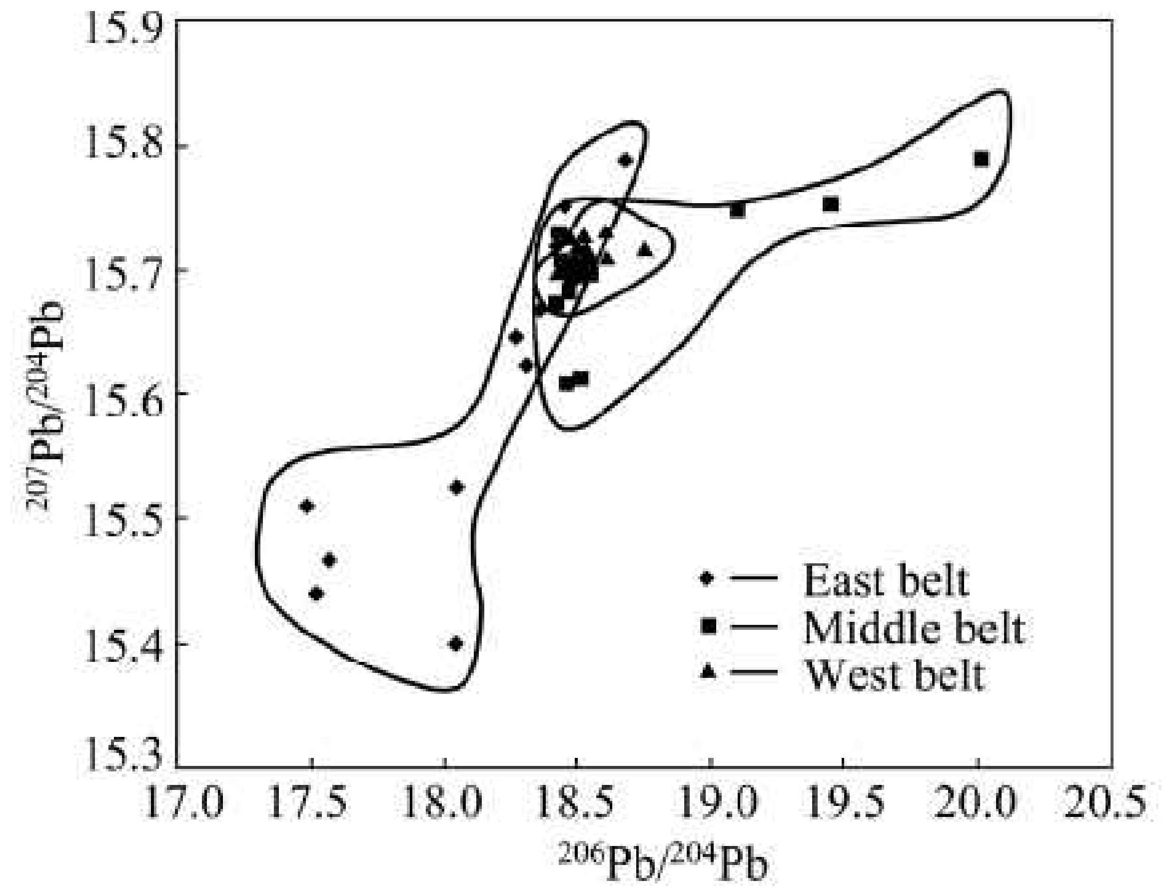

Fig. 3 $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram of sulfides from Dachang ore field

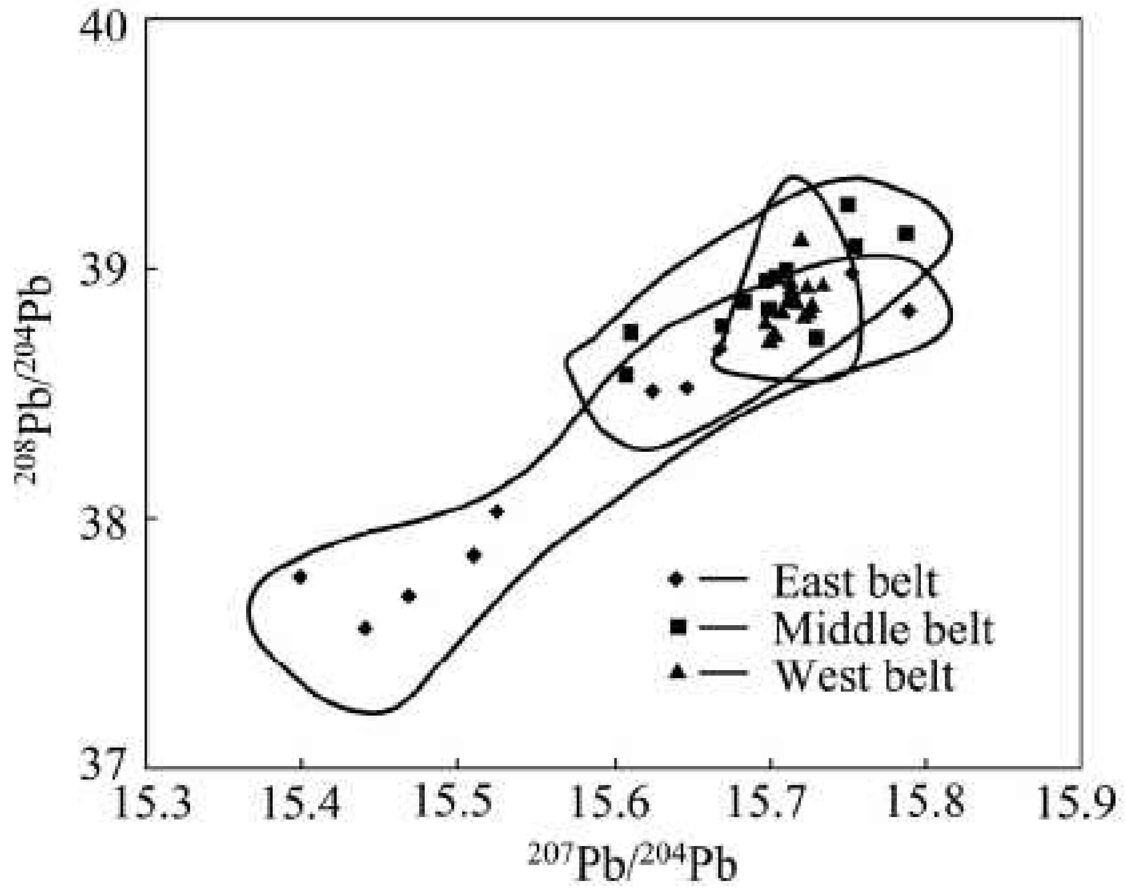

Fig. 5 $^{208}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ diagram of sulfides from Dachang ore field

According to Fig. 4, the projection points of $^{208}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ for the west belt are also most concentrated, suggesting the narrow scope of the ratio. Similarly, for the other two ore belts, the projection points scattered in a wider range. From the east belt, west belt to middle belt, the values increase gradually, being the same to the diagram of $^{207}Pb/^{204}Pb$—$^{206}Pb/^{204}Pb$ (Fig. 3). In Fig. 5, the projection points of the three ore belts overlap seriously, among which the values of the west belt are still concentrated mostly, being scattered for the other two ore belt. So, on the basis of the above analysis, it shows that in the west ore belt the lead isotope composition is highly consistent. In the other two ore belts, the lead isotope composition is scatter in a wide range. Overall, in the middle and east ore belts, it is characterized by the maximum and minimum, respectively. From the east belt, west belt to middle belt, it seems to appear the trend of the linear growth (Figs. 3, 4 and 5).

The similar lead isotope composition of the different types and occurrences ore implies the same

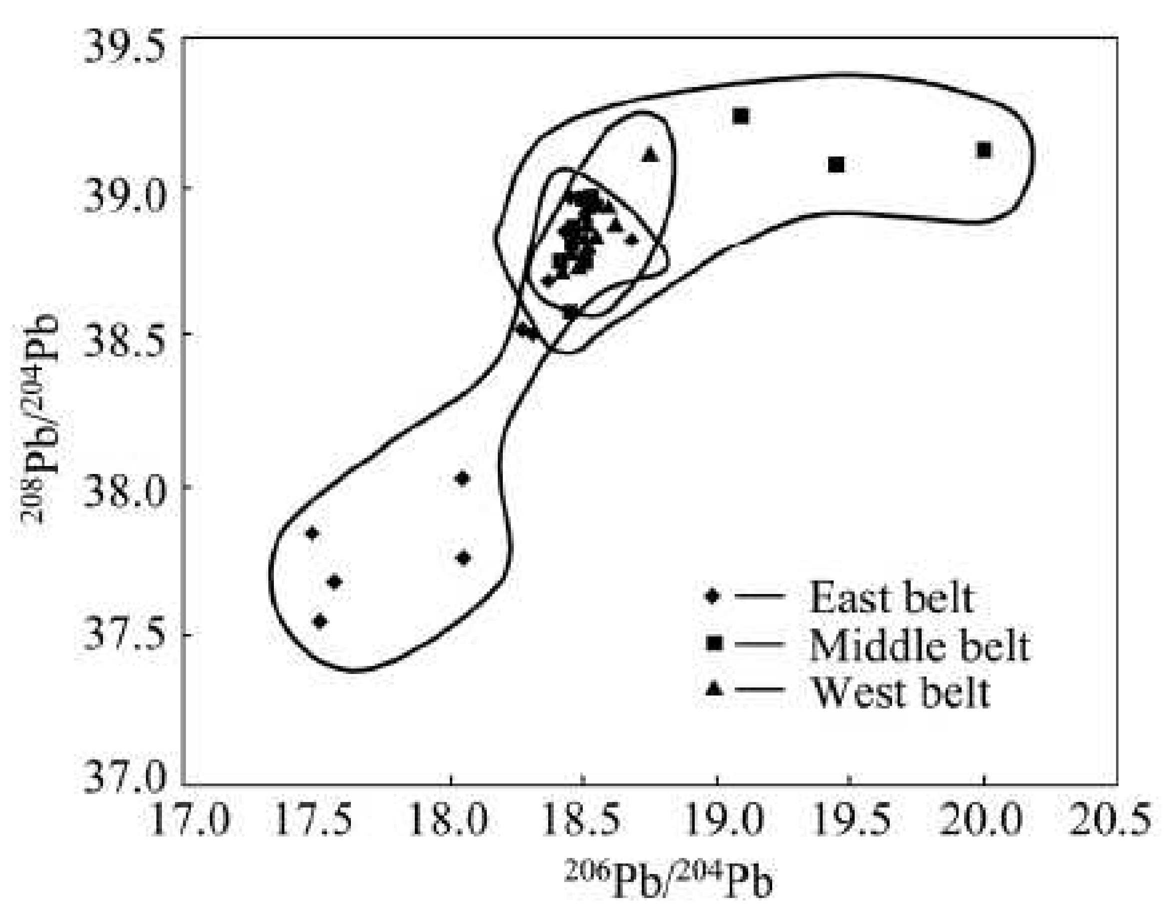

Fig. 4 $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram of sulfides from Dachang ore field

source and evolution [30]. ZARTMAN and DOE [31] put forward the tectonic model on the relation between lead isotope and tectonic setting. This model is the most common isotope-tracing method and is helpful to determine the ore source. Since the 1990s, many researchers have proposed the isotope contrasting methods to trace ore lead.

On the basis of ZARTMAN and DOE tectonic model [31], the lead isotope diagrams are projected as $^{207}Pb/^{204}Pb$ — $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ — $^{206}Pb/^{204}Pb$ (Figs. 6 and 7). From the projection, the different ore belts are characterized by the different lead isotope tectonic models (Figs. 6 and 7). In the diagram of $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ (Fig. 6), the lead isotope composition of the east ore belt is located in a large scope. The projection points of the west belt are mainly situated in the upper mantle. For the middle belt, the values are projected in the upper mantle and orogenic belt zones. In Fig. 7, the values are mainly projected in the zone between the lower crust and the orogenic zone. A small number of points scatter in the zone of the upper mantle and upper crust (Fig. 7). Overall, the lead isotope values mainly project onto the zones of the upper mantle, orogenic zone and upper crust. It suggests that the ore lead is mainly derived from both mantle and crust and the upper crust is the primary lead-rich source for the mineralization. In the west ore belt, the lead source may be more single than the other two ore belts. The lead isotopes indicate that the Dafulou ore deposit is also the product of the crust–mantle interaction, similarly to the Tongkeng−Changpo deposit [32]. The lead originates mainly from the crust-derived magmatism; however, this does not exclude the involvement of lead from igneous intrusion [28].

Meanwhile, the discussion of the lead source in the Dachang ore district has an amount of research data on the ore genesis and mechanisms. More recently, LIANG

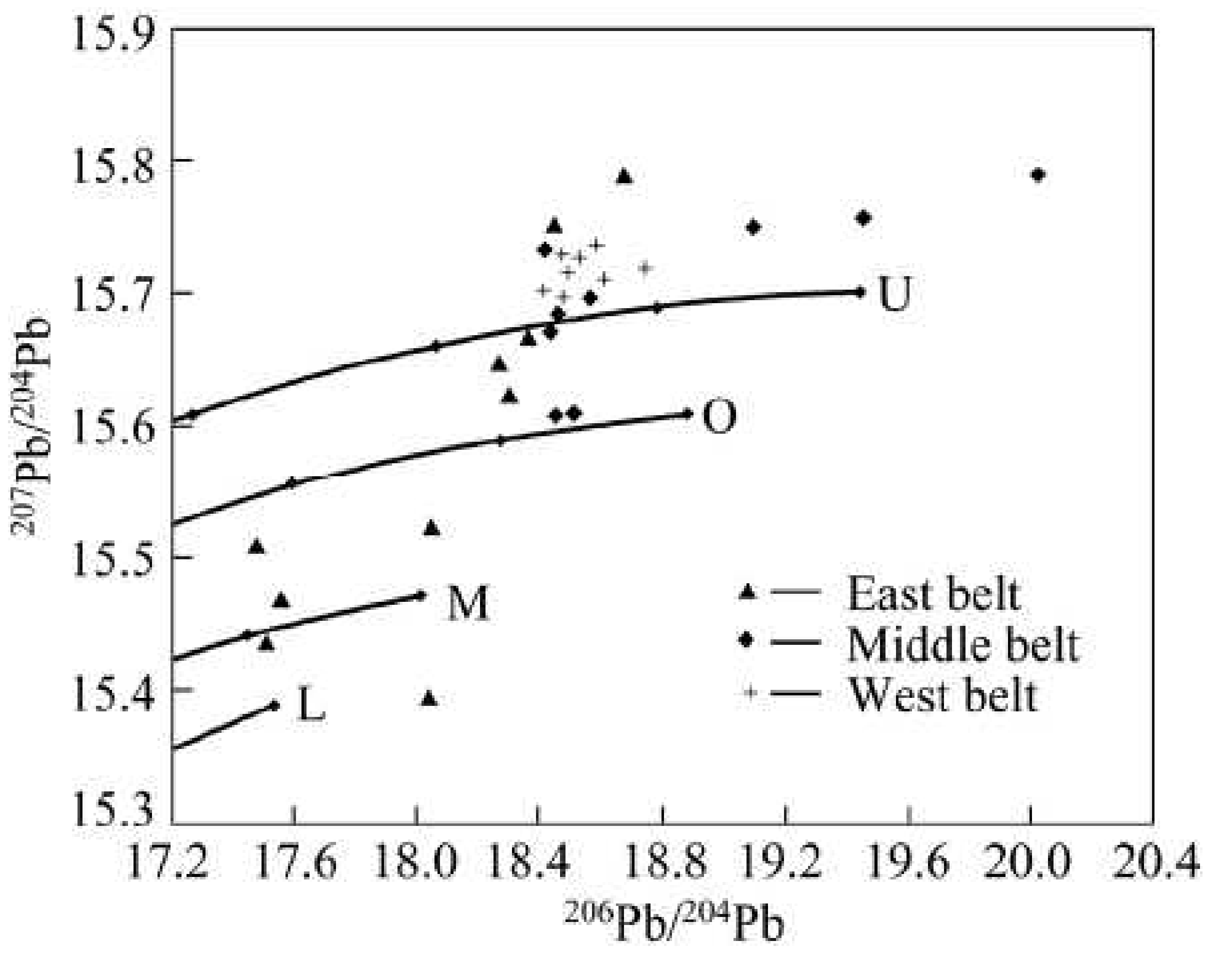

Fig. 6 $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ growth curve of Dachang ore field: M—Upper mantle; L—Lower crust; O—Orogen; U—Upper crust [31]

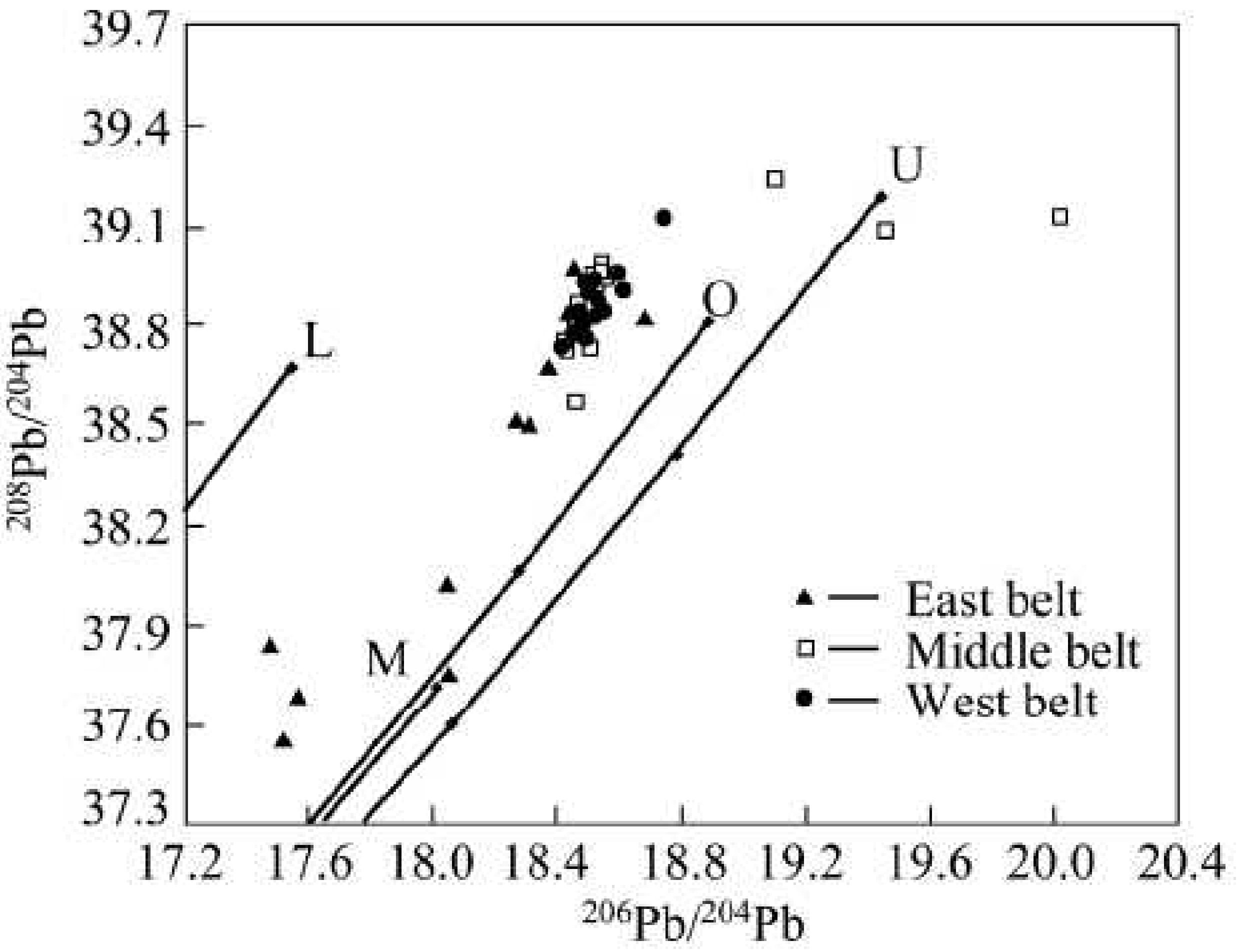

Fig. 7 $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ growth curve of Dachang ore field: M—Upper mantle; L—Lower crust; O—Orogen; U—Upper crust [31]

et al [28] studied the lead isotope composition of the Dachang ore field, which suggests that the values of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ range from 18.45 to 20.02, 15.6816 to 15.788 and 38.7849 to 39.241, respectively. The findings suggest that the different types and occurrences of tin-polymetallic ore deposits share the similar lead isotope characteristics, and mainly originate from the crust, only less from the mantle. By the lead isotope discrimination model, the Dafulou tin ore deposit should have formed in the orogenic environment and the crust is the important material source.

ZHU [33] put forward the $\Delta\gamma$—$\Delta\beta$ range diagram of the different genetic ore deposits based on the lead data, which has better tracer significance than the other global evolution models in theory because of the elimination of the time impact. According to the projection of the lead isotope data (Fig. 8), the values are mainly located in three zones, involving the upper crust, the mixed crust and mantle subduction, and the orogen. So, it clearly suggests that the ore lead consists of the upper crust lead, the mixed crust and mantle subduction zone lead, and the orogenic lead. The upper crust and magmatism are the main lead sources, besides a little orogenic lead. In the Dachang ore field, the mineralization should be the result of the crust−mantle interaction to some extent.

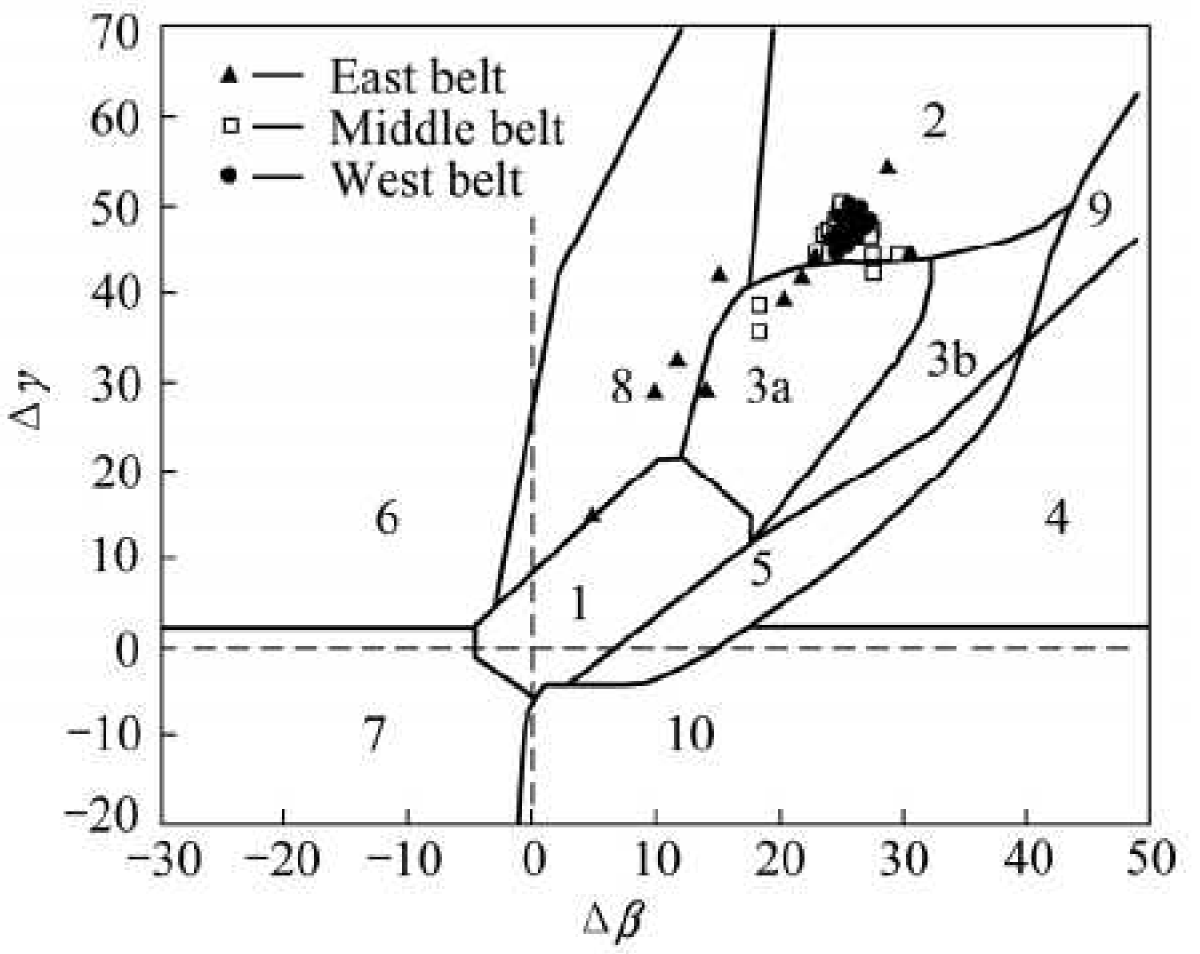

Fig. 8 $\Delta\gamma$—$\Delta\beta$ diagram of ore lead from Dachang ore field in Guangxi, China: 1—Mantle-derived lead; 2—Upper crust lead; 3—Mixed crust and mantle subduction zone lead (3a—Magmatism, 3b—Sedimentation); 4—Chemical sedimentation lead; 5 — Submarine hydrothermal lead; 6 — Medium metamorphic lead; 7—High-grade metamorphic lower crust lead; 8—Orogenic lead; 9—Ancient shale upper crust lead; 10—Retrograde metamorphic lead [33]

4 Conclusions

1) The lead isotope composition from the west ore belt is more consistent than the east or middle ore belt. And, in the middle and east ore belts, the isotope values are the maximum and minimum, respectively. The lead source of the west ore belt may be more single than the other two ore belts.

2) In the Dachang ore field, the ore lead mainly consists of the upper crust lead, the mixed crust and mantle subduction zone lead, and the orogenic lead. In the whole, the ore lead is mainly derived from both the mantle and crust. The upper crust and magmatism are the important lead sources for the mineralization. A minority of lead was still supplied by the orogenesis.

3) The Dafulou tin-polymetallic ore deposit is related to the orogenic tectonic events, or maybe has been formed in the tectonic setting of the orogenic belt. To a certain extent, it is the result of the interaction between the crust and mantle.

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广西大福楼矿床铅同位素组成及其对矿床成因的约束

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摘 要：利用大福楼矿床新开采坑道的矿石样品进行铅同位素分析，探讨了矿床的成矿物质来源及其构造背景。结果表明，$^{206}Pb/^{204}Pb$、$^{207}Pb/^{204}Pb$ 以及 $^{208}Pb/^{204}Pb$ 分别位于 17.478~18.431、15.440~15.717 以及 37.556~38.839，Φ 值位于 0.592~0.638，μ 值为 9.26~9.69，Th/U 取值范围为 3.74~3.97。比较大厂矿田不同矿带的铅同位素组成的结果表明，西矿带的铅源可能更加单一，中矿带的铅同位素值相对最大，而东矿带的铅同位素值则最小；大厂矿集区的铅源主要由上地壳铅、壳幔混合俯冲带铅以及造山带铅所组成。根据铅同位素构造判别图，矿石铅主要来自于地幔和地壳，尤其是上地壳以及岩浆活动在成矿作用过程中发挥了重要作用。然而，造山作用也提供了少量铅源，矿床应该属于壳幔联合作用的产物，更可能形成于造山带成矿环境中。

关键词：铅同位素；矿源；构造背景；大福楼；大厂矿田

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