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The granites of south China and their metallogeny

The widespread granites of south China with their vast amounts of non-ferrous, rare, and rare earth metals, are well known around the world. By the use of data on initial strontium isotopic ratios of over 300 plutons, oxygen isotopes of more than 200 plutons and neodymium isotopes of more than 100 plutons, the granites of south China are divided into six belts. A model of their genesis is suggested on the basis of four important collision events. In the light of the different origins of the granite belts and the concept of minerogenic series, five minerogenic series and their sub-series are recognised. The importance of the minerogenic series for regional mineral assessment and the roles of multiperiod and multi-stage petro-minerogenic principles in the evaluation of superlarge deposits are stressed.

Temporal and spatial distribution and isotopic composition

The granites of south China were emplaced in the Proterozoic (Sipunian), the early Palaeozoic (Caledonian), the late Palaeozoic, and from the earliest Mesozoic (Variscan–Indosinian) to the Jurassic–Cretaceous (Yanshanian). In space, they extend from the north-west to the south-east. The early Palaeozoic, and particularly the Jurassic–Cretaceous, were peaks of granitic magmatism. The distribution of the available initial strontium isotope ratio Sr_i of more than 300 granite plutons defines two Sr_i isolines: 0.708 and 0.724 (Figure 1). On the basis of the Sr_i isolines plus data on oxygen isotopes for more than 200 granite plutons, and neodymium isotopes for more than 100 granite plutons, the granites of south China can be roughly divided into 6 belts which are different from each other in petrology, geochemistry and mineralisation (Figure 2 and Table 1).

The Zhejiang–Fujian–Guangdong coastal belt (ZFGB) is characterized by I-type granites except in the coastal region and on the

Figure 1 The distribution of Sr_i in the granites of south China.

Batholith names:

- 1 Jiuling
- 2 Wugongshan
- 3 Wangyangshan
- 4 Zhuguangshan
- 5 Qitianling
- 6 Jiuyishan
- 7 Baimashan
- 8 Miaoershan
- 9 Yeuchengling
- 10 Dayunshan
- 11 Yunkaidashan
- 12 Jiulianshan
- 13 Wuyishan

Table 1 Isotopic characteristics of the granites of south China.

Granite belt	ZFGB	HJGB	HGIB	AJB	MLYR	JZB
Sr_i	<0.708	0.708–0.724	>0.724	0.708–0.722	<0.708	<0.708
$\delta^{18}O$ ‰	7–9	9–12	10–13	6–11	8–10	8–9
$\epsilon Nd(T)$	>–6	–6––12	–7––14	>–7	<–10 (even to –17)	+0.7––1.9
T_{DM} (Ga)	<1.4	>1.8	1.8–2.4	1.4–1.5	1.6–2.0	0.697–1.085
Age of metamorphic basement (Ga)	Hexi Group, east Zhejiang, (1.6–2.06)	Mayuan Group, northern Fujian and Badu Group, western Zhejiang (1.8–2.0)	Sipun Group, northern Guangxi, (1.7–1.8); Lengjiaxi Group, western Hunan, (1.9)	Shuangqiaoshan Group, northern Jiangxi, (1.1–1.5); Shangxi Group, southern Anhui, (1.63–1.69)	Archaean basement, (3.0–3.3)	Shangxi Group, north-eastern Jiangxi, (0.817–0.916); Shangxi Formation, north-western Zhejiang, (0.806–0.894)
Granite type	I and A	S	High - Al S	I and S	I	I
			Sn, Nb, Ta	weak	Cu, Fe, Au	Cu, Au

Figure 2 The regional subdivisions of the granites of south China.

I Zhejiang–Fujian–Guangdong coastal belt (ZFGB)	V middle–lower Yangtze River belt (MLYR)
II Hunan–Jiangxi–Guangdong transitional belt (HJGB)	VI north-eastern Jiangxi–north-western Zhejiang belt (JZB)
III Hunan–Guangxi intracontinental belt (HGIB)	VII Jiangnan old land
IV Southern Anhui–southern Jiangsu belt (AJB)	

islands off the coast where there are A-type alkaline and subalkaline granites. Their Sm-Nd model ages (T_{DM}) are younger than those of the metamorphic rocks of the basement indicating that mantle components were added to the crustal source rocks of the granites. This is consistent with the relatively low Sr_i and $\delta^{18}O_{\text{‰}}$ and high ϵNd values.

The Hunan–Jiangxi–Guangdong transitional belt (HJGB) is dominated by S-type granites. Their T_{DM} are similar to the ages of the metamorphic rocks of basement, which suggests an important contribution of old continental materials to the source rocks of granites. The granites could have been produced by the partial melting of rocks similar to those of the basement. This model is also consistent with the Sr, O and Nd isotope study results.

The Hunan–Guangxi intracontinental belt (HGIB) is characterised by high-Al S-type granites, including cordierite granite. Although metamorphic rocks of the basement have not been discovered so far in this belt, the T_{DM} ages of the granites are basically consistent with those of the metamorphic rocks of the basement along the south-west edge of the Jiangnan old land. Considering the Sr, O and Nd isotopic compositions and the peraluminous nature of the granites, the source rocks of the granites in this belt should be of almost pure continental crust.

The granites of the southern Anhui–southern Jiangsu belt (AJB) can be subdivided into two kinds. The first is the late Proterozoic cordierite-bearing peraluminous granites which have Sr_i of 0.704 to 0.706, $\epsilon Nd(T)$ of -0.4 to -2.2 and $T_{DM} > 1.8$ Ga; the second is the Mesozoic I-type and S-type granites which have Sr_i of 0.710 to 0.723, $\epsilon Nd(T)$ of -5.1 to 7.2 and T_{DM} 1.4 to 1.5 Ga. For the first belt, it is noticed that the granites are not only temporally similar to ophiolites and associated spatially with them, but also have similar isotopic compositions (Zhou et al., 1989; Xing et al., 1992). The igneous materials from the ophiolites obviously originated in the upper mantle. The granites could be formed by rapid partial remelting of juvenile crustal materials with a similar mantle origin (Zhou and Wang, 1988). The T_{DM} values of the second (Mesozoic granites) are consistent with the ages of metamorphic rocks of the basement, and they have similar isotopic composition. All this indicates that the granites could have been formed by partial melting of metamorphic basement.

The middle–lower Yangtze River belt (MLYR) is characterised by Mesozoic I-type granodiorite. On the basis of Sr_i and $\epsilon Nd(T)$ data, it is suggested that this granodiorite may be the product of mixing between mantle and crust materials, the crustal end member having higher negative values of ϵNd (Chen et al., 1993), and could have formed from old continental rock with ages of 3.0–3.3 Ga on the Yangtze plate (Sun, 1994).

The north-eastern Jiangxi–north-western Zhejiang belt (JZB) is characterized by Mesozoic I-type granodiorites. Although their Sr_i and $\delta^{18}O_{\text{‰}}$ are similar to those of the ZFGB and MLYR, they have higher $\epsilon Nd(T)$ and a T_{DM} of 697–1085 Ma which are quite different from those of the latter two. The ophiolites of Zhangshudeng, north-eastern Jiangxi, have Sm-Nd isochron ages of 1034 ± 24 to 1154 ± 43 Ma, $\epsilon Nd(T)$ of +4.4 to +5.5 ± 1.2 (Chen et al., 1991; Zhou et al., 1991; Xing et al., 1992), and Sr_i of 0.7026 (Xu and Qiao, 1989). The Shangshu Group consists dominantly of intermediate–basic rocks with Rb-Sr ages of 817.6 ± 916 Ma. It is held that the granitic rocks could have formed by partial melting of mantle-derived materials similar to the Proterozoic ophiolites or basic volcanic rocks, and that the magma could have ascended to, and crystallised at, a higher crustal level too quickly to interact effectively with the surrounding crust.

Tectonic setting and genesis

As described above, the 0.708 line and 0.724 line are considered not only as geochemical boundaries, but also as important geological boundaries. The 0.708 line passing through Zhejiang, Fujian and Guangdong provinces may be a suture zone covered by Mesozoic

Table 2 Metallogenetic series (MS) and their sub-series (SS) in the granite belts of south China* (simplified).

MS I	Cu(Au)-Mo-Pb-Zn(Ag)-W(Sn), Nb, Ta deposits related to I- and A-type granite activity of shallow depth in the ZFGB belt. Sub-series: I-1 Sn and Nb-Ta. I-2 Porphyry Au-Cu and epithermal Ag-Pb-Zn-Au.
MS II	W-(Sn)-Mo-Bi-Be-U-Nb-Ta-Au-REE deposits related to S-type granite activity of medium to shallow depth in the HJGB belt. Sub-series: II-1 W-Nb-Ta-REE. II-2 Au. II-3 Porphyry Sn. II-4 W-Nb-Ta-REE, W-Sn-Mo-Bi-Be, U and wolframite.
MS III	Sn-W-Mo-Bi-Be-Pb-Zn(Cu)-Sb-Hg-As-Nb-Ta-Au-U deposits related to high-Al S-type granite activity of deep to medium depth in HGIB belt. Sub-series: III-1 Sn-Cu and Sn-Cu-Pb-Zn. III-2 Cu-Zn, Sn and Pb-Zn-Hg-Sb-As. III-3 Nb-Ta-W-Sn-Mo-Bi and Pb-Zn. III-4 U. III-5 Pb-Zn-W-Au-Cu.
MS IV	Fe-Cu(Pb,Zn)-S-Au deposits related to I-type granite activity of medium depth in the MLYR belt. Sub-series: IV-1 porphyry iron. IV-2 Fe-Cu-Au-S.
MS V	Cu-Mo-Au-Pb-Zn-Ag-(Nb-Ta-W) deposits related to I-type granite activity of medium depth in JZB belt. Sub-series: V-1 Cu-Mo-Au-Pb-Zn-Ag. V-2 Nb-Ta-W-Sn-Mo.

*Due to weak metallisation, the AJB granite belt has no MS.

magmatic rocks. The HJGB on the west side towards the suture zone belongs to the Cathaysia plate and its foreland, and the ZFGB on the east side belongs to the south-east coast of the China plate. The 0.724 line may also be a suture zone covered by Palaeozoic sedimentary rocks between the Yangtze plate (its south-east edge is called 'Jiangnan old land') and the Cathaysia plate. Thus, the HGIB may be the foreland belt of the Yangtze plate. The 0.708 line along the middle–lower Yangtze valley may be a tensional depression belt formed after the collision–amalgamation between the Yangtze plate and north China plate during the Triassic. A model of the genesis of granites in south China is suggested on the basis of four important collision events as follows.

- 1 Collision between the Yangtze plate and Cathaysia plate along the Jiangshan–Shaoxing fault and the 0.724 line at the beginning of the late Proterozoic resulted in a united palaeo-south China plate and produced the late Proterozoic granites. Splitting took place roughly along the collision belt at the end of the late Proterozoic, forming the Caledonian intracontinental miogeosyncline on a foundation of continental crust.
- 2 The south-east coast of the China plate was separated from a more southerly continent, South-east Asia, at the end of the early Palaeozoic by seafloor spreading, which created a palaeo-south China ocean (Hsu et al., 1990). It drifted north-westwards and collided with the palaeo-south China plate along the 0.708 line, resulting in a large scale sinistral NE–SW fault system and detachment fault system at depth. The sinistral shear along the detachment may have resulted in partial remelting of the crust to form the Caledonian granites in the Wuyi and Yunkai Mountains. At one time, the more north-westerly Caledonian miogeosyncline was folded and uplifted by the collision, causing thick-

Figure 3 Diagrammatic model of metallogenic series (MS) of the Zhejiang, Fujian, Guangdong and Hunan-Guangxi granite belts.

Ar high-grade metamorphic rocks
 Pt low-mid-grade metamorphic rocks
 Pz carbonate sedimentary rocks
 J₁₋₂ quartzitic sandstone and tuffaceous phyllite
 J₃ dacitic rhyolite and tuffaceous sandstone
 K tuffaceous sandy shale
 Gng gneissic granite
 γ biotite (muscovite) granite or Al-rich alaskite or Li-albite granite,
 γ₂ Shipunian,
 γ₃ Caledonian,
 γ₄ Variscan,
 γ₅ Yanshanian
 γδ granodiorite
 γπ granoporphyrite
 ag alkaline granite
 MS-I, II and III metallogenic series
 I-1, I-2, II-2, II-2 metallogenic sub-series
 CSC, SC, VC carbonate-, silicate-, volcanic-country rocks respectively
 (1) volcanogenic vein type Au and porphyry Cu deposit (Zhijinshan)
 (2) epithermal replacement-filling type Ag-Pb-Zn-Au deposit (Yinhen, Wubu)
 (3) volcanogenic vein type Sn deposit (Changpu)

(4) albitisation granite type Nb-Ta deposit (Boluo)
 (5) I-2-pegmatite type Nb-Ta deposit (Nanpin)
 (6) porphyry Sn deposit (Yinshan)
 (7) shear zone alteration type Au deposit (Hetai)
 (8) I-2-albitisation granite type W-Nb-Ta-REE deposit (Dajishan)
 (9) greisen-skarn type W-Sn-Bi-Mo-Be deposit (Yaogangxian)
 (10) hypothermal vein type wolframite deposit (Xihuashan)
 (11) alteration granite-skarn-hydrothermal replacement type Nb-Ta-W-Sn-Be-Pb-Zn deposit (Xianghualing)
 (12) greisen-skarn type W-Sn-Mo-Bi-Be deposit (Shizhuyuan)
 (13) hydrothermal replacement type Pb-Zn-Ag deposit (Dongpue)
 (14) skarn type Pb-Zn-W deposit (Huangsapin)
 (15) skarn type Pb-Zn-Au deposit (Shuikoshan)
 (16) hydrothermal replacement type Cu deposit (Tuengshan)
 (17) alteration granite type U deposit (212)
 (18) skarn type Cu-Zn(Sn) deposit (Lamue)

(19) hydrothermal cassiterite sulphide deposit (Dachang)
 (20) hydrothermal replacement type Pb-Zn-Sb-Hg deposit (Mangchang)
 (21) greisen type Sn-Cu deposit (Baotan)
 (22) hydrothermal replacement type Sn-Cu-Pb-Zn deposit (Jiumao)
 CLM continental lithosphere mantle
 CLMDS delamination slab of CLM
 OCS ocean crust subduction
 CTPR crust thickening partial remelting body
 GMC granitic magma chamber
 JMU Jiangnan old land uplift
 JMD Jiangnan old land marginal depression
 HGGFD Hunan-Guangxi-Guangdong faulted depression
 SJU southern Jiangxi uplift
 W-YFU Wuyi-Yunkai faulted uplift
 FGVB Fujian-Jiangxi volcanic basin
 GFFV Guangdong-Fujian faulted volcanic basin
 YP&FL Yangtze plate and foreland
 CP&FL Cathaysia plate and foreland
 SECP south-east China plate
 ZFGB, HJGB and HGIB see text
 arrow with age: collision-obduction episode.

ening of the crust. This may have caused the downward bending of the Moho roughly along the 0.724 line, thus creating a Moho topography. This overthickened lithosphere mantle became gravitationally unstable, and was catastrophically removed, resulting in delamination (Bird, 1979; Kay and Kay, 1993; Collins and Vernon, 1994). The delaminating slab rapidly sank and was accompanied by hot asthenosphere upwelling along the *décollement* structure, which resulted in rapid heating and fusion of lower and middle crust to generate the array of intraplate Caledonian S-type and I-type granites. The South-east Asia plate shifted north-westward during the Permian, resulting in the consumption of the palaeo-south China ocean and the closure of the Qinzhou remnant geosyncline which was at the southwestern end of the Caledonian mio-geosyncline. The localised crustal thickening induced the delamination of continental lithosphere mantle and the asthenosphere upwelling, forming the Hercynian–Indosinian high-Al S-type granites.

- 3 The Yangtze plate collided with the north China plate along the Qinling–Dabie suture during the Triassic and the MLYR and JZB were extended and depressed as a result. Mantle materials ascended and mixed with the crust, but the interaction between mantle and crust materials was confined to quite a narrow belt. This generated the Jurassic–Cretaceous granites in the area.
- 4 The South-east Asia plate collided with the Asia continent along the Changle–Nan’ao fault belt during the late Triassic–early Cretaceous, and the palaeo-south China ocean was closed. The collision was oblique to the margin of the Asia continent. Besides compression, there was strike-slip movement along the boundary between the two plates, resulting in a sinistral strike-slip fault system. Because these two plates are larger in size than the Yangtze, Cathaysia and south-east coast of the China plate, there could have been a more rapid convergence during this collision than any former one and the force induced by the collision was greater. Under such strong horizontal compressive stress and the unstable amalgamation between the Yangtze, Cathaysia and south-east coast of the China plate, the localised crustal thickening, roughly along old sutures such as the 0.724 line and 0.708 line, induced once again the delamination of continental lithospheric mantle, causing large-scale Jurassic S-type granitic magmatism and its planar distribution.

The collisions were complex, including obduction of the crust and continuous subduction of the oceanic lithosphere after the amalgamation of continental blocks (Harris et al., 1986). The latter could have resulted in remelting with volcanic arc characteristics, and the extensive mixing between mantle and crust materials to form the Early Cretaceous I-type granites in the south-east coast area. In the end, the crust became stable, and a change from a compressive to an extensional geodynamic environment took place, creating favourable conditions for the generation of A-type alkaline and subalkaline granites by the volatile and/or magma derived from mantle (Hong et al., 1987). Thus, we can see the distribution pattern from S-type through I-type to A-type granites from the Jurassic to the Late Cretaceous and from the north-west to south-east in the study area during the Yanshanian.

Metallogenic series related to granites in south China

A metallogenic 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. In the case of the polygenetic granite belts of south China, sub-series (SS) can be established where the tectonic unit to which a MS belongs is large and second-order structural units may be distinguished by their own characteristics, (Cheng and Chen et al., 1979, 1983; Chen and Pei et al., 1989; Zai et al., 1992; Cheng, Chen and Pei et al., 1994; Chen

and Pei et al., 1955). The authors proposed five MS and their SS in six granites belts of south China (Table 2). Because of space limitations, only three major MS (from the coastal belt to the intracontinental belt) will be discussed here.

Metallogenic series I

This series, (of Cu(Au)-Mo-Pb-Zn(Ag)-W(Sn), Nb, Ta deposits, related to shallow I- and A-type granites in the ZFGFB belt) lies on the south-east coast of the China plate in a collision-subduction setting. It consists of the east–west-trending SS I-1 of Sn and Nb (Ta) deposits associated with volcano-intrusive rocks ($\lambda\pi$) in a volcanic basin and the north-east-trending SS I-2 of porphyry Au-Cu and epithermal Ag-Pb-Zn-Au deposits associated with shallow intrusive rocks ($\lambda\delta$) in faulted volcanic basin. The difference in the assemblage of ore-forming elements between the two SS is obviously caused by the difference in the basement composition and tectonopetrogenic environment (Chen and Pei et al., 1989). The ore-forming source of SS I-1 is derived from partial remelting of continental crust by collision while that of SS I-2 is from ocean crust by subduction. The spatial distribution of deposit types in this series is shown by the diagrammatic model (Figure 3, MS-I).

Metallogenic series II

This series (of W(Sn)-Mo-Bi-Be-U-Nb-Ta-Au-REE deposits related to S-type granite activity of medium to shallow depth in the HJGB belt) is situated in the Cathaysia plate. Two episodic delaminations of the continental lithosphere mantle occurred in the Caledonian and Variscan epochs and were affected by collision of Yanshanian epoch. SS II-1, II-2 and II-3 (Figure 3) are linked up with metamorphosed granitoids which underwent intense dynamic thermomorphism and formed autochthonous migmatitic granite (Caledonian), para-autochthonous granite (Variscan) and allochthonous high level grano-porphyrite (Yanshanian). The metallisation of these SS is associated with granites of different periods, but that of SS II-2 is more concentrated than that of SS II-1. Additionally, SS II-3 has inherited the character of SS II-1 and II-2 to form a porphyry-type Sn deposit. This MS is a distinct example of inheritance evolution in the ore-forming process. SS II-4 involves the super-large wolframite quartz-vein deposits (Dajishan–Xihuashan) of China. These deposits are genetically related to a composite granite body which was formed by four stages of Yanshanian comagmatic complementary (or pulsatory) differentiation with a total duration of 40 Ma. Mineralisation occurred in all four stages, resulting in the accumulation of large quantities of ore-forming materials in the ore belt, thus producing super-large ore deposits. (Pei and Wu, 1993). The deposit types are illustrated in Figure 3, MS-II.

Metallogenic series III

This series (of Sn-W-Mo-Bi-Be-Pb-Zn(Cu)-Sb-Hg-As-Nb-Ta-Au-U deposits related to high-Al S-type granite activity of deep to medium depth in the HGIB belt) lies in the Yangtze plate and its foreland. These collided with the Cathaysia plate in the Proterozoic (Shipunian) and were strongly affected by the South-east Asia plate colliding with the Asia continent in the Triassic–Early Cretaceous (Yanshanian). SS III-1 is related to Proterozoic metamorphosed granites and shows a mode of occurrence of an autochthonous–allochthonous nature. Its cupola of high-level granite is favourable for the formation of ore deposits. SS III-1, III-2, III-3 and III-4 constitute a complete metallogenic spectrum of lithophile ore-forming elements (Nb-Ta-W-Sn-Mo-Bi-Be-Pb-Zn-Hg-Sb-As-Au-U), and exhibit a series of deposit types (magmatic deuteric alteration, pneumatogenic, pyrometasomatic, hydrothermal replacement, and fissure filling) (Figure 3, MS-III). Among them, the super-giant Shizhuyuan W-Sn-Mo-Bi-Be deposit is related to HHPy, with BEBLIF granite concentrating at its contact with carbonatite country rocks. On this ground, through super-strong alteration, the exceptional skarn and greisen-type deposits were generated (Pei and Wu, 1994). The com-

plete differentiation of magmatism is also shown by the SS III-5. It was generated by the differentiation of high-Al granitic magma at the latest stage of the Yanshanian which formed slightly basic granodiorite and a series of deposits of sulphide elements (Pb-Zn-Cu-Ag). Another super-giant cassiterite sulphide deposit (dachang) in SS-III-2 is situated in the marginal depression of the Yangtze plate where tin is anomalously high (Chen and Pei et al., 1989). The margin of the Yangtze plate was probably an ore source area and might have evolved to provide the source for SS III-1 and SS III-2 during the Proterozoic-Mesozoic. The evolutionary relationships between the deposit types in this MS are shown in Figure 3, MS-III.

Conclusions

Since the six granite belts of south China belong to different lithospheric plates, different types of lithosphere may control the mineralisation characteristics of different granite belts and a definite metallogenic series may exist in a definite granite belt. This metallogenic speciality of different granite belts for MS is very important for regional mineral assessment.

In the light of the multiperiodic and multistage petrogenic-minerogenic development of the granites in south China, two main features may be deduced:

- the mineralisation is associated with a later or individual period of asynchronous granites;
- the mineralisation is associated with a later or individual stage of synchronous granites.

These features are closely related to the co-magmatic pulsatory (multi-episodic) nature of the mineralisation which was either continuous or intermittent. If the mineralisation was continuous and lasted for a long time in an ore district, it would constitute a special minerogenic event that could produce a superlarge ore deposit (Pei and Mao, 1988; Pei and Wu, 1993).

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