

Multiple-aged granitoids and related tungsten-tin mineralization in the Nanling Range, South China

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The Nanling metallogenic belt in South China is characterized by well-developed tungsten-tin mineralization related to multiple-aged granitoids. This belt is one of the 5 key prospecting and exploration areas among the 19 important metallogenic targets in China. Important progress has been made in recent years in understanding the Nanling granitoids and associated mineralization, and this paper introduces the latest major findings as follows: (1) there exists a series of Caledonian, Indosinian, and Yanshanian W-Sn-bearing granites; (2) the Sn-bearing Yanshanian granites in the Nanling Range form an NE-SW trending aluminous A-type granite belt that stretches over 350 km. The granites typically belong to the magnetite series, and dioritic micro-granular enclaves with mingling features are very common; (3) the Early Yanshanian Sn- and W-bearing granites possess different petrological and geochemical features to each other: most Sn-bearing granites are metaluminous to weakly peraluminous biotite (hornblende) granites, with zircon $\varepsilon_{\text{Hf}}(t)$ values of ca. -2 to -8 , whereas most W-bearing granites are peraluminous two-mica granites or muscovite granites with $\varepsilon_{\text{Hf}}(t)$ values of ca. -8 to -12 ; (4) based on the petrology and geochemistry of the W-Sn-bearing granites, mineralogical studies have shown that common minerals such as titanite, magnetite, and biotite may be used as indicators for discriminating the mineralizing potential of the Sn-bearing granites. Similarly, W-bearing minerals such as wolframite may indicate the mineralizing potential of the W-bearing granites. Future studies should be focused on examining the internal relationships between the multiple-aged granites in composite bodies, the metallogenic peculiarities of multiple-aged W-Sn-bearing granites, the links between melt evolution and highly evolved ore-bearing felsic dykes, and the connections between granite domes and mineralization.

Nanling Range, tungsten-bearing granites, tin-bearing granites, mineralizing potential, ore-forming peculiarities

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The Nanling Range is situated in the central-southern part of South China (111° – 117° E, $23^{\circ}20'$ – $26^{\circ}40'$ N) and covers a total area of some 200000 km² (Shu, 2007). The region is characterized by widespread granitoids of different ages and different geneses, and the granitoids are commonly associated with tungsten, tin, and rare-metal mineralization. The Nanling Range possesses unique ore-forming conditions and a great potential for mineralization.

Geological investigations of the Nanling Range started in

the 1940s. Li (1942) confirmed the existence of the E-W trending Nanling structural belt in his article “Where is the Nanling Range?”. Later, he further emphasized that the Nanling structural belt consists of a series of E-W trending local folds and granite bodies.

In the Nanling Range, magmatic activities have been intensive, and magmatic rocks are widely distributed, especially granitoids of differing ages. Systematic investigations of the granitoids and their metallogenic relationships began in the 1960s. Xu (formerly spelled as Hsu in Wade-Giles Romanization) and his colleagues discovered a series of

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metamorphosed granites of the Caledonian age, and published the first monograph on the polycyclic granites in the Nanling Range (Hsu et al., 1960, 1963a,b; DG-NJU, 1966). Work on the Nanling multiple-aged granitoids accelerated markedly in the late 1970s to 1980s, resulting in the publication of important monographs by IG-CAS (1979), Huang and Ren (1980), DG-NJU (1981), and Mo et al. (1980). These works explored the relationships between the spatial distribution of the granites and regional tectonics, as well as the multiple-aged or polycyclic character of the Nanling granitoids, and the granitoids were subdivided into the transformation series, the syntaxis series, and the mantle-derived series (Xu et al., 1984). A number of international scientific conferences were also organized, focusing on the granites and related mineralization, including the Tungsten Geology Symposium in Nanchang (1981), the Granite Geology Symposium in Nanjing (1982), the Tin Geology Symposium in Nanning (1984), and the Second Granite Geology Symposium in Guangzhou (1987).

Tungsten, tin, rare-metal, and polymetallic deposits are widely distributed within the Nanling Range, and they include various genetic types (Chen et al., 1989; NGRG, 1989). Studies on the ore-forming characteristics and mechanisms have provided an important theoretical basis for the exploration of these metallic mineral deposits. Based on the ore-forming characteristics of tungsten deposits in the provinces of southern Jiangxi and northern Guangdong, a “Five-floor building” model was established and successfully applied to prospecting and exploration for vein-type wolframite deposits in the Nanling Range (Gu, 1981; Wang et al., 2010a). The W, Sn, and rare-metal mineralization in the Nanling Range took place mainly in the middle Yanshanian period, and this mineralizing event has been called the Mesozoic Metallogenic Explosion (Hua et al., 1999; Mao et al., 1999).

Since the mid-1980s, high-precision isotopic geochronological dating techniques and modern trace element and isotope geochemical methods have been applied to studies of the Nanling granites, and they have catalyzed a number of comprehensive investigations into the geotectonic settings, the magmatic processes, crustal evolution, and metallogenesis of the Nanling granites. Hsü et al. (1990) proposed an intracontinental terrane collision orogeny model for the tectonic-magmatic activities in South China. Gilder et al. (1991, 1996) put forward a basin-and-range type of tectonic model for South China, and employed a continental rifting plus strike-slip model to explain its Mesozoic history. Yang and Mei (1997) considered that the zone from Qinzhou Bay to Hangzhou Bay is a belt representing the conjunction of the Yangtze and Cathaysia paleo-plates. This belt was also the place where Yanshanian movements were initially triggered in South China, and the related granitic magmatism and mineralization propagated to both the NW and SE sides of the belt. Zhou et al. (2006) emphasized the importance of a tectonic transition from the mainly E-W trending paleo-Asian regime to the mainly NE-SW trending

Western Pacific regime during the Triassic to Middle Jurassic, and they proposed the following two-stage model for genesis of the Mesozoic magmatic rocks: a continent-continent collision orogeny that first generated the early Mesozoic Indosinian granitoids, and then later a back-arc extensional orogeny during the westwards convergence of the Western Pacific Plate towards the paleo-Asian continent that created the Late Mesozoic Yanshanian granitoids and volcanics. Subsequently, Li and Li (2007) proposed a flat-slab model. They suggested that, beginning from ca. 265 Ma, the Pacific Plate was subducted beneath the continent of South China as a flat slab, and that slab break-off and the consequential delamination at ca. 190 Ma triggered large-scale Yanshanian magmatism.

The Nanling Metallogenic Belt is one of the 5 key prospecting and exploration areas among the 19 important metallogenic targets in China. In recent years, important progress has been made in theoretical studies and in the application of sound geological practice to prospecting the Nanling granitoids. In particular, the rock-forming and ore-forming mechanisms of these multiple-aged composite granitic plutons have been discussed and elucidated in recent research. The differences and similarities between the W- and Sn-bearing granites have attracted much attention, and establishing the criteria of mineralizing potential is clearly critical for future exploration. This paper reviews the recent progress in studies of tungsten and tin mineralization associated with the multiple-aged granites of the Nanling Range.

1 Caledonian granites and tungsten-tin mineralization

Caledonian granitoids are found worldwide, including in eastern England (Kalsbeek et al., 2001), Scotland (Soper, 1986), the Lachlan Fold Belt of Australia (Williams et al., 1992), and New Zealand (Muir et al., 1994). The existence of Caledonian granites in the Nanling Range was predicted by Huang as early as in 1945 (Huang, 1994). However, it was not confirmed until 1957, when reliable geological evidence at E'gongtou in Xinfeng county and at Doushui in Shangyou county, southern Jiangxi Province (Hsu et al., 1960), demonstrated that Devonian strata lie unconformably on the Longhui and Doushui granites. This discovery marked the start of an investigation into the multiple-ages of the granitoids.

The Caledonian granitoids in the Nanling Range are mainly present in the boundaries between Hunan, Jiangxi, Guangxi, and Guangdong (Figure 1). High-precision isotopic dating has provided further evidence of Caledonian ages in a series of granitoids in the Nanling Range, such as the Daning granodiorite in Guangxi (419 Ma; Cheng et al., 2009), the Xuehuading granodiorite in the Jiuyishan Mountains (432 Ma; Fu et al., 2004), the Qinjia granite in Guangxi (412–442 Ma; Wang et al., 2010b), the Shilei quartz diorite

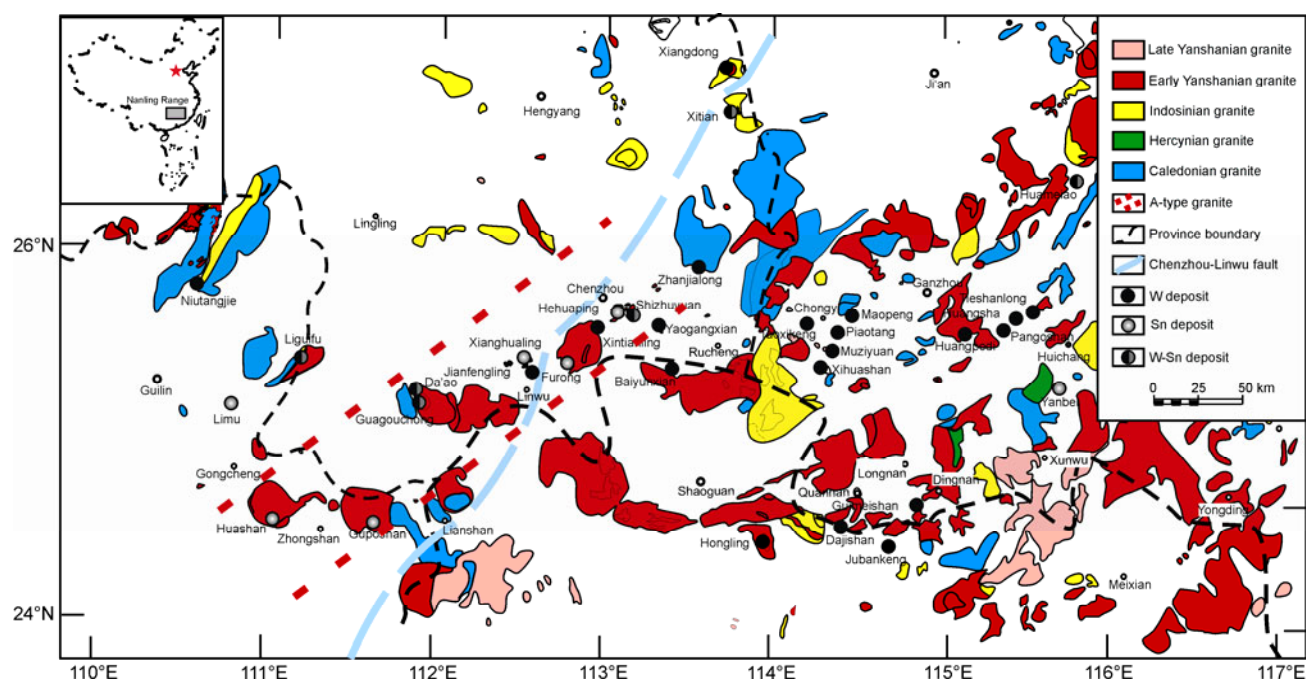


Figure 1 Distribution map of tungsten/tin-bearing granites in the Nanling Range. Compiled after Sun (2006), Zhu et al. (2008) and Mao et al. (2008).

in southern Jiangxi (433 Ma; Li et al., 2010), and the Penggongmiao granite and later-stage aplites in southern Hunan (Zhang et al., 2011).

Among the Caledonian granitoids, a few are syn-orogenic, and formed during the Early Caledonian period at ca. 460–440 Ma, but most of them are post-orogenic, and formed in the Late Caledonian period at ca. 440–410 Ma (Zhang et al., 2009). Geochemically, 58.6% of the Caledonian granites (in terms of surface area) are peraluminous S-types (Sun, 2006). The others are I types, involving a certain amount of mantle material, and formed mainly within an intra-plate setting.

An important research question has been asked about whether the Caledonian W-Sn-bearing granitoids exist in the Nanling Range. In the 1960s and 1970s, because of the absence of W-Sn deposits associated with or close to reliably dated Caledonian granites, the Caledonian granites were thought to be not W-Sn-bearing (Hsu et al., 1963b). However, despite the W-Sn deposits in the Nanling Range being mainly Yanshanian in age, Huang and Chen (1986) considered that the W-Sn mineralization could also be poly-cyclic and concluded that W-Sn deposits of other ages could not be excluded. Chen et al. (1995) also paid attention to possible genetic relationships between W-Sn mineralization and the Caledonian granites. The Yuechengling granite in Guangxi and the Penggongmiao granite in Hunan are two typical Caledonian plutons. Recently, several W-Sn deposits and mineralization sites have been discovered inside or near these granites, and their ore-forming ages have been isotopically determined as Caledonian. This finding is an important breakthrough in terms of understanding the ore-forming processes of Caledonian granites in the Nanling

Range.

1.1 The Penggongmiao Caledonian W-bearing granite

The Penggongmiao granite of Hunan Province is a large batholith in the Nanling Range (Li et al., 1963). In recent years, several W deposits or mineralizations have been found near the pluton. Among them, the Zhangjialong mine was opened along the southern margin of the Penggongmiao batholith. At the contact between the medium-coarse-grained porphyritic biotite granite and the country rocks, 11 scheelite-quartz veins of 400–1800 m in length have been detected. In addition, small aplite dykes (30–50 cm wide) cut the biotite granite with sharp contacts.

Zhang et al. (2011) obtained LA-ICP-MS zircon U-Pb dates for the major phase of the Penggongmiao granite batholith (a medium-coarse-grained biotite granite), and determined its emplacement age to be 435–436 Ma, with the aplites emplaced at 426.5 Ma. Petrographic and electron-microscopic studies detected the existence of magmatic scheelite in the aplites. Consequently, the Penggongmiao granite is now proven to be Caledonian W-bearing granite.

1.2 The Niutangjie Caledonian W-bearing granite

The Niutangjie skarn scheelite deposit of northern Guangxi is the basis of an operating mine located on the southern margin of the Caledonian Yuechengling batholith. However, a lack of precise information on the ore-forming age made it very difficult to judge whether the mineralization is related to the Caledonian granite. Recently, Yang (2013) obtained

isotopic dating results on the crystallization age of the Niutangjie granite and the age of the scheelite skarn. The LA-ICP-MS U-Pb age for zircons from the Niutangjie medium- to fine-grained muscovite (two-mica) granite is (421.8 ± 2.4) Ma, implying it is a late-stage fractionation and differentiation product of the Yuechengling batholith. The scheelite Sm-Nd isochron age obtained from five scheelite samples is (421 ± 24) Ma. These data indicate that the scheelite ore was the product of the magmatic-hydrothermal evolution of the granite during late Caledonian tectonic-magmatic activity.

2 Indosinian W-Sn granites

In recent years, Indosinian granites are successively re-determined in the Nanling Range. Among these granites, some are mineralized (Wu et al., 2012), e.g., Limu Sn-Nb-Ta granite in Guangxi (zircon U-Pb age of 214–218 Ma, Kang et al., 2012; muscovite Ar-Ar age of 214 Ma, Yang et al., 2009), Yuntoujie muscovite granite in the Miaoershan-Yuechengling composite granite body in northern Guangxi (zircon U-Pb age of about 220 Ma) related to the Yuntoujie W-Mo deposit (molybdenite Re-Os age of 216 Ma, Wu et al., 2012).

The Wangxianling granite is recently much studied because of its associated W deposits such as Maojialong, Renxingling, and Yejiwo. Zhang (2010) obtained zircon U-Pb ages of 223.5 Ma and 212.6–224.9 Ma, respectively, in the central and marginal zones. Granite samples at Maojiawo contain 43–306 ppm W. Those from Yejiwo have W contents as high as 4856 ppm, and contain wolframite grains. Molybdenite Re-Os dating also gave an Indosinian mineralization date (224 Ma, Cai et al., 2006).

3 The southern Hunan-northeastern Guangxi aluminous A-type W-Sn-bearing granite belt

Many large and super-large W and Sn deposits exist in the Nanling Range, and W-Sn mining has a prolonged history in the area. The cassiterite placer near the Huashan-Guposhan granite was first mined in the 1930s. The Shizhuyuan scheelite skarn deposit was discovered in the 1950s and it is associated with the Qianlishan granite. In recent years, the Furong super-large Sn deposit was discovered within the Qitianling granite batholith (Huang et al., 2003). Subsequently, large-tonnage Sn deposits at Xitian and Hehuaping have been confirmed (Wu, 2006; Long et al. 2009). These Sn-W-bearing granites are distributed mainly in the western-central part of the Nanling Range (Figure 1). Investigations have indicated that these occurrences represent a unique SW-NE-trending aluminous A-type Sn-W-bearing granite belt with the following characteristics.

(1) The Sn-bearing granite belt is located in the region between northeastern Guangxi and southern Hunan. It trends

SW-NE, and is made up of the Huashan, Guposhan, Jiuyishan, Qitianling, and Xitian batholiths, as well as other nearby stocks. It stretches for about 350 km and occupies a total area of more than 3000 km² (Zhu et al., 2008). It is part of the Qinzhou-Hangzhou Belt, probably formed by the conjunction and amalgamation of the Yangtze and Cathaysia paleo-blocks (Yang and Mei, 1997).

(2) The Sn-bearing granites commonly have aluminous A-type geochemical affinities. The major rocks present are usually medium- to coarse-grained biotite (hornblende) granites, frequently accompanied by contemporaneous intermediate (diorite, granodiorite, quartz monzonite) stocks or acidic volcanic-intrusive complexes. The alumina saturation index (ASI or ACNK) is usually between 0.9 and 1.1, categorizing the rocks as metaluminous to weakly peraluminous. In terms of trace element geochemistry, the rocks are generally enriched in Nb, Zr, Ce, Y, and HFSEs. On the discrimination diagram of Pearce (1984), the rocks usually plot in the “within plate” field. On the discrimination diagram of Whalen et al. (1984) that distinguishes A-types from undifferentiated M, I, and S-types, the rocks mostly fall in the A-type granite field (Figure 2).

(3) The results of SHRIMP zircon U-Pb isotopic dating show that these A-type granitoids were mostly emplaced in the Early Yanshanian period (165–146 Ma). However, within the same composite complexes, the time span from the earliest to the latest ages is 10–20 Myr. In the case of the Qitianling batholith, the first major granite was emplaced at 163–60 Ma, the second major granite at 5–10 Myr later, and the third fine-grained granite at 150–146 Ma.

(4) Existence of dark dioritic micro-granular enclaves with magma-mingling features is very common in the A-type granite belt. The most typical examples are found in the central zone of the Guposhan granite (in Lisong township). The enclaves are mostly round and ellipsoidal in shape. The whole-rock Sr and Nd isotopic results, together with the zircon Hf isotopic data, indicate the involvement of variable proportions of mantle-derived materials in the granite-forming process.

(5) These granites formed under a variety of physical-chemical conditions. Based on whole-rock Fe₂O₃/FeO ratios, Blevin (2004) subdivided the granites into five categories: extremely oxidized, strongly oxidized, moderately oxidized, moderately reduced, and strongly reduced. According to the whole-rock chemistry, most of the Sn-bearing granitoids in the Nanling Range are moderately oxidized. This observation is also supported by mineralogical studies. In the Fe²⁺/Fe³⁺/Mg diagram for biotite, these granites plot between NNO (Ni-NiO) and HM (hematite-magnetite). The existence of magnetite as the major Ti-Fe oxide mineral also indicates these granites are oxidized types (Tagagi and Tsukimura, 1997). The zircon-saturation temperatures calculated for these granites are mostly higher than 850°C, and the perthitic texture of the alkali feldspar is consistent with this, indicating hypersolvus crystallization.

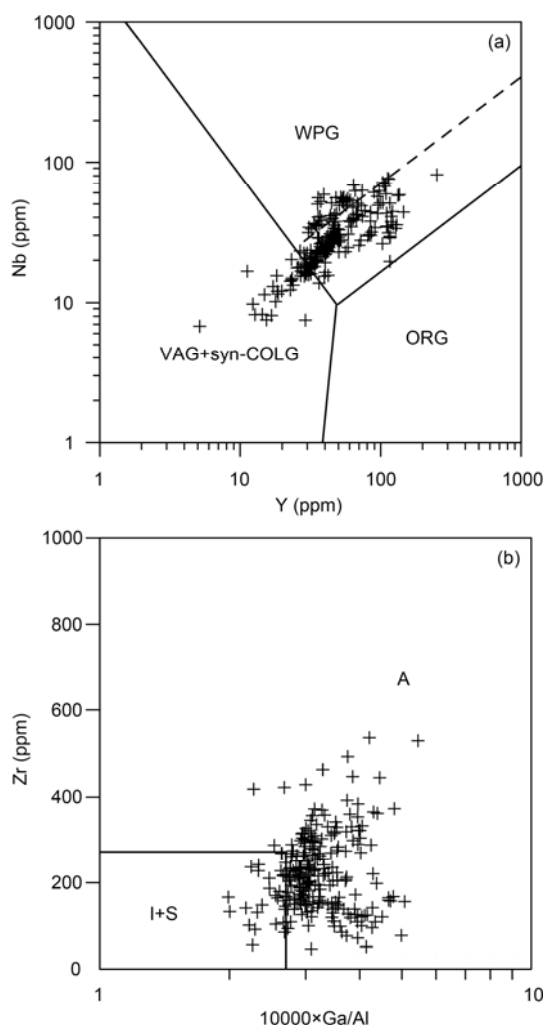


Figure 2 Discriminating diagrams for Sn-bearing granites in the Nanling Range. (a) Y vs. Nb discrimination diagram of structural environments (after Pearce et al., 1984); (b) Ga/Al vs. Zr discrimination diagram of granite genetic types (after Whalen et al., 1987). Data sources: Zhu et al., 2006; Xie et al. 2010, and unpublished data of the authors. WPG, within-plate granite; VAG, volcanic arc granite; syn-COLG, syn-collision granite; ORG, ocean ridge granite. A, I, S represent A-type, I-type and S-type granites, respectively.

Elsewhere in the world, the Olympic Dam super-large Fe-Cu-Au-U-REE deposit in Australia (Skirrow et al., 2007), the Pitinga super-large Sn-Zr-Nb-Y-REE deposit in Brazil (Bastos Neto et al., 2009), and several important Sn-Be-W-Zn deposits in Finland, Ukraine, and India (Haapala, 1997; Frost et al., 2007) have all been proved to be related to aluminous A-type granites. In the future, much attention should be paid to this type of granite and related mineralization.

4 Comparisons between W- and Sn-bearing granites

Tungsten and Sn mineralizations are frequently associated with each other. In the Central Plateau of France, several

composite granite bodies exhibit close associations and consanguineous relationships between W- and Sn-bearing granites. For example, in the Echassiere region, the La Bosse granite (associated with wolframite-quartz veins) and the La Colette granite (associated with cassiterite-quartz veins) have a common magma chamber (Cuney et al., 1992). The Nanling Range is one of the most important W, Sn, and rare metals mining regions in the world. Previous researchers have recognized a spatial zonation in the distribution of W and Sn deposits in this region (Figure 1). Specifically, the eastern part of the Nanling Range (including southern Jiangxi, northern Guangdong, and part of southern Hunan) is a post-Caledonian uplift area, characterized by extensive development of the wolframite quartz-vein type of W deposit, whereas the western part of the Nanling Range (including northeastern Guangxi and most of southern Hunan) is a Hercynian-Indosinian depression area, characterized by the widespread distribution of tin deposits. How does one interpret such a regional difference in metallogeny? This is an important problem that is posed for specialists in ore genesis, and in recent years, many have tried to solve the problem from the viewpoint of two different types of ore-forming granites. Several new important clues have been obtained (Table 1), and are discussed below in detail.

(1) Comparisons show that in the Nanling Range region, most Sn-bearing granites are metaluminous to weakly peraluminous biotite (hornblende) granites, with aluminous A-type geochemistries. They are enriched in Nb, Zr, Ce, Y, and HFSEs. The Ti, (Ba+Sr), and Pb contents, LREE/HREE, and CaO/(K₂O+Na₂O) ratios are relatively high, and the Rb/Sr ratios relatively low. In contrast, most W-bearing granites are two-mica or muscovite granites, peraluminous, and S-types with relatively high Y, Rb, and Rb/Sr values, and relatively low values of (Ba+Sr), Ti, and LREE/HREE, with strong negative Eu anomalies, and signatures of high degrees of fractionation and geochemical differentiation (Chen et al., 2008).

(2) The results of zircon U-Pb dating show that the ages of these two types of granites are very similar, all dated mainly from the period 165–146 Ma. However, the zircon saturation temperatures of the Sn-bearing granites are obviously higher than those of the W-bearing granites. The Nd model ages of the former (1.4–1.7 Ga) are much younger than those of the latter (1.8–2.2 Ga).

(3) Studies of zircon Hf isotopes have shown large differences in the nature of source materials (Figure 3). The $\varepsilon_{\text{Hf}}(t)$ values of the Sn-bearing granites are mainly in the range of ca. –2 to –8, whereas those of the W-bearing granites are in the range ca. –8 to –12 (Zhao et al., 2010; Shu et al., 2011). This implies that considerable amounts of mantle materials were involved in the formation of the Sn-bearing granites, but that the source materials were mainly crustal in the case of the W-bearing granites. Sillitoe (1974) thought that tin-bearing granites above mantle hot spots in the Jos Plateau in Nigeria may be of products of mantle magmatism.

Table 1 Compared petrological and geochemical features of W-, and Sn-bearing granites in the Nanling Range

	W-bearing granite	Sn-bearing granite
Location	Eastern part of the Nanling Range (South Jiangxi, North Guangdong, South Hunan)	Western part of the Nanling Range (North Guangxi, South Hunan)
Tectonic setting	Late-Caledonian uplift zone	Hercynian-Indosinian depression zone
Rock type	Mainly two-mica granites and muscovite granites, belonging to highly-fractionated, strongly peraluminous S-type granites	Mainly coarse-middle-grained (amphibole) biotite granites, belonging to metaluminous A-type granites
Dark enclaves	Not observed	Commonly observed
Al saturation index (ASI)	>1.1	0.9–1.1
Geochemical features	High Y, Rb, Rb/Sr, low LREE/HREE, strongly depleted Eu	Enriched HFS elements such as Nb, Zr, Ce, Y, high TiO ₂ , LREE/HREE
Age	165–146 Ma	165–146 Ma
Fe-Ti oxide minerals	Mainly ilmenite	Mainly magnetite
Accessory minerals	Spessartine, monazite, xenotime, wolframite, wolframioxiolite, etc	Titanite, allanite, cassiterite, etc
Zircon ε_{Hf}	–8––14	–2––8

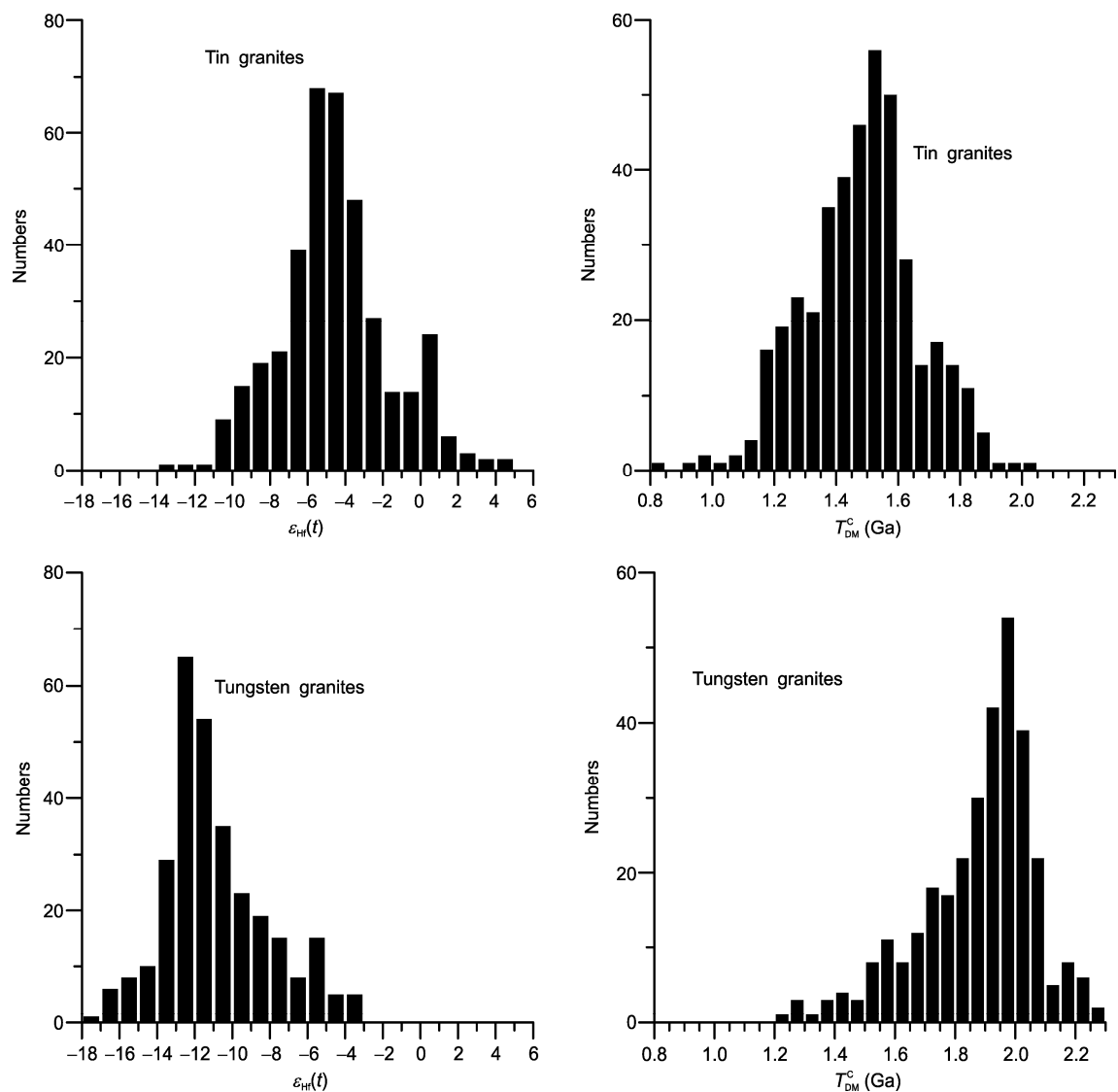


Figure 3 Comparison of zircon Hf isotopic characteristics between W-bearing and Sn-bearing granites in the Nanling Range. Data sources: Li et al., 2009; Guo, 2010; He et al., 2010; Zhao et al., 2010; Liu et al., 2010; Huang et al., 2011; Liu, 2011; Zheng and Guo, 2012, and unpublished data of the authors.

After systematic studies on the Qianlishan granite and associated igneous rocks, Zhao et al. (2001) found similarities in tempo-spatial associations, petrochemistry, trace-element and isotope geochemistry between basaltic, alkaline and granitic rocks in the Shizhuyuan metallogenic area. This suggests existence of strong mantle magmatic activities during the formation of the Shizhuyuan super-large deposit.

5 Mineralogical discrimination criteria for the W-Sn mineralizing potentials of granites in the Nanling Range

The W-Sn deposits in the Nanling Range are closely related to intensive periods of granitic magmatism (Chen et al., 2000), and the mineralization types are various, including quartz veins, greisens, skarns, etc. How does one differentiate the ore-forming granites from among the other widely distributed and common granites of the region? This is a problem of much concern in prospecting and exploration work. Although previous researchers have proposed many petrological and geochemical criteria (Xu et al., 1984), these may be obscured by late-stage alteration and weathering processes. Some minerals may preserve information on metal enrichment during the magmatic-hydrothermal evolution process, and may therefore be used as mineralogical criteria for evaluating the mineralizing potential of the granites.

5.1 Mineralogical criteria for the Sn-mineralizing potential of granites

Tin is an element with various possible valency states. In the granite magma system, it can be present as Sn^{2+} or Sn^{4+} . The geochemical behavior of tin could vary under different oxygen fugacity conditions. In the reduced-types of granite ($\log f_{\text{O}_2} < \text{FMQ} + 2.5$), the dominant species of tin is Sn^{2+} , and this can easily enter the fluid phase, thus favoring the formation of hydrothermal tin deposits (Linnen et al., 1995; Bhalla et al., 2005). On the other hand, in the oxidized-type granites, the dominant species of tin is Sn^{4+} , which easily enters into minerals. Besides the possible existence of the mineral cassiterite, tin may also enter into Ti- and Fe-bearing minerals such as titanite, magnetite, and biotite, as an isomorphic replacement of Ti^{4+} and Fe^{3+} (Lehmann, 1982; Linnen and Cuney, 2005; Farges et al., 2006). As mentioned above, the Sn-bearing granites in the Nanling Range are mostly of the oxidized type, and these common Ti-Fe minerals can be used as indicator minerals for the mineralizing potential of Sn-bearing granites (Wang et al., 2012).

The Sn-bearing granites in the Nanling Range are mainly biotite (hornblende) granites. In biotite, one of the most important rock-forming minerals, the mineral-melt partitioning coefficient for Sn is >1 (Linnen and Cuney, 2005). Consequently, biotite is one of the major carriers in the Sn-bearing granites. In biotites in the Qitianling granite, the

Sn contents are ca. 100–200 ppm (results of EMP and LA-ICP-MS analyses). During the chloritization of biotite, Sn can be leached out to form cassiterite or Sn-rich rutile.

Titanite is a very common accessory mineral. It is also an important indicator mineral for Sn-bearing granites (Wang et al., 2008; Xie et al., 2009). Ti^{4+} in titanite can be replaced by Sn^{4+} isovalently (Paul et al., 1981), forming Sn-rich titanite. A complete replacement of Ti^{4+} by Sn^{4+} leads to the formation of malayite (CaSnSiO_5). Wang et al. (2011) found that all titanites in the Qitianling, Huashan, and Guposhan Sn-bearing granites, either magmatic or hydrothermal, are characterized by relatively high contents of Sn (more than 0.4 wt% SnO_2 on average) (Figure 4(a)), indicating a high potential for Sn mineralization. Among the other three neighboring consanguineous granites that lack any known important Sn mineralization, the titanites in the Lianyang and Dadongshan granites have little Sn, in fact less than 0.1 wt% SnO_2 (Figure 4(b)). However, the titanites in the Jiufeng granite are very similar to those in the Huashan granite and are enriched in Sn, and the magmatic and hydrothermal titanites may contain as much as 3 wt% and 2 wt% SnO_2 , respectively (Figure 4(c)), indicating a good prospect for Sn exploration. Therefore, titanite is a useful indicator mineral for determining the Sn-mineralizing potential.

In the oxidized type Sn-bearing granites of the Nanling Range, the magnetite occurs as a major Ti-Fe oxide mineral. The Sn contents in magnetite are usually relatively low (Chen et al., 1992), but in many cases ilmenite flakes are found as an exsolution product, sometimes in association with micron-scale cassiterite as oxy-exsolution products of tin-bearing magnetite in oxidized granites (Wang et al., 2012).

5.2 Mineralogical criteria for the W-mineralizing potential of granites

Previous experimental studies have shown that the solubility of tungsten in a granitic melt might reach 1000 ppm (Štemprok, 1990). Consequently, in common cases, it would be very difficult for W in the granitic melt to be saturated and for W minerals to be crystallized (Linnen and Cuney, 2005). A challenge is thus raised: can W-bearing minerals provide an effective indicator of tungsten ore-bearing granite?

Che et al. (2013) performed experimental studies on the solubility of hubnerite and ferberite in a flux-rich water-saturated haplogranitic melt. The results show that at near-solidus temperatures and under Li-subaluminous and Li-peraluminous conditions ($ASI_{\text{Li}} > 1$, where $ASI_{\text{Li}} = \text{molar Al}/(\text{Na} + \text{K} + \text{Li})$), the saturation content in the Yaogangxian granitic melt is 35–56 ppm. Consequently, it is possible that the wolframite can be crystallized at the magmatic stage in the W-bearing granites. Experimental results have provided an important basis for indicator-mineral studies in relation to evaluating the W-mineralizing potential of granites.

The Yaogangxian granite is important W-bearing granite

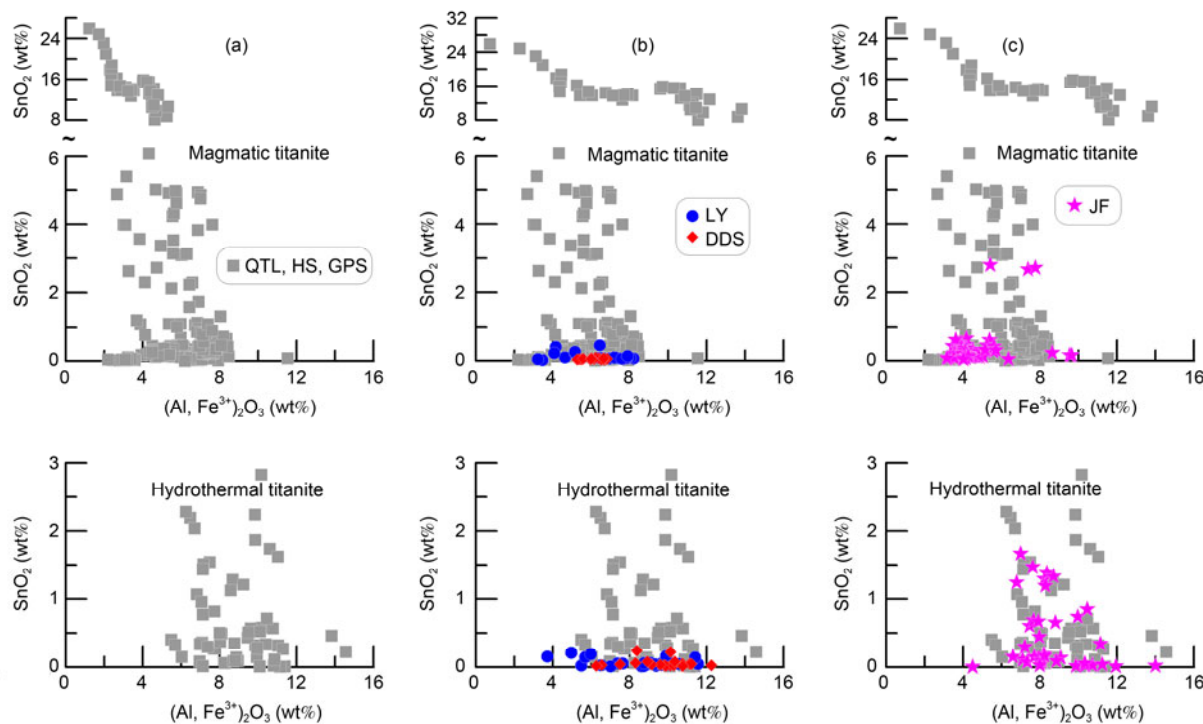


Figure 4 Comparison of SnO_2 contents in titanite for different granite bodies in the Nanling Range (after Wang et al., 2011). (a) Qitianling (QTL), Huashan (HS), and Guposhan (GPS) granites; (b) Lianyang (LY) and Dadongshan (DDS) granites; (c) Jiufeng (JF) granite.

in the Nanling Range. Its nearly idiomorphic wolframite is included in, or closely associated with, magmatic rock-forming minerals with no hydrothermal alteration (Che, 2011). Magmatic wolframite is very common in the W-bearing granites of the Nanling Range; in addition, other examples include scheelite in aplite dykes that cut the Penggongmiao Caledonian granite pluton (Zhang et al., 2011), wolframite in the Wangxianling granite, wolframite and W-rich rutile in the Xintianling granite (Zhang R Q, personal communication), and Nb-rich wolframite in the Xihuashan granite (Wang et al., 2003).

6 Problems and prospects in studies on ore-bearing granites of the Nanling Range

6.1 Internal relationships among the multiple-aged granitoids in the composite plutons of the Nanling Range

The granitoids of the Nanling Range are the products of multiple cycles of episodic tectonic-magmatic activities. Spatially, they occur frequently as granite complexes, comprising granitoids of different ages. For example, the Miaershan complex contains Caledonian, Indosinian, and Yanshanian granites. Is there any link between the granitoids of different ages in terms of genesis and source materials? Could the ore-forming materials of the earlier granitoids (if they existed) be inherited by the later granitoids? In other words, is there any pre-concentration of ore-forming

materials in the pre-Yanshanian granitoids? How did the later granites influence the earlier granites? These are important issues worthy of further study.

6.2 Metallogenetic peculiarities of multiple-aged granitoids

Undoubtedly, the tungsten, tin, rare metals, and REE mineralizations in the Nanling Range are related mainly to the Yanshanian granites. However, more and more Caledonian and Indosinian ore-bearing granites are being discovered. It is interesting to note that several newly discovered W-bearing granites are of scheelite type. Is this a common characteristic of the Caledonian ore-bearing granites? Is this type of mineralization controlled by the material sources and rock-forming conditions of the Caledonian granites? Again, these questions require further study.

6.3 Ore-bearing felsic dikes and their relationship with magmatic evolution

Fractionation and differentiation of granitic melts may lead to metal enrichment and ore formation. The ore-bearing felsic dykes in the Nanling Range are usually well-evolved and are late-stage parts of the high-level magmatic products. They are important for understanding the mechanisms of the generation and evolution of the granitic melts in the region, as well as the processes of metal enrichment during the entire magmatic-hydrothermal evolutionary process. They are

also of great value in prospecting and exploration practice. These rocks are very common in the Nanling Range. The No. 431 dyke in the Xianghualing district, described by Du and Huang (1984) and Zhu et al. (1993), is one of the most representative examples of felsic dykes. Unfortunately, little is known of these rocks, and further study is required.

6.4 Granite domes in the Nanling Range and their metallogenic relationships

If we look carefully at the geologic map of the Nanling Range, we find an interesting phenomenon: the Penggongmiao, Qitianling, Guposhan, Huashan, and other batholiths all have rounded forms in plan view. They have the shapes of typical granite domes, and are all found in the Qinzhou-Hangzhou belt. In the central part of the Guposhan granite there are dense populations of numerous dark dioritic microgranular enclaves, of different sizes, and commonly with magma-mingling features. It is quite possible that this part of the Guposhan pluton was the pathway for the upwelling of mantle-derived magma. These observations indicate that the geodynamic environment of the granite dome formation was closely related to some form of crust-mantle interaction. What roles do the domes play in the W-Sn ore mineralization? This is another important problem for further investigation in the Nanling granite belt.

To sum up, when undertaking studies of the large-scale development of Yanshanian ores in the Nanling Range, we should pay much more attention to the pre-Yanshanian magmatic events and associated mineralization. In particular, we need to recognize the contribution of the Caledonian tectonic-magmatic activities to the development and evolution of the South China crust, and their important influences on Yanshanian magmatism and metallogenesis. We will not fully understand the pre-Yanshanian granites and their related mineralization without systematic investigations of the petrogenesis and metallogenesis of the Nanling granites, and further investigation of the ore-forming mechanisms in the Nanling composite granites. We may then gain a more comprehensive understanding of the overall picture of the rare metal mineralization in the Nanling region, and a deeper understanding of the nature of the Mesozoic Metallogenic Explosion event in the Nanling Range.

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