Crust-mantle interaction and its contribution to the Shizhuyuan superlarge tungsten polymetallic mineralization

ZHAO Zhenhua (赵振华), BAO Zhiwei (包志伟), ZHANG Boyou (张伯友) & XIONG Xiaolin (熊小林)

Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
Correspondence should be addressed to Zhao Zhenhua (email: zhaozh@gig.ac.cn)

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Abstract The Qianlishan granite, which is closely related to the Shizhuyuan tungsten polymetallic mineralization, is aluminous alkali-type granite. The intimate temporal and spatial association among the basaltic, syenite and granitic rocks in the mining area, and their major and trace elements, and Nd, Pb, Sr, O isotopic compositions indicate that the crustal-mantle interaction probably was an important constraint on, and participated in, the formation of the superlarge ore deposit.

Keywords: Shizhuyuan, superlarge deposit, crustal-mantle interaction, aluminous alkali granite.

The view that the tin bearing granite on the Juss Plateau, Nigeria, was the product of the mantle hotspot activities, and tin was derived directly from the mantle[1], was a breakthrough of the conventional understanding that the tin could only be derived from the crust. Later, the nonlinear metallogeny was developed to survey the formation and distribution of the lithospheric mantle related metallic ore deposits within the crustal tectonics. In the 1990s, the continental lithospheric dynamic researches showed that ore-forming material from both the mantle and the crust participated in spontaneously or imposed within short time interval on the metallic ore mineralization within individual ore deposit.

For decades, many investigations have been conducted on the Shizhuyuan superlarge tungsten polymetallic ore deposit, Chenzhou, Hunan Province, and its relationship with the Qianlishan granite[2—7], and it has been considered that the ore-forming processes are closely related to the S-type Qianlishan granite. On the contrary, our work shows that the Qianlishan granite is not typical S-type, but potassium rich and sodium poor alkali granite. Its Sr, Nd, Pb, O isotopic compositions indicate that significant mantle material participated in the granite genesis. Regarding the Pb and Os isotopic compositions of the ores, crustal-mantle interactions and the related magmatic activities were apparently involved in ore formation.

1 Regional tectonic and geophysical background

The Shizhuyuan superlarge tungsten polymetallic ore deposit occurs in the NE trending Lingxian-Chenzhou-Linwu deep fault (part of the Linxian-Lanshan fault). Two gravity gradient belts, which border the dilatation part of the Lingxian-Lanshan fault, namely the Zixing-Chenzhou-Linwu and the Zixing-Yizhang-Linwu gravity gradient belts are important deep faults in southern Hunan Province (fig.1, ref. [8]). The Qianlishan biotite granite, and associated syenite and basaltic rocks occur right within the dilatation. The sedimentary formations on either side of the Linxian-Lanshan fault are quite different. The east part belongs to early Paleozoic rise consisting of Precambrian and Cambrian to Sinian two-layered basement structure with Upper Paleozoic cape formation. The west side of the fault belongs to late Paleozoic downwarping region.

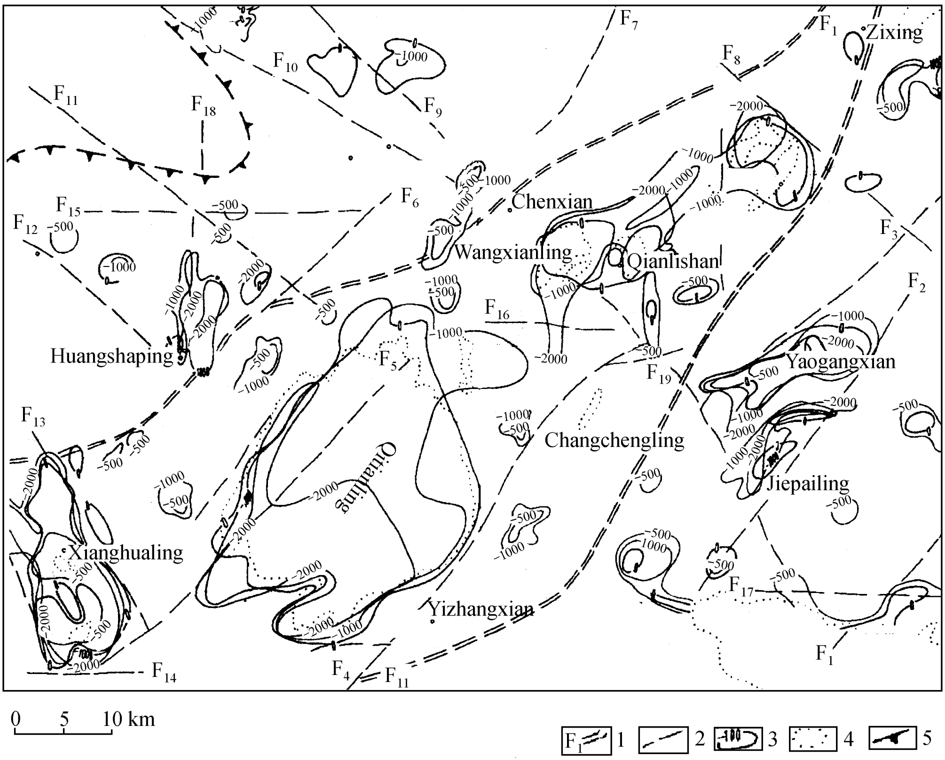

Fig. 1. Diagram showing the distribution of the deep faults and the magmatic rocks in Chenzhou-Guiyang area (modified after Tong, 1995[8]). 1, Deep fault belts; 2, basement faults; 3, contour of the blind plutons; 4, cropped area of the plutons; 5, lifted block.

The mining area occurs in the east-west trending Nanling complex mantle structure zone. The thickness of the lithosphere in between the Hengdong-Shuangpai and Chaling-Linwu deep faults ranges from 120 to 150 km, to the east of the Chaling-Linwu fault, the thickness of the lithosphere increases to about 150 to 200 km and the bottom planar of the lithosphere dips to southeast while the thickness of the crust increases from 32 to 37 km. It is clear that the Shizhuyuan superlarge deposit occurs above the slope of the mantle rise where the crust and the lithosphere change from thin to thick.

The mantle rise is characterized by high temperature and low pressure. The heat flow at the surface and depths is rather high, with a heat flow of 66.035 MW/m^2 at the surface. The heat flow anomaly in the research area is overlapped with the Huangshaping-Qianlishan-Yaogangxian east-west trending magnetic anomaly. In addition, a large number of modern geothermal systems were observed at Chenzhou, Qitianling, Yizhang, and Rucheng around the mining area, most of which are middle high temperature types except the Rucheng thermal spring that is high temperature type.

The palaeo-tectonic setting of the research area is Early Paleozoic active continental margin. The regional mantle uprising since Permian period resulted in the crustal extension, and formed a series of NE trending extensive and chasmic tectonic systems. It was referred to as Eastern Hunan rifting system[9], and the Chaling-Chenzhou-Hexian fault was considered to be the eastern boundary of the rifting system[10]. Based on the Sm-Nd, Rb-Sr isotopic studies of the Yanshannian granitoids and the palaeomagnetic data in the area, Gilder et al.[11] concluded that the tectonic movement of the research area was dominated by strike-slip faulting and rifting during the Yanshannian movement. It is interesting to note that the Qianlishan granite and the Shizhuyuan superlarge ore deposit occur right within the rift or rifting surroundings.

2 Granitoids, syenite and basaltic rock association

Not much attention has been paid to the association of the Yanshannian syenite, basaltic rocks and other mantle source involved magmatic rocks with the superlarge deposit in southern Hunan Province during the foregoing metallogenetic investigations, or they were even neglected. Many basaltic rocks dated from late Indosinian to late Yanshannian were recognized along the Zixing-Yizhang fault, which include the Changchengling, Shangchitang, Jiaotashui, Pinghe, and Shangbaju basaltic rocks. The basaltic rocks are also widespread at Ningyuan-Daoxian, Guanshijie and Chunjiangpu at the southwest and north part of the area occurring as swarms or belts. The occurrences of the Changchengling olivine tholeiite and tholeiite, the Shangchitang gabbro-diabase, olivine odinite, Jiaotashui olivine odinite and the Pinghe basalt, olivine odinite, minette, etc., and the diabase porphyrite dikes in the mining area[12], all suggest that the crust-mantle interaction during Yanshannian were quite extensive and cannot be ignored.

Syenite intrusives are also observed in the area. The Shashanling syenite, consisting of pyroxene syenite and augite garnet syenite, was observed at the suburban area of Chenzhou City with a cropped area about 0.2 km^2. Many syenite dikes (NE trending) were recently reported in the Indosinian-Yanshannian (middle Triassic to upper Jurassic Period) multi-stages Qitianling granite south of the Qianlishan granite. The Qitianling granite itself consists of mainly hornblende biotite orthoclase granite, and is very abundant in alkaline, especially at Qingshanli, Liangkoutang, Zhangxishui, Fengshuxia, Wuliqiao, and Niutouling, the K_2O+Na_2O ranges from 7.9 to 9.9% ($K_2O > Na_2O$), the Wright alkaline ratio (A.R.) = 2.3—3.8, and thus the granite itself is of alkali type.

Ultra-mafic rocks such as limburgite, along with a great deal of olivine tholeiite, quartz tholeiite, alkali-basalt, and basanite was observed in a NE trending belt to the northwest of the mining area at Ningyuan and Daoxian.

Yanshannian lamprophyre and olive lamprophyre dikes at depth were also observed in neighboring area of the Xikuangshan superlarge antimony deposit. Yanshannian diabase dikes were observed at the Lujing large uranium deposit within the area and the Fankou superlarge Pb-Zn deposit in the neighboring area.

The above-mentioned syenite, basaltic and mafic dikes were formed in the Yanshannian period (Jurassic to late Cretaceous period) (table 1). Their ages are close to that of the Qianlishan granite (129—182 Ma) and the known active epoch of the Yanshannian granite intrusion (150—165 Ma) and the late Yanshannian movement (110—140 Ma, 90 Ma)[13]. They are also coincident with the ore-forming age of the Shizhuyuan superlarge deposit, of which the Re-Os isochron of the skarn was dated to be (151.03 ± 3.5) Ma[14], while the Sm-Nd isochron of the massive skarn-garnet-diopside dated to be (160.8 ± 2.4) Ma[15].

3 The aluminous alkali-type Qianlishan granite

The Qianlishan granite used to be defined as S-type or crustal sourced type granite. However, its major and trace elements' geochemical characteristics are significantly different from the contemporaneous S-type granitoids related with tungsten mineralization in South China. Actually, it is very similar to those of the aluminous alkali granite[16—18], and thus should be nominated as aluminous alkali granite with high potassium and low sodium (table 2).

The Qianlishan granite is characterized by (1) high silicon ($SiO_2 > 75\%$), low aluminum ($Al_2O_3 < 13\%$, A/CNK—1.11, sub-aluminous , (2) potash rich, with Wright alkaline index ranging from 2.83 to 3.91, and falling in alkaline series on A.R.-SiO_2 diagram, and significantly (3) the mica in the granite belonging to Li-Fe series. All these are very similar to those of the typical alkali granites. The Qianlishan granite belongs to sub-alkali type, if we group the granitoid rocks into three types as alkali, sub-alkali, and calc-alkali according to KN/A ratio (0.95, 0.95—0.75, $<$0.75). Mao et al.[14] also noticed that the Qianlishan granite share some common geochemical characteristics of typical alkali granite.

The Qianlishan granite is enriched in Ga (22.9 $\mu g \cdot g^{-1}$—31.3 $\mu g \cdot g^{-1}$), with a mean Ga/Al×10000 value of 3.85 (3.11—4.52) which is higher than the average of the A-type granite worldwide (3.75). The Qianlishan granite falls in the A-type on Ga/Al-Nb, Ce, Zn, Zr discrimination diagrams (fig. 2). The chondrite normalized REE patterns of the Qianlishan granite are characterized by strong Eu negative anomalies (Eu/Eu* 0.02—0.43), relatively enriched in HREE (heavy rare earth elements), and show rather flat "V"-type patterns with $(La/Yb)_N$ ~1 (1.08—2.30) (fig. 3). The Qianlishan granite is enriched in Cr, Ni, Co, Sr, and Ba, which clearly suggests a mantle materials involvement. It is also significantly high in volatile components, such as F, Cl, B with contents up to 3500—9895 $\mu g \cdot g^{-1}$, 220—504 $\mu g \cdot g^{-1}$, 60—72 $\mu g \cdot g^{-1}$ respectively, which apparently differs from the common tungsten related granites in southeast China.

Table 1 Sr, Nd, and Pb isotopic compositions of the Mesozoic basaltic rocks and syenite in south Hunan Province

Sample No.	CJP-1	YTK-1	XTB-1	XTB-3	DXB-2		CZS-1
Location	Chunjianpu	Changchengling	Baoanxu	Baoanxu	Huziyan	Qianlishan	Shanshanling
Nomination	tholeiite	tholeiite	alkali basalt	alkali basalt	limburgite	diabase-porphyrite	pyroxene syenite
T /Ma	81	178	177	177	204	142	135
Rb / $\mu g \cdot g^{-1}$	26.66	81.08	6.854	9.264	67.53		
Sr / $\mu g \cdot g^{-1}$	259.4	663.8	1047	1126	277.9		
$^{87}Rb/^{86}Sr$	0.2963	0.3523	0.0189	0.0237	0.7005		2.002
$^{87}Sr/^{86}Sr$	0.706 189	0.709565	0.704414	0.704281	0.706657		0.709996± 11
$\varepsilon Sr(t)$	20.49	62.23	1.06	–1.00	5.18		23.55
Sm / $\mu g \cdot g^{-1}$	4.064	4.910	8.081	7.877	7.227	3.200	1.336
Nd / $\mu g \cdot g^{-1}$	17.28	21.74	39.67	38.99	35.91	11.80	22.45
$^{147}Sm/^{144}Nd$	0.1428	0.1366	0.1231	0.1221	0.1217	0.1641	0.0360
$^{143}Nd/^{144}Nd$	0.512 78	0.512584	0.512756	0.512897	0.512733	0.512955	0.512565 ± 15
$\varepsilon_{Nd}(t)$	3.33	0.31	3.97	6.74	3.81	6.78	1.34
$f_{Sm/Nd}$	–0.274	–0.306	–0.374	–0.379	0.381	–0.166	–0.817
$^{206}Pb/^{204}Pb$	18.456	18.560	19.486	19.487	19.022		19.237
$^{207}Pb/^{204}Pb$	15.694	15.749	15.589	15.659	15.614		15.683
$^{208}Pb/^{204}Pb$	38.949	39.048	39.406	39.579	38.771		38.683

Table 2 Petrochemical characteristics of the Qianlishan granite and comparison with typical A-type granites in the world

Components (%)	Qianlishan granite[2, 3]			S-type granite in southeast China[a)]	A-type granite in the world[16] (148)
	Pophyritic biotite granite	Equigranular Biotite granite	Granite porphyry		
SiO_2	75.48 (74.20—77.20)	76.13 (74.34—78.68)	73.68 (72.65—76.37)	72.82	73.81 (60.4—79.8)
Al_2O_3	12.71 (11.88—13.03)	12.89 (11.62—13.96)	12.67 (12.26—13.02)	13.51	12.40 (7.3—17.5)
Na_2O	2.72 (2.64—3.44)	3.09 (2.11—3.72)	2.49 (2.32—2.68)	2.73	4.07 (2.8—6.1)
K_2O	4.88 (4.35—5.29)	4.42 (4.02—5.07)	5.00 (4.73—5.25)	4.40	4.65 (2.4—6.5)
$\frac{K_2O+Na_2O}{Al_2O_3}$	0.77	0.78	0.78	0.69	0.94
$\frac{Al_2O_3}{K_2O+Na_2O+CaO}$	1.12	1.14	1.12	1.18	0.95
$\times 10^4$	3.41	4.52	3.11		3.75
Eu/Eu[a)]	0.12—0.20	0.02—0.06	0.30—0.43	0.46	
$(La/Yb)_N$	2.30	1.08	10.0	9.44	
$\delta^{18}O$	2.8—14.4, mainly around 5—7 per mil			>10	low, large range of variation, sometimes negative
$(^{87}Sr/^{86}Sr)_i$	0.7032–0.7290			>0.710	relatively low with wide range variation
$^{143}Nd/^{144}Nd$	>0.5120			<0.5120	>0.5120

a) After Xu et al. (1992), the values listed are average of 300 samples.

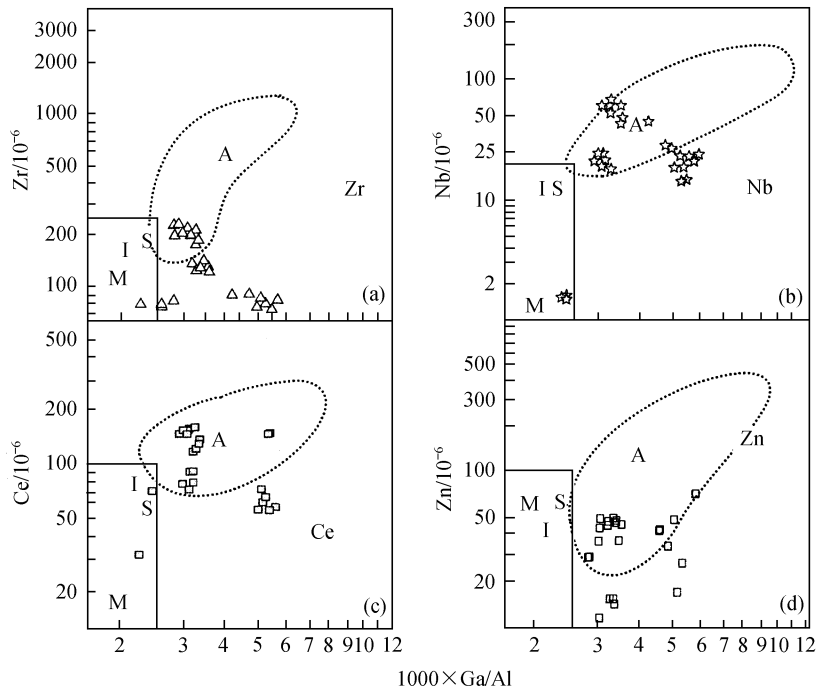

Fig. 2. 1000×Ga/Al—Zr, Nb, Ce, Zn discrimination diagrams of the Qianlishan granite[10] (data from ref. [2] and Liu, 1994). ×, Qianlishan granite; A, I, S, M represent the average value of AISM type granite respectively. The dashed line shows the area of fractionated felsic granites; the solid square represents I-S-M type granite area.

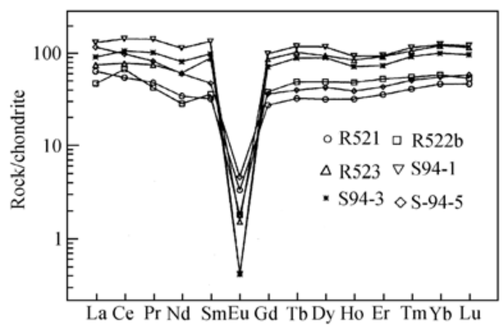

Fig. 3. The chondrite normalized REE patterns of the Qianlishan granite.

The Sm-Nd isotopic compositions of the Qianlishan granite are characterized by high $^{143}Nd/^{144}Nd$ ratios, ranging from 0.512112 to 0.512344, with an initial ratio of 0.512015—0.512076[4, 6]. On the εNd-T diagram, the Qianlishan granite diverges off the area of crustal evolution of the southeast China and shifts towards the mantle evolution line (fig. 4). The lower Nd model age of the Qianlishan granite (T_{DM} ranging from 1.18 to 1.57Ga) relative to the S-type granites in southeast China, also suggesting that the mantle material participation during the crust- mantle interaction.

Some other granites showing similar Sm-Nd isotopic compositions have been noticed by some workers. Gilder et al.[11] noticed that there is a belt lying from Xiangshan, Jiangxi Province to the Shiwandashan, Guangxi, within which the granites are characterized by high Sm, Nd contents (>8 μg • g^{-1} and 45 μg • g^{-1} respectively), high εNd (T) (from – 4 to – 8), and low Nd model ages, and termed it Shi-Hang high Sm, Nd low Nd model age belt. Chen et al.[19] also reported the

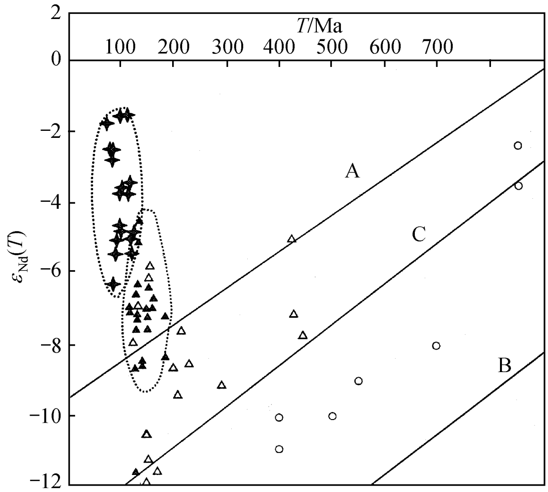

Fig. 4. εNd-*T* diagram of the regional granites. A, Evolution line of the strata in the Yangtze block; B, the mean evolution line of the strata in southeast China; C, evolution line of the strata within the Xiang (Hunan Province)-Yue (Guangdong Province)-Gan (Jiangxi Province)-Gui (Guangxi) conjunctive area (for reference use only, further data needed). +, Alkali rich granite from the coastal area of the Fujian and Zhejiang Provinces; Δ, granites within the Xiang -Yue-Gan -Gui conjunctive area; ○, sedimentary and metamorphic rocks of the Yangtze and Huaxia block; ▲, Qianlishan granite.

occurrences of NE trending low Nd model age granite belts in southeast China. The authors[1)] noticed that the Nd isotopic compositions of Qianlishan, Shangbao, Pangxemu, and Qitianlian granite shows similar Nd isotopic compositions (Sm7.5—22 μg • g^{-1}, Nd30—69 μg • g^{-1}, εNd (*t*)-2— – 7.5) which suggested the contribution of mantle material.

The initial Sr isotopic composition of the Qianlishan granite varied from 0.70322 to 0.73282, with rather low Rb/Sr ratios (average 39.67), the ε_{Sr} (*T*) values vary widely from 43.1 to 506.2. The $\delta^{18}O$ values are rather low but vary widely, the majority of the values are round 5‰—7‰ [14, 20].

Comparison of the above with the typical A-type granites listed in table 2 shows that the Qianlishan granite is low in (K_2O+Na_2O)/Al_2O_3 ratios (averaging 0.78 (0.66—1.00)), due to its low Na_2O contents, while the other specifications are quite similar. So the Qianlishan granite is referred to as high potassium low sodium aluminous alkali type granite here by the authors.

4 Geochemistry of the syenite and the basaltic rocks

The Shashanling alkali syenite is rich in alkaline (K_2O+Na_2O＞11%), especially potassium (K_2O＞9%). The chondrite normalized REE patterns of the syenite show smooth right dipping lines without apparent Eu anomalies. Isotopically, the syenite is characterized by $^{143}Nd/^{144}Nd$ = 0.512565, εNd (*T*) = + 1.34 (table 1), T_{DM}= (618 Ma), $(^{87}Sr/^{86}Sr)_i$ = 0.7060; on the Pb isotopic tectonic model diagram, the syenite lies around the orogenic Pb evolution line.

The basaltic rocks in the area are predominated by tholeiitic and alkali basaltic rocks, characterized by LREE enrichment, without Eu anomaly, and the "W-type" V, Cr, Mn, Fe, Co, Ni, Cu chondrite normalized patterns with apparent Cr and Ni depletions. The trace element characteristics show that the basalts were derived from partial melting of lherzolite. The high field strength element (HFSE) ratios like Nb/Ta, Zr/ Hf are 16.05—18.5 and 39.60—44.41 respectively, higher

1) Zhao et al., Fundamental researches centered on the locating of the superlarge ore deposits: the prospecting areas of Cu, Au, and U in the conjunctive area of Xiang-Yue-Gang-Gui, Report, 1996.

than or equal to those of the primordial mantle (17.5±2.0 and 36.27 respectively). No Nb anomalies were observed on the primitive mantle normalized trace element patterns, which indicates that crustal contamination is minor and negligible[12]. However, the incompatible element ratios such as La/Ce, Ce/Nd, Zr/Nb, etc., are significantly different from those of the primitive mantle. The initial $^{87}Sr/^{86}Sr$ values range from 0.704 221—0.708 673, εSr (T) = –1.00 — + 62.23, and the $^{143}Nd/^{144}Nd$ varied from 0.512733 to 0.512955, $f_{Sm/Nd}$ = –0.166 — –0.381, εNd (T) = +0.31—+6.78 (table 1), among which the diabase-porphyrite and alkali basalt show the highest values (6.78 and 6.74 respectively). On the εSr-εNd diagram the basaltic rocks drift off the mantle array, and their $^{207}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$ compositions are similar to that of EMII, which suggest that the regional mantle had been fertilized[12].

5 Compositions of the ores

5.1 Lead isotopic composition

$\Delta\beta$, $\Delta\nu$ parameters[13] of the ores from the Shizhuyuan deposit suggest that the lead in the ore deposit might be derived from a mixture of crustal and mantle sources can be analogous to those in subduction zone or orogenic belt.

5.2 Re-Os isotopic composition

The initial $^{187}Os/^{186}Os$ ratio of the molybdenite from the skarn type ore body equals 2.17×0.08[14], which is close to modern mantle (+1.06) and apparently lower than the modern crust (＞+5).

5.3 Volatile components

The F contents of the altered rocks are usually higher than 2% and can be up to 15% with a mean value of 5%. The average CaF_2 content of the ores is 19.69%1) and the total reservation of elemental F is up to 1170 million tone. The ores also contain many Cl-rich minerals, such as hyacinthine, hornblende, etc. The inclusions of the minerals in the ores often contain Cl-bearing daughter minerals, the Cl/ΣFe ratios of the inclusions in hornblende and diopside are 40.25 and 64 respectively. B in the ores is mainly concentrated in the tourmaline.

The high degree enrichment of volatile components in the Shizhuyuan superlarge deposit could not be explained only by high degree fractionation of the granitic magma, the participation of the mantle material might be an applause explanation, as the F and Cl content in the mantle are 1 to 2 orders greater than that of the crust, and B content in the mantle is twice that of the crust.

6 Crust-mantle interactions in the mining area of the Shizhuyuan superlarge ore deposit

1) The basaltic rocks in the area can be divided into tholeiite and alkali basalt series. Basaltic trachyandesite, tephriphonolite, leucite basanite, basanite and other alkali basaltic rocks were ob-

1) Liu Yimao et al., The study on the ore-forming conditions of Shizhuyuan tungsten polymetallic deposit, Hunan, China, Report, 1994.

served in the Huziyan potash basalt, Daoxian. Three types of basaltic magma series, olivine tholeiitic, leucite basanitic, and basanitic magmas, have been suggested to occur in the area[21]. These mantle magmatic activities coincide spatially and temporally with the Qianlishan aluminous alkali granite, the Shashanling alkali rocks, the alkali granite and many syenite veins within the Qitianling granite batholith.

2) The petrology, mineralogy and geochemistry investigations of the mantle xenoliths in the basaltic rocks show that ever since the beginning of Yanshannian movement, the uprising of the aesthenosphere caused extensive lithosphere extension and thinning, and also the underplating of gabbro magma within the lower to middle crust. The Sm-Nd isochron of the gabbro xenoliths was dated to be (224 ± 24) Ma, $^{143}Nd/^{144}Nd$ 0.513050, εNd (*T*) = +8.8. The $^{143}Nd/^{144}Nd$ ratios of spinel lherzolite range from 0.5134 01 to 0.513 667. Chemically, they are classified into fertilized I-type mantle xenoliths on mineral and it can be deduced that the top boundary of the aesthenosphere was about 70 to 80 km in depth at the time of the basaltic eruption[22].

3) The Shizhuyuan superlarge deposit was located on the shrink area of steep geochemical boundary and inside the Cathaysia block[23], i.e. on the steep variation zone of Pb and Nd model ages. This resulted from crust-mantle interaction along the boundary of the different blocks.

4) The regional mantle experienced metasomatism or fertilization. The mantle metasomatism or fertilization is evidenced by the discordance between the isotopic depletion and the enrichment of the incompatible mother and daughter elements . For instance, the εNd (*T*) of the syenite and basaltic rocks are +1.34 and +0.31 to +6.78 respectively while all have negative $f_{Sm/Nd}$ values (–0.17 to –0.82). The characteristics of HFSE ratios of rocks exclude the possibility of crustal contamination, and it is most probably due to the metasomatism or fertilization taking place before the partial melting of the mantle source[12]. Amphibolization was observed in the mantle enclaves of the Huziyan alkali olivine basalt, amphibole replacing and surrounding clinopyroxene and forming embayed alteration structure in the spinel lherzolite enclaves.

On the Nb normalized primitive Nb, P, Zr, Ti, Y diagram, the basaltic and alkali rocks in the area all show right dipping non-scatter pattern, which indicates that they were probably derived from fertilized mantle sources[8]. Their incompatible elements and the ratios are similar to those of the EMI and EMII mantle end members. In addition, the Cretaceous basic dikes that occur in the neighboring area are also similar to the EMII mantle end member[24].

7 Contrast between the Shizhuyuan superlarge deposit and the large tungsten deposit in neighboring area

Due to the differences between the geological background, regional magmatic association, major and trace elements, Nd, Sr, O isotopic compositions, and volatile components of the related granite (the Qianlishan and the Yaogangxian granite), the adjacent Yaogangxian tungsten deposit is smaller in size than the Shizhuyuan deposit (table 3).

Table 3 Contrast between geological and geochemical features of ore-forming related granite in Shizhuyuan, Yaogangxian and Xihuashan ore deposit

Geological background	Shizhuyuan	Yaogangxian, Xihuashan
	downwarp area	uplift area
Host rocks	carbonate	clastic rocks
Ore types	greisen, skarn, network or vein type	skarn, network or vein type
Ore forming metal	W, Bi (super-large),Sn, Mo, Be(large)	W, Ag
K_2O/Na_2O	1.15—1.95	1.13
F/ μg • g^{-1}	3 295—9 899	400—2200 (2096)
Ga/Al×10000	3.41—4.52	2.78
K/Rb	65.1	33.5
Rb/Sr	22.3	255.7
Nb/Ta	3.5	1.6
$(La/Yb)_N$	1.6	0.38
Sr / μg • g^{-1}	124	4.7
Ba / μg • g^{-1}	206.7	12.9
Cr / μg • g^{-1}	14	7.5
Ni / μg • g^{-1}	16	<4
Co / μg • g^{-1}	36.2	21.9
$(^{87}Sr/^{86}Sr)_i$	0.703 2—0.729 0	0.783 43, 0.71 63—0.716 9 (Xihuashan)
$^{143}Nd/^{144}Nd$	0.51211-0.51234	0.512 05—0.512 19 (Xihuashan)
εNd (*T*)	−6.6 — −8.5	−10.7 — −11.4 (Xihuashan)
$\delta^{18}O$ (per mil)	2.8—14.4 (peak value 5—7)[20]	11.22—11.59 (11.4)

8 Conclusion

1) The Qianlishan granite associated with the Shizhuyuan superlarge tungsten polymetallic mineralization is high potassium low sodium aluminous alkali granite (A2 type). Its high $^{143}Nd/^{144}Nd$, low T_{DM}, $^{87}Sr/^{86}Sr$ and $\delta^{18}O$, as well as high Nb/Ta and low Rb/Sr ratios, and the enrichment of Cr, Ni, Co, Sr, Ba all suggest the participation of the mantle material during the petrogenesis. The crust-mantle interaction played a very important role in mineralization of Shizhuyuan superlarge deposit.

2) The metallogenesis of the Shizhuyuan superlarge tungsten deposit is closely related to the accompanying extensive mantle involved magmatic activities. It is evidenced by the typical Yanshannian mantle related magmatic rock association, such as the aluminous alkali granite, alkali igneous, basaltic rocks (especially the potash alkali basalts), diabase, etc.

3) Mantle metasomatism or fertilization took place during or before the ore-forming processes of the Shizhuyuan super-large tungsten polymetallic deposit.

4) The superlarge Shizhuyuan tungsten polymetallic deposit was formed in a long-term extension and downwarp environment, and also in the thin-to-thick transition zone of the lithosphere and the mantle slope of the mantle rising. The mantle domain is high temperature and low pressure type.

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