Deep Tectonic Processes and Superaccumulation of Metals Related to Granitoids in the Nanling Metallogenic Province, China

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Abstract The Nanling region is an important nonferrous and rare metal metallogenic province in South China, in which most of the deposits are related to granitoids in genesis. It covers southern Hunan, southern Jiangxi, Guangxi, Guangdong and Fujian provinces, with a total area of about 550,000 km^2. This metallogenic province is well known in the world for its rich tungsten and tin resources. In the past 40-odd years, a vast amount of mineral exploration activities and studies of the geology of mineral deposits have been carried out and great achievements obtained in the province. This paper is focused on a discussion about the deep tectonic processes in the orogenic belt during the Mesozoic and their contribution to the superaccumulation of metals. Tectonically, this metallogenic province is composed of three units: (1) the marginal continental orogenic belt in the Southeastern Coast fold system in the Yanshanian; (2) the intercontinental orogenic belt in the collision suture belt between the Yangtze and Cathaysian plates mainly in the Caledonian; and (3) the intracontinental orogenic belt induced by subduction of the ocean crust and delimination of the mantle lithosphere in the Yanshanian. It is suggested that superaccumulation of metals in this metallogenic province was caused by the existence of mantle rooted tectonics at the depth based on comprehensive studies of geophysical information of seismic, geothermal and magnetotelluric surveys in Nanling and its adjacent areas. The Xihuashan wolframite quartz vein deposit, the Shizhuyuan W, Sn, Mo, Bi greisen-skarn deposit and the Dachang tin-polymetallic deposit are three typical examples of the deep tectonic processes. However, this kind of deep tectonic processes only act as the "engine" of the superaccumulation of metals, which means that they should have to correspond with the super-crust ore-controlling pattern of "lines-rows-clusters" (L-R-C). This recognization is expected to play an important role in assessment of mineral resources in this province.

Key words: deep tectonic process, superaccumulation of metals, Nanling, China

1 Tectonic Setting

The Nanling metallongenetic province spans 3 tectonic units; from west to east, they are the Yangtze plate (YZP), Cathaysian plate (CYP) and Southeastern Coast fold system (SECFS) (Fig. 1) (Chen et al., 1989).

1.1 Yangtze plate

The Yangtze plate was built up in the stable Proterozoic and is believed to have been consolidated during the Jinning orogeny about 1000 Ma ago (Yang et al., 1986). The basement of the Yangtze plate is known to be late Archaean in age based on the zircon U-Pb age of about 2.8 Ga for granitic gneiss (Zheng et al., 1991). The Mesoproterozoic and Neoproterozoic are widely distributed in the Yangtze plate. Both of them consist mainly of low-grade metamorphic clastic sediments intercalated with minor amounts of volcanic rocks. The age of the so-called Banxi Group (Fig. 1) is the most controversial. However, two Sm-Nd dating results (935±10 Ma and 1034±24 Ma) of ophiolite in the Banxi Group have been obtained recently (Chen et al., 1991). Additionally, Palaeozoic and Mesozoic magmatism was relatively well developed in the Yangtze plate and closely associated with mineralization.

1.2 Cathaysian plate

The Cathaysian plate lies to the south of the Yangtze plate and is separated by the Jiangshan-Shaoxing-Pingxiang-Yushan deep fault as a suture zone (Fig. 1, boundary No. 1). The Cathaysian plate

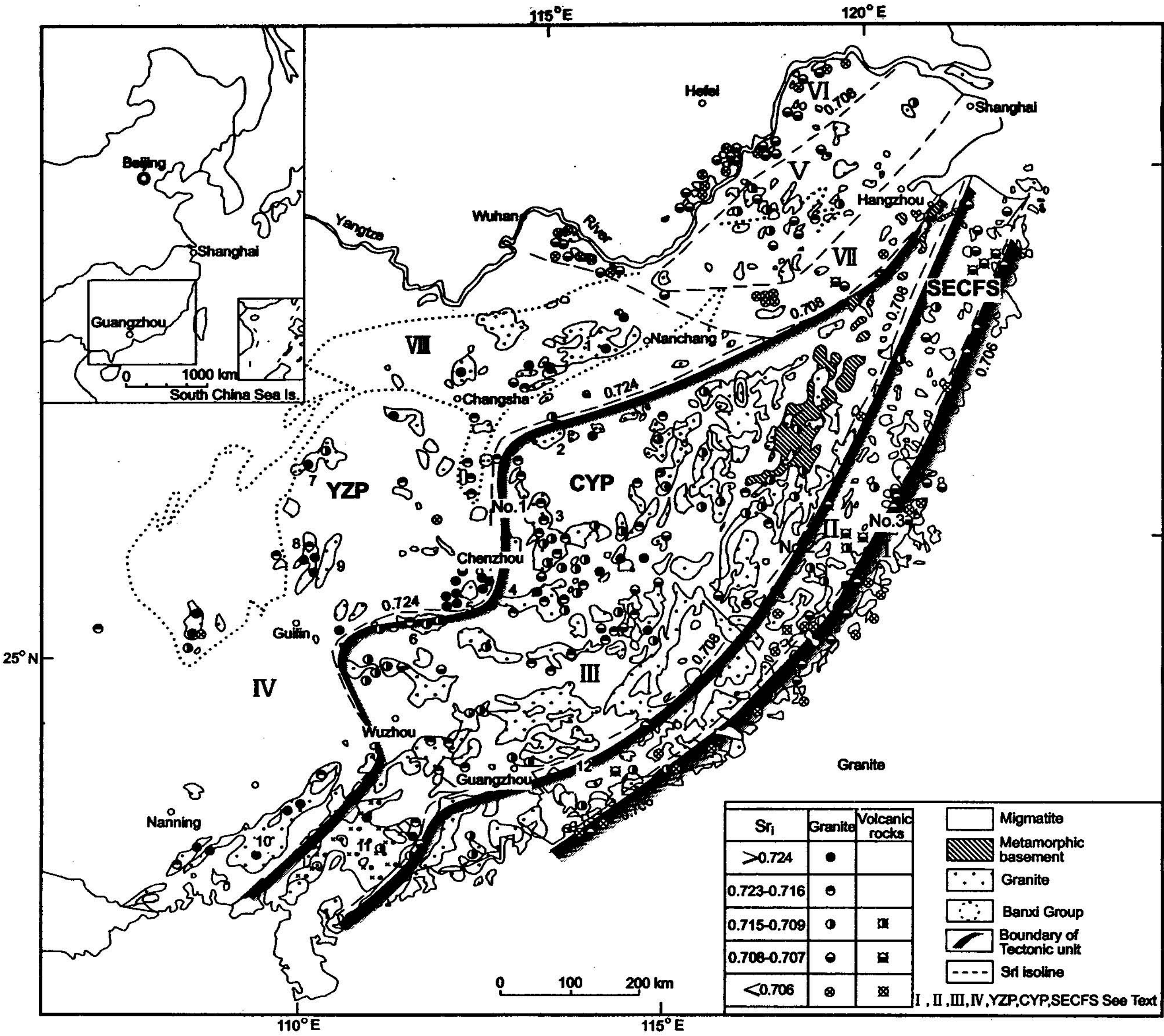

Fig. 1. Schematic map of tectonic units and types of granitoids in the Nanling metallogenic province.

consists of a Precambrian basement and covers of Sinian to Mesozoic sedimentary and volcanic rocks. A possible exstence of the Archaean basement in Cathaysia has been suggested based on a late Archaean age of 2.5 Ga (Li et al., 1989) given by relict zircons from the basement. The lower part of the sedimentary cover (Sinian to lower Palaeozoic) is represented by a thick series of folded and slightly metamorphosed marine sediments. The upper Palaeozoic to Mesozoic sedimentary sequences are considered to be a thick accretionary wedge as the foreland of Cathaysia. The entire Cathaysian plate contains extensive records of Neoproterozoic to Mesozoic granitic intrusions. Of them, the late Mesozoic granitoids are especially associated with mineralization.

1.3 Southeastern Coast fold system

The Southeastern Coast fold system is situated to the southeast of the Cathyasian plate and bounded by the Zhenghe-Dapu deep fault (Fig. 1, boundary No. 2). It is characterized by development of mineralization related to Cretaceous volcanism and plutonism of the Zhejiang-Fujian-Guangdong coastal granite belt (ZFGCB) (Hong et al., 1998). Further

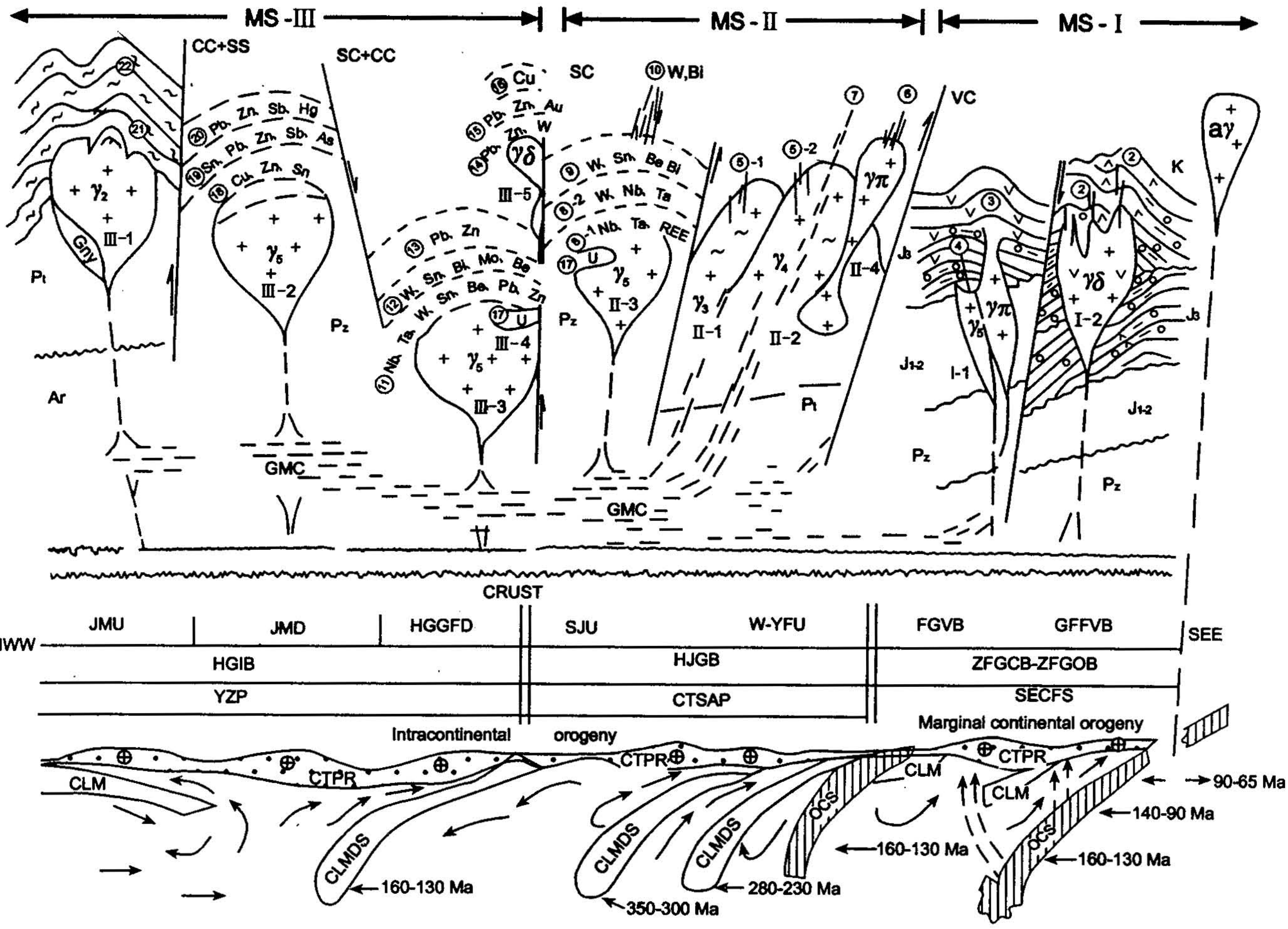

Fig. 2. Schematic diagram of minerogenetic series and ore-forming evolution through deep tectonic processes of intracontinental orogenic belt in the Nanling metallogenic province.

Ar–high-grade metamorphic rocks; Pt–low-medium-grade metamorphic rocks; Pz–carbonaceous sedimentary rocks; J_{1-2}–quartzitic sandstone and tuffaceous phyllite; J_1–dacitic rhyolite and tuffaceous sandstone; K–tuffaceous sandy shale; Gnγ–gneissic granite; γ–biotite (muscovite); granite or Al-rich monzogranite or Li-albite granite; γ_2–Sipunian granite; γ_3–Caledonian granite; γ_4–Variscan granite; γ_5–Yanshanian granite; γδ–granodiorite; γπ–granoporphyrite; αγ–alkaline granite; MS-I, II and III–minerogenic series; I-1, I-2, II-1, II-2, II-3, II-4, III-1, III-2, III-3, III-4 and III-5–metallogenic sub-series; CC, SC and VC–carbonite, silicate and volcanic country rocks, respectively; (1) (=①, the same below) volcanogenic vein type of Au and porphyry Cu deposit (Zijinshan); (2) epithermal replacement-filling type of Ag-Pb-Zn-Au deposit (Yinkeng, Wubu); (3) volcanogenic type of Sn deposit (Changpu); (4) albitization granite type of Nb-Ta deposits (Boluo); (5)–1 and 2 pegmatite type of Nb-Ta deposits (Nanping); (6) porphyry Sn (Yinyan) deposit; (7) shear zone alteration type of Au deposit (Hetai); (8)–1 and 2-albitization granite type of W-Nb-Ta-REE deposit (Dajishan); (9) greisen-skarn type of W-Sn-Bi-Mo-Be deposit (Yaogangxian); (10) hypothermal wolframite quartz vein type deposit (Xihuashan); (11) alteration granite-skarn-hydrothermal replacement type of Nb-Ta-W-Sn-Be-Pb-Zn deposit (Xianghualing); (12) greisen-skarn type of W-Sn-Mo-Bi-Be deposit (Shizhuyuan); (13) hydrothermal replacement type of Pb-Zn-Ag deposit (Dongpo); (14) skarn type of Pb-Zn-W deposit (Huangshaping); (15) skarn type of Pb-Zn-Au deposit (Shuikoushan); (16) hydrothermel replacement type of Cu deposit (Tongshan); (17) alteration granite type of U deposit (212); (18) skarn type of Cu-Zn (Sn) deposit (Lamo); (19) hydrothermal cassiterite sulphide deposit (Dachang); (20) hydrothermal replacement type Pb-Zn-Hg deposit (Mangchang); (21) greisen type Sn-Cu deposit (Baotan); (22) hydrothermal replacement type of Sn-Cu-Zn deposit (Jiumao); CLM–continental lithosphere mantle; CLMDS–delamination slab of CLM; OCS–ocean crust subduction; CTPR–partial remelting of crust thickening; GMC–granitic magma chamber; JMU–Jiangnan Old Land uplift; JMD–Jiangnan Old Land marginal depression; HGGFD–Hunan-Guangxi-Guangdong fault-bounded depression; SJU–southern Jiangxi uplift; W-YFU–Wuyi-Yunkai faulted uplift; FGVB–Fujian-Jiangxi volcanic basin; GFFV–Guangdong-Fujian faulted volcanic basin; YZP–Yangtze plate and foreland; CTSAP–Cathaysian plate and foreland; SECFS–Southeastern Coast fold system; ZFGCB-ZFGOB, HJGB and HGIB see text; arrow with age: collision-subduction episode.

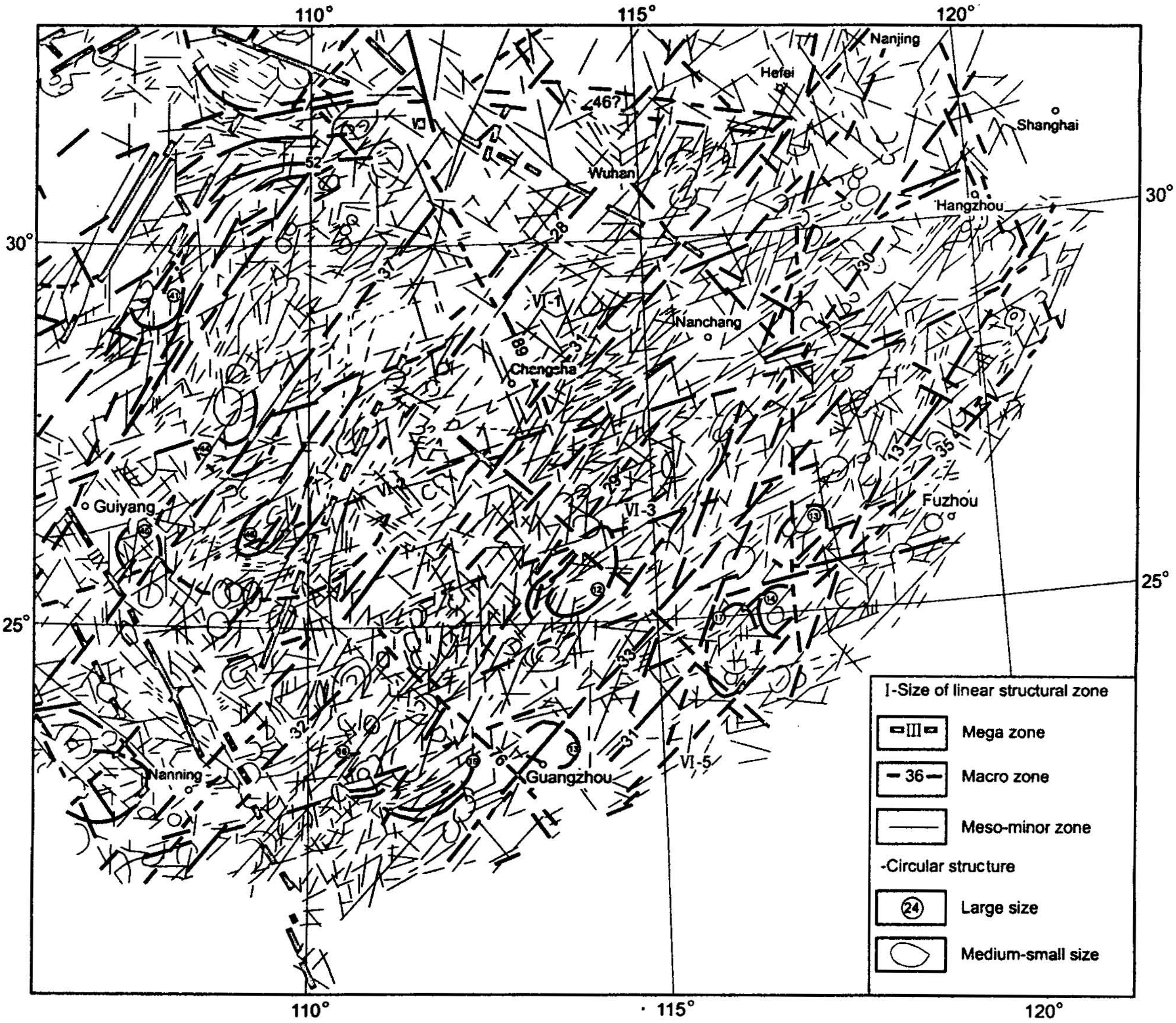

Fig. 3. Schematic map of linear and circular structures in the Nanling region.

more, the Zhejiang-Fujian-Guangdong coastal granite belt lies to the southeast of the ZFGCB, separated by the Changle-Nan'ao deep fault zone (Fig. 1, boundary No. 3) (Chen et al., 1998), and is characterized by relatively weak mineralization.

1.4 Tectonic evolution

Three stages of crustal development can be recognized based on the tectonic features mentioned above, i.e. cratonization of the Yangtze plate and Cathaysian plate in the Precambrian; intercontinental collision orogeny of the Yangtze plate and Cathaysian plate in the Caledonian resulting from crustal consumption and convergence; and intracontinental orogeny and activation of the Nanling region caused by subduction of the Pacific oceanic crust beneath the continental crust in the late Mesozoic, in the form of accretional crustal convergence and consumption. Accordingly, the Nanling metallo-genic province is tectonically manifested by the stable Precambrian basement resulting from cratonization, the Caledonian fold belt formed by intercontinental orogeny and the

Yanshanian continental mobilization caused by intracontinental orogeny. All of the three tectonic events belong to important transformations of regional tectonic evolution through the geological history (conceptional model in Fig. 2) (Pei and Hong, 1995).

1.5 Ore-controlling pattern

Based on the map of the linear and circular structures of this region (Fig. 3), the diversity and complexity of structure forms can be recognized (Yu et al., 1989). In the Mesozoic, regional E-W- and N-S-striking fault structures joined together and were superimposed by regional NE- and NW-striking fault structures, forming a structural pattern of a combination of E-W- and N-S-striking rows, NE- or NW-striking lines and intersection points of lines and rows, which is called the "L-R-C" ore-controlling model (Pei et al, 1995). Under exceptional conditions, some clusters may coincide with circular structure(s) to become a best ore-controlling factor on the supercrust. However, among such widely distributed patterns, only those corresponding to deep tectonic processes and combined with the vertex structures at the intersection points are possible to control the superaccumulation of metals.

2 Geophysical evidence

Deep tectonic processes are revealed through a synthetic analysis of geophysical data including those of seismic, geothermal and magnetotelluric surveys.

2.1 Seismic and geothermal surveys

The crust of Nanling and its adjacent region is about 29–33 km in thickness (Fig. 4) (Zhang, 1988; Zhu, 1986); that of the coastal areas (ZFGOB and ZFGCB) is relatively thin, about 29 km, and gradually changes to 33 km in the intracontinental area

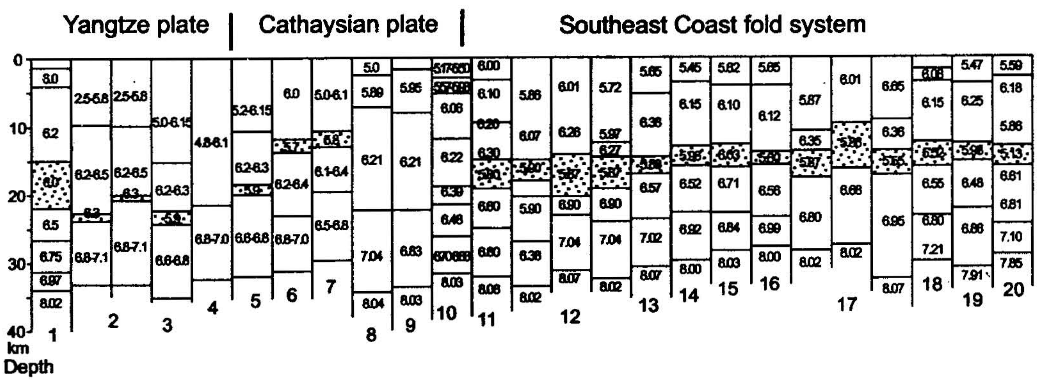

Fig. 4. Crustal structures in Yangtze-Cathaysia-Southeast coast of China (Vp: km/s).
8 and 9 after Zhu Jieshou, 1996; 1 and 10 after Jiangxi Geophysical Survey Group, 1990; 2–7 after Liu Guodong, 1994; 12–20 after Liao Qilin et al., 1988.

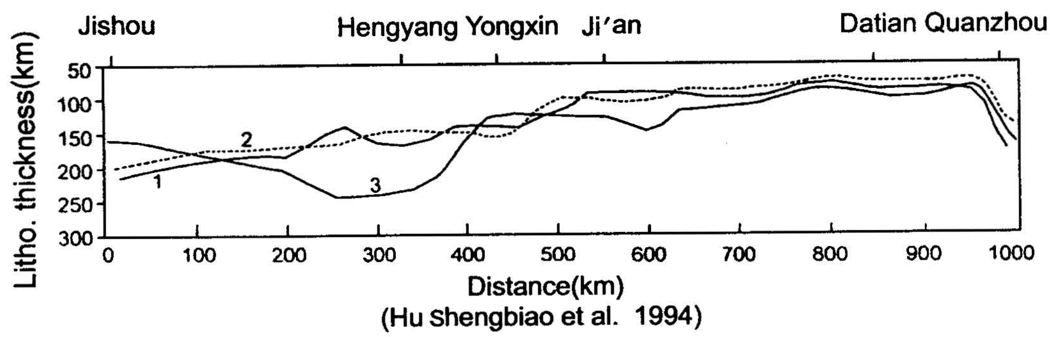

Fig. 5. Thickness of lithosphere in geothermal sections from Quanzhou of Fujian Province and Jishou of Hunan Province.
1. Result from temperature; 2. result from thermal field; 3. result from MT; after Hu Shengbiao et al., 1994.

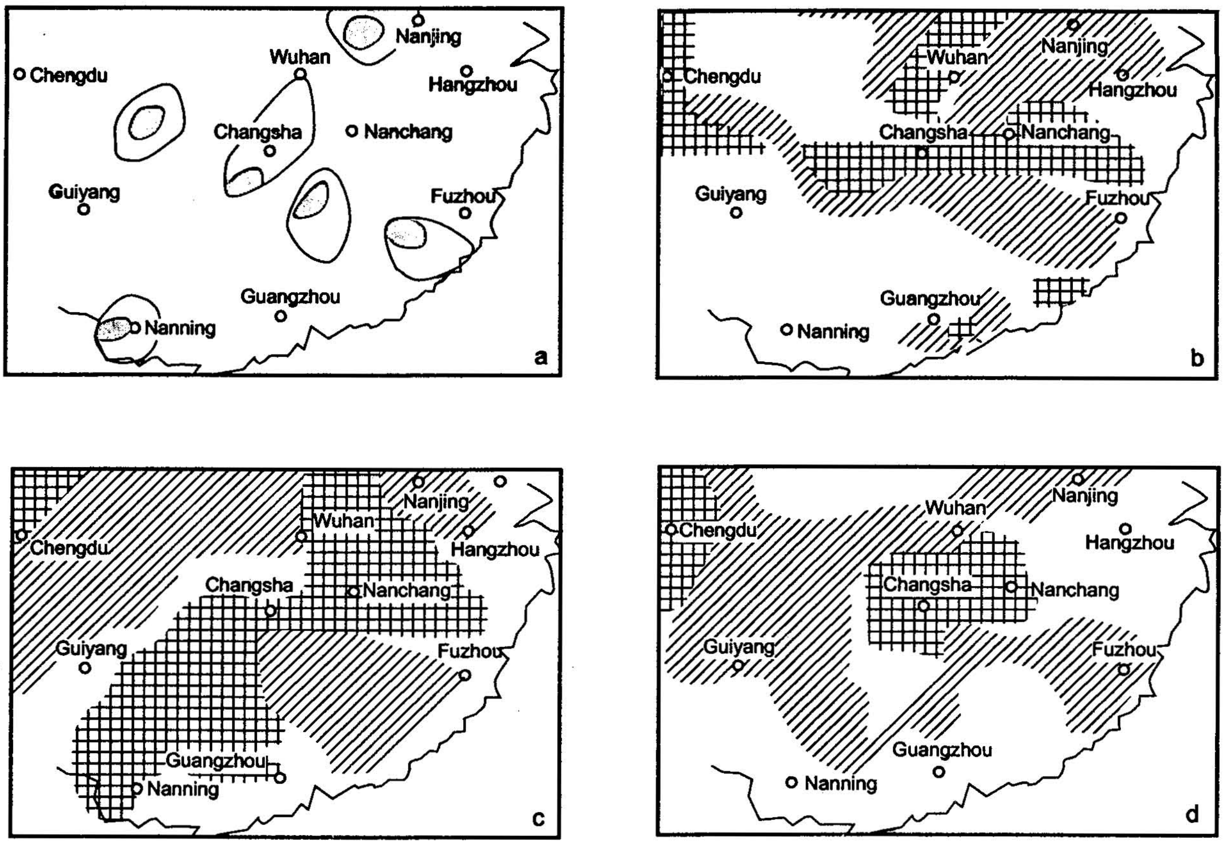

Fig. 6. Distribution of resistivities (MT) in Nanling and its adjacent areas.

a. The low-resistivity areas at depths <15 km (shadow) and depths <20 km (circle); b. the low-resistivity areas (oblique lines) and the high-resistivity areas (checkers) at the depth of 30 km; c. the low-resistivity areas (oblique lines) and the high-resistivity areas (checkers) at the depth of 90 km; d. the low-resistivity areas (oblique lines) and the high-resistivity areas (checkers) at the depth of 150 km.

(HJGB and HGIB) characterized by occurrence of a mountain root. The thicknesses of the upper crust in the coastal area are 8–10 km, with the velocity (*Vp*) changing from 5.0 km/s to 6.20 km/s; the middle crust is 10 km in thickness, with *Vp* betweem 6.20 km/s and 6.6 km/s; the lower crust is 12 km thick, with *Vp* from 6.60 km/s to 7.07 km/s. There is a low velocity zone with a *Vp* of 6.38 km/s on the boundary between the lower crust and the upper mantle (Fig. 4), implying that some remelting magmatic materials are distributed on the boundary, presumably caused by subduction of the Pacific plate underneath the Cathaysian plate. Additionally, in the coastal area near the Taiwan Straits, there is an anomalous zone in the upper mantle, with *Pn* changing from 7.90 km/s to 7.95 km/s, which coincides with an active zone in the crust. Therefore, the coastal area may produce a transitional characteristic of marginal continental structure from an oceanic crust toward the continental crust.

The thickness of the upper crust in the intracontinental areas (HJGB and HGIB) of this region is 10 km, with *Vp* varying between 6.00 km/s and 6.20 km/s; the middle crust is 10 km in thickness, with *Vp*= 5.80 km/s at the lower part; the lower crust is 13 km in thickness, *Vp*=6.80 km/s. It may be suggested that low *Vp* zones (5.55–6.03 km/s) are discontinually distributed in the middle crust like a pumicite, which may be a reflection of the heterogeneity of material between the curst and the upper mantle (Peng, 1996). The distribution pattern of seismic velocities in the intracontinental areas (the Yangtze plate and Cathaysian plate) is obviously different from that in the coastal areas (the Southeastern Coast fold system). A reasonable explana-

Table 1 Isotopic characteristics for granitoids of the Nanling region (after Pei and Hong, 1995; Hong and Zhang, 1998)

Granitoid belt	ZFGOB	ZFGCB	HJGB	HGIB
Sri	>0.706	0.706–0.708	0.708–0.724	>0. 724
$\delta^{18}O$(‰)	5–9	7–9	9–12	10–13
ε Nd(T)	-1.7– -5.3	-3.7– -7.4	-6– -12	-7– -14
ΣTDM	<1.2Ga	1.2–1.4Ga	>1.8Ga	8–2. 4Ga
Age of basement	1.5–1.7Ga	1.6–2.0–Ga	1.8–2.0Ga	1. 7–1. 8Ga
Granite type	A	I	S	High-Al S
Mineralization	· weak	Cu-Au-Pb-Zn	W(Sn)-Nb-Ta-Pb-Zn-U	Sn(W)-Pb-Zn-Hg-Sb

Table 2 Minerogenic series (MS) and their sub-series (SS) in the Nanling metallogenic province (simplified)

MS-I: Cu(Au)-Mo-Pb-Zn(Ag)-W(Sn)-Nb-Ta deposits related to I- and A-type granite activity of shallow depths in the ZFGOB and ZFGCB granite belt of the Southeastern Coast fold system.

SSI-1: Sn and Nb-Ta deposits associated with valcano-intrusive rocks (γπ) in a volcanic basin [Fig. 2, MSI-1, (3) and (4)].

SSI-2: Cu-Au and Pb-Zn(Ag) deposits associated with shallow intrusive (sub-volcanic) rocks (γδ) in a faulted volcanic basin [Fig. 2, SSI-1, (1) and (2)].

MS-II: W (Sn)-Mo-Bi-Be-U-Nb-Ta-Au-REE deposits related to S-type granite activity of medium to shallow depths in the East of HJGB belt of the Cathaysian plate.

SSII-1: Au-Nb-Ta-REE-Sn deposits associated with migmatitic granite with pegmatite in the uplift zone [Fig. 2, SSII-1, (5)-1, (5)-2 and (6)).

SSII-2: W (Sn)-Mo-Pb-Zn deposits associated with porphyry granite in the top of faulted uplift zone [Fig. 2, SSII-2, (7)].

SSII-3: W (Sn)-Be-Mo-Bi-Nb-Ta-REE-U deposits associated with biotite granite in a depression zone [Fig. 2, SSII-3, (8), (9) and (10)].

MS-III: Sn-W-Mo-Bi-Be-Pb-Zn (Ag)-Sb-Hg-As-Nb-Ta-Au-U deposits related to high-Al S-type granite activity of medium to deep depths in the HGIB granite belt of the Yangtze plate.

SSIII-1: Sn-Cu-Pb-Zn deposits associated with gneissic granite in the marginal uplift of ancient basement zone [Fig. 2, MS-III, (21) and (22)].

SSIII-2: Cu-Zn (Sn)-Sn-Pb-Zn-Ag-Hg-Sb-As deposits associated with biotite granite and hosted in Devonian sediments in a marginal depression [Fig. 2, SSIII-2, (18), (19) and (20)].

SSIII-3: W-Sn-Bi-Mo-Be-Nb-Ta deposits associated with biotite (muscovite) granite in a faulted depression [Fig. 2, SSIII-4, (11), (12) and (13)].

SSIII-5: Pb-Zn-W-Cu-Ag deposits associated with dioritic granite in a faulted uplift [Fig. 2, SSIII-4, (14), (15) and (16)].

tion for such a distribution pattern may be the delamination and going up of remelt to the supercrust caused by lithospheric thickening during the intracontinental orogeny.

Based on the deduction out of the geothermal data, the thickness of the lithosphere is about 70 km in coastal areas, and changes to 240 km in the intracontinental areas, where a mountain root probably exists, which suggests that there are at least two active zones along both sides of the deep mountain root at the depth of the boundary areas between the Yangtze plate and the Cathaysian plate (Fig. 5) (Hu et al., 1994). On the surface of the crust, the Ganjiang deep fault and the Wuchuan-Sihui deep fault roughly correspond to the two active zones. So it is inferred that those two active zones extending deep from the surface were the most important structures for the deep tectonic processes of metallogeny in the Nanling area.

2.2 Magnetotelluric survey

According to the results of the magnetotelluric survey (Fig. 6), high-resistivity areas at depths of 90 km and 150 km are surrounded by low-resistivity areas. At the depth of 30 km, corresponding to the crust-mantle boundary, the high-resistivity areas appear as E-W-direction zones and separate the low-resistivity areas into relatively small areas (Fig. 6b). The low-resistivity areas at the depth of 15 km appear as random irregular circles (Fig. 6a) (Li, 1996). Such distribution patterns suggest a possibility of upraising magmatism.

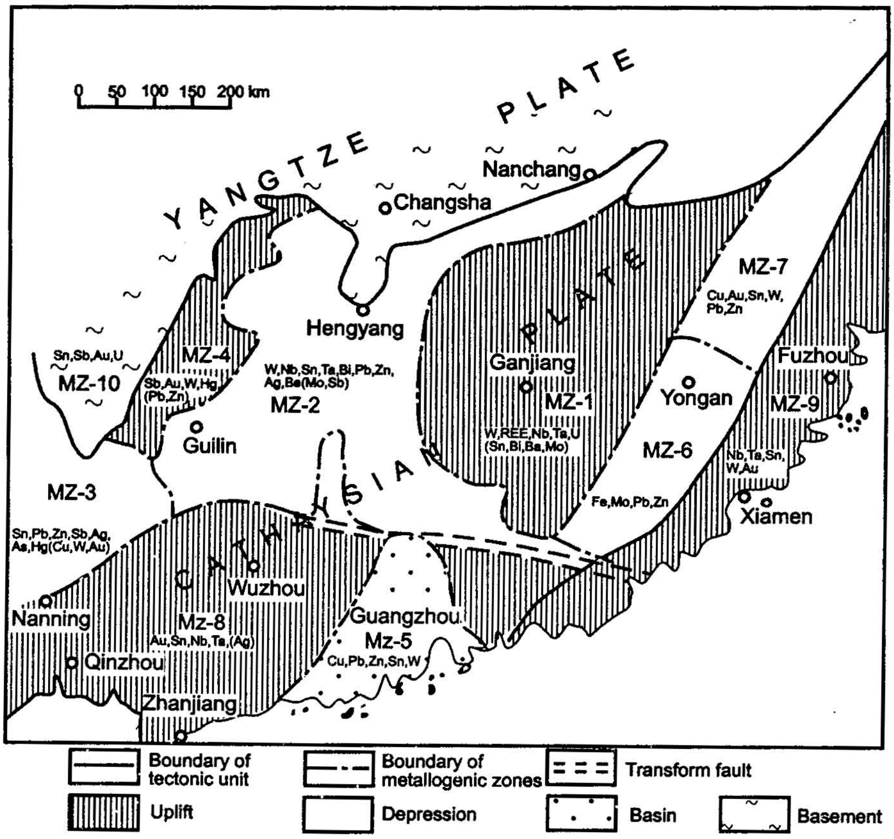

Fig. 7. Schematic map showing metallogenic zones of the Nanling metallogenic province. MZ-1: W, REE Nb, Ta, U (Sn, Bi, Be, Mo) metallogenic zone in the southern Jiangxi-northern Guangdong uplift; MZ-2: W, Nb, Sn, Ta, Bi, Pb, Zn Ag, Be (Mo, Sb) metallogenic zone in the Hunan-Guangdong-Guangxi depression; MZ-3: Sn, Pb, Zn, Sb, Ag, As, Hg (Cu, W, Au) metallogenic zone in the northern Guangxi Hechi-Nandan depression; MZ-4: Sb, Au, W, Hg (Pb, Zn) metallogenic zone in the western Hunan-northeastern Guangxi uplift; MZ-5: Cu, Pb, Zn, Sn, W metallogenic zone in the eastern Guangdong Yangchun basin; MZ-6: Fe, Mo, Pb, Zn metallogenic zone in the southwestern Fujian depression; MZ-7: Cu, Au, Sn, W, Pb, Zn metallogenic zone in the Fujian-Guangdong volcanic fault-bounded depression; MZ-8: Au, Sn, Nb, Ta (Ag) metallogenic zone in the Yunkai uplift; MZ-9: Nb, Ta (Sn, W, Au) metallogenic zone in the northwestern Fujian uplift; MZ-10: Sn, Sb, Au, U metallogenic zone in the northern Guangxi ancient basement (marginal craton).

3 Metallogeny Associated with Magmatism of Granitoids

3.1 Isotopic zoning of granitoids

According to the study of available initial strontium isotope ratios (Sr_i) for more than 300 granitoid plutons, combined with oxygen and neodymium isotopes, four isotopic value zones of granitoids have been recognized (Table 1 and Fig. 1) (Pei and Hong, 1995). These four zones are divided by three Sr_i isolines: 0.706, 0.708 and 0.724, respectively. The isotopic characteristics of each zone are as follows:

(1) The Zhejiang-Fujian-Guangdong onshore granitoid belt (ZFGOB) east of the Sr_i isoline of 0.706 is characterized by predominance of Cretaceous A-type alkaline granitoids.

(2) The Zhejiang-Fujian-Guangdong coastal granitoid belt (ZFGCB) between the Sr_i isolines of 0.706 and 0.708 is characterized by predominance of Jurassic and Cretaceous I-type monzogranites and syenogranites.

(3) The Hunan-Jiangxi-Guangdong transitional granitoid belt (HJGB) between the Sr_i isolines of 0.708 and 0.724 is dominated by early Palaeozoic to Cretaceous S-type monzogranites, syenogranites and alkali feldspar granites.

(4) The Hunan-Guangxi intracontinental grani-toid belt (HGIB) west of the Sr_i isoline of 0.724 is characterized by high-Al S-type monzogranites from the early Palaeozoic to Cretaceous, including cordierite monzogranite from the Permian to Trias sic (Hong et al., 1998).

The zoning pattern of isotope values of granitoids may have resulted from different tectono-magmatism of deep tectonic processes. Such diversities of tectono-magmatism lead to diversities of metallogeny in the whole Nanling region. The mineralization features of the zones differ from each other as listed in Table 1.

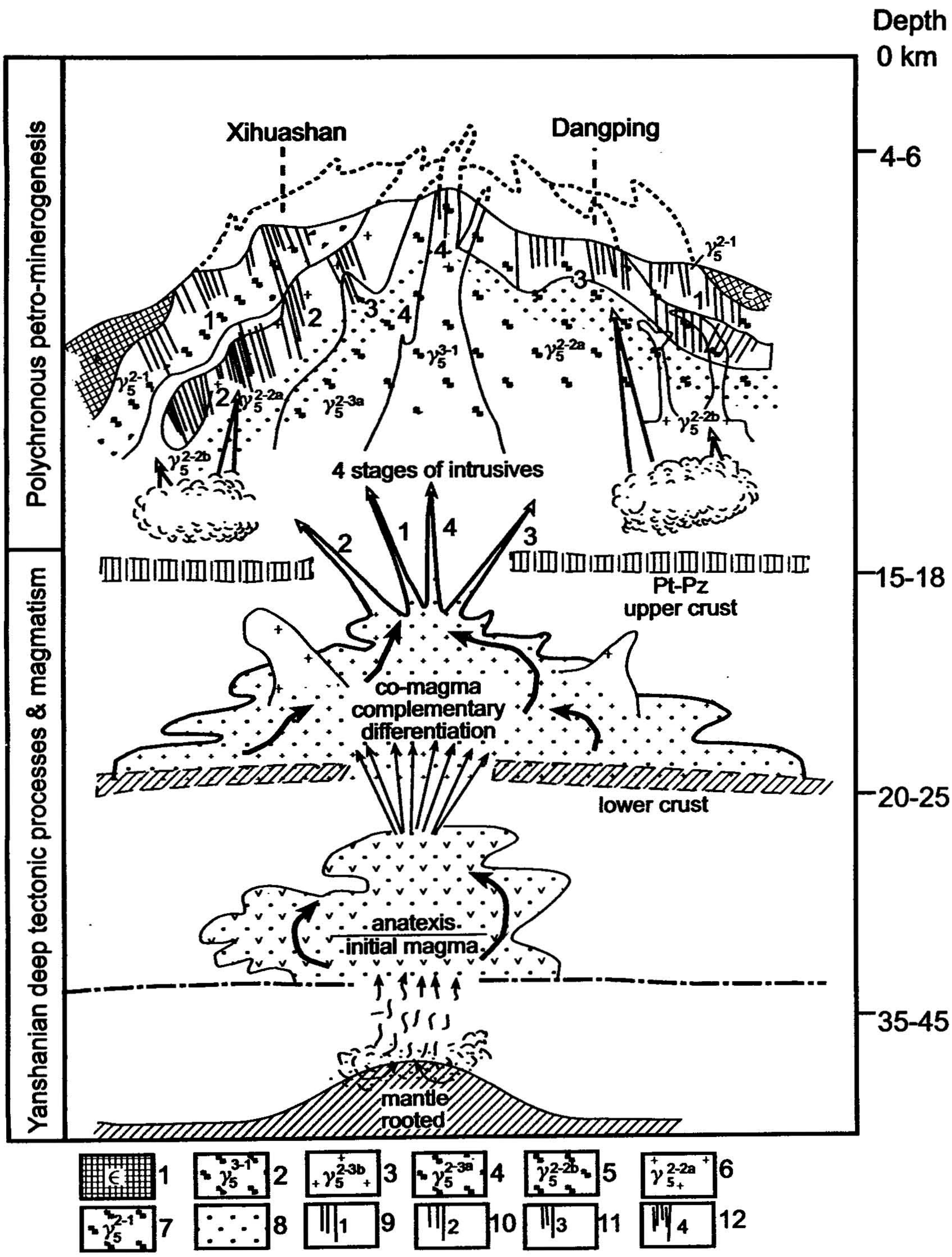

Fig. 8. Deep tectonic processes and polychronous petro-minerogenesis of magmatism in the Xihuashan tungsten ore field.
1. Precambrian metamorphic rocks; 2. Late Yanshanian Ist-stage fine-grained granite (γ_5^{3-1}); 3. Early Yanshanian 3rd-stage fine-grained bi-mica granite (γ_5^{2-3a}); 4. Early Yanshanian 3rd-stage porphyric medium-grained biotite granite (γ_5^{2-3a}); 5. Early Yanshanian 2nd-stage porphyric fine-grained biotite granite (γ_5^{2-2b}); 6. Early Yanshanian 2nd-stage medium-grained biotite granite (γ_5^{2-2a}); 7. Early Yanshanian 1st-stage porphyric medium-grained biotite granite (γ_5^{2-1}); 8. K-feldspar alteration; 9. 1st-stage W and Mo ore vein; 10. 2nd-stage W (Mo, Bi) ore vein; 11. 3rd-stage W, Be and Mo ore vein; 12. 4th-stage W and Sn ore vein.

3.2 Metallogenic zoning

Based on the tectonic settings, geophysical data and isotopic zoning of granitoids discussed above, 10 metallogenic zones can be divided as follows (Fig. 7) (Zhang et al., 1987).

Different metallogenic zones are controlled by different tectonics. In general, zones of lithophile elements are mainly controlled by uplift areas in ancient basement, while zones of chalcophylic elements are mainly controlled by depressions and faulted basins.

3.3 Minerogenic series

A minerogenic series (MS) is an assemblage of several ore types that are genetically related to each other, formed in different parts of a certain geotectonic unit in a definite geological epoch and associated with some definite geological processes (Cheng et al. 1998). Three types of minerogenic series (MS) and eleven sub-series (SS) in the Nanling metallogenic province (Table 2, Fig. 2) are grouped, through synthetical analyses for tectonics, geophysics and geochemistry combining the metallogenic zones based on the concept of minerogenic series.

Minerogenic series I is distributed in the metallogenic zones of MZ-5, MZ-6, MZ-7 and MZ-9 in the Southeastern Coast fold system (Fig. 2, MS-I). The ore-forming materials of this series may have mainly been derived from the partially remelted subducted Pacific Ocean crust. However, the remelting depths of related granitoids are different between SSI-1 and SSI-2. The remelting depth of SSI-1 in the west is deeper than that of SSI-2 in the east, and the ore-forming materials of SSI-1 are more heavily contaminated by the crust than those of SSI-2. So the ore-forming elements of SSI-1 are mainly lithophile and different from those of SSI-2, which are chalcophile-dominant.

Minerogenic series II is distributed in the metallogenic zones of MZ-1, MZ-2, and MZ-8 in the Cathay-sian plate and its foreland. In the deep part, two episodic delaminations of continental lithospheric mantle might have happened in the Caledonian and Variscan epochs, which led to intensive dynamic thermormetamorphsim, forming autochthonous magma-tic granite associated with mineralization of SSII-1 and para-autochthonous granite associated with mineralization of SSII-2 and SSII-4. In the Mesozoic, an intensive magmatism occurred on the metamorphosed basement, and SSII-3 and SSII-4 were formed by a superaccumulation of metals. The typical examples are the Xihuashan and Dajishan world-class deposits [Fig. 2, MS-II, (8) (9) and (11)], which resulted from co-magmatic complementary differentiation (Pei, 1996) through deep tectonic pro-cesses during Mesozoic intracontinental orogeny. Deep tectonic processes may be induced by the mantle-rooted magmatism for superaccumulation of metals (Fig. 8). As the chemical composition of multistage intrusions shows oscillation curves caused by the complementary effect between partial and total compositions of the co-magma in the process of differnentiation (Table 3; Fig. 9), the co-magma complementary differentiation is different from the pulse magmatic differentiation.

Minerogenic series III is distributed in the metallogenic zones of MZ-3, MZ-4 and MZ-10 in the Yangtze plate and its marginal depression. The Yangtze plate collided with the Cathaysian plate in the Palaeozoic-Mesozoic and was strongly affected by the Mesozoic intracontinental orogenic belt. There were extensive crust thickening and well-developed delamination of the continental lithosphere. In addition, a "mantle-rooted" structure

Table 3 Isotopic ages and chemical compositions of the multistage intrusives in the Xihuashan ore field

Rock bodies	Isotopic age (Ma)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss	Total
γ_5^{3-1}	106	76.37	0.04	12.09	0.18	1.22	0.11	0.20	0.75	3.73	4.46	0.05	0.66	99.86
γ_5^{2-3}	145-139	75.47	0.05	1.69	0.34	1.25	0.10	0.27	0.68	3.83	4.52	0.07	0.65	99.92
γ_5^{2-2}	156-149	75.84	0.03	12.64	0.22	1.18	0.11	0.17	0.57	4.16	4.29	0.05	0.62	99.87
γ_5^{2-1}	163	74.61	0.10	12.60	0.35	1.73	0.07	0.45	1.19	3.39	4.71	0.05	0.70	100.04

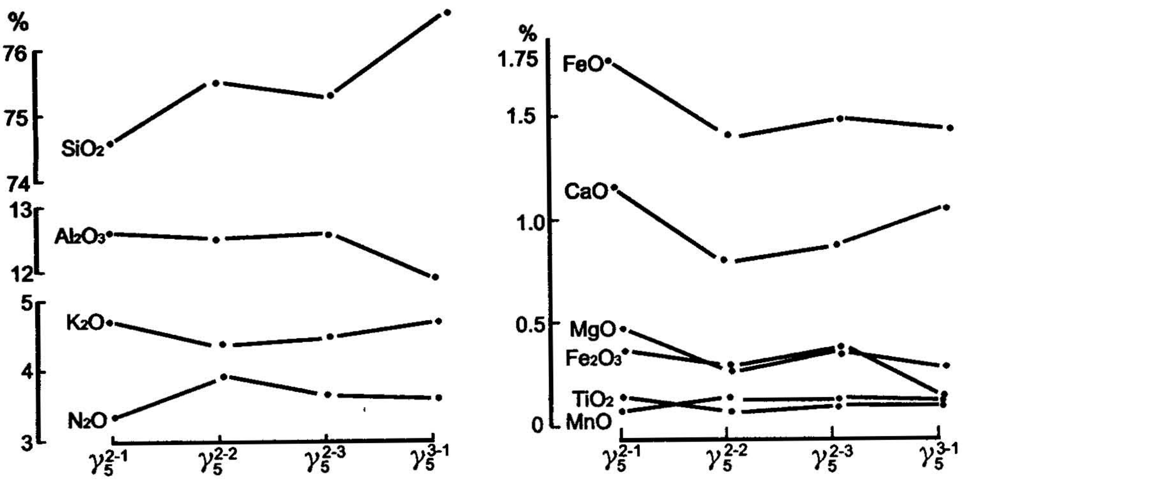

Fig. 9. Oscillation variable curves showing complementary differentiation of compositions of multistage intrusives in the Xihuashan ore field.

probably appeared at depth. On this basis, SSIII-1, SSIII-2 and SSIII-3 constitute a complete metallogenic spectrum of ore-forming lithophile elements and exhibit a series of deposit types (magmatic deuteric alteration, pneumatogenic, pyrometasomatic, hydrothermal replacement and fissure filling) (Fig. 2, MS-III). Among them, the world-class supergiant Shizhuyuan and Dachang deposits are formed in SSIII-3 and SSIII-2. The former is a W-Sn-Mo-Bi-Be deposit associated with HHP and BEBLIF granites subjected to super-strong skarn-greisen alteration [Fig. 2, SSIII-3, (12)]; the latter is a cassiterite sulphide deposit associated with high-Al granite of the Mesozoic, which may have been derived from stratiform orebodies with carbonaceous sediments of the Devonian [Fig. 2, SSIII-2, (19)] (Pei, 1995). All of the ore-forming sources might have been provided by intercontinental to intracon-tinental orogenies on the basis of deep tectonic processes during the Proterozoic-Mesozoic.

4 Summary

Based on the tectonic settings, geophysical data and metallogenic features mentioned above, the authors summarize the deep tectonic processes and superaccumulation of metals in the Nanling metallogenic province as follows:

(1) Continental orogeny is generally divided into 3 types: the marginal continental, intercontinental and intracontinental. The orogenic belt of the Nanling metallogenic province consisted of the Western Pacific Rim active region in the Southeastern Coast folded system as the marginal continental orogenic belt in the Mesozoic and the collision suture belt in the Jiangshan-Shaoxing fault between the Yangtze and Cathaysian plates and their forelands as the intercontinental orogenic belt in the late Proterozoic to Devonian. After that, a large-scale intracontinental orogenic belt was formed by subdution of the oceanic crust and delamination caused by crust thickening in the Mesozoic and almost completely superimposed on the above two orogenic belts.

(2) Eight metallogenic zones and three minerogenic series (MS-I, MS-II, MS-III) have been divided in the Nanling metallogenic province, based on the tectonic settings and the concept of minerogenic series. The mineralization of MS-I is related to continental margin orogeny; and that of MS-III is related to intracontinental orogeny; MS-II is situated in the transitional belt between the two orogenic belts.

(3) The typical examples of superaccumulation of metals are the Xihuashan wolframite quartz-vein type deposit, the Dachang Sn-Pb-Zn-Sb cassiterite sulphide deposit and the Shizhuyuan W-Sn-Mo-Bi-Be greisen-skarn type deposit. The huge amount of metals in these deposits are provided by deep tectonic processes.

(4) Deep tectonic processes play the role of only

a metallogenic "engine" for the superaccumulation of metals in the Nanling metallogenic province, the "L-R-C" structural pattern must be coupled with the deep tectonic processes in order to form a supergiant ore deposit.

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