Genesis of S-type Granites in the Pengshan Sn-polymetallic Ore Field, Northern Jiangxi Province and its Implications

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Abstract: The Pengshan Sn-polymetallic ore field is located in the southeastern part of the Yangtze block, spanning the southeast edge of the MLYDZ and the northern edge of the mid-segment of the Jiangnan Uplift, and on one side of the MLYDZ. The studies of LA–ICP–MS zircon U–Pb chronology and petrogeochemistry for Early Cretaceous acid granites from the Pengshan ore field were carried out in this paper. We report zircon U–Pb geochronology and whole-rock geochemistry for acid granites in the Pengshan ore field. The zircon U–Pb ages of the muscovite-granite, biotite adamellite and granite-porphry are 127.6 ± 1.7 Ma, 126.9 ± 1.6 Ma and 126.6 ± 2.0 Ma, respectively. The granites in Pengshan are characterized by a high silicon content and are rich in alkali. They belong to high-potassium, calc-alkaline, peraluminous granite. The rocks have a relatively high Rb/Ba ratio, and the data points for muscovite-granite and biotite adamellite all fall within the clay-rich sources region, near the pelite-derived end-member, showing that the Pengshan muscovite-granite and biotite adamellite mainly originated from the partial melting of metapelites with high maturity. The transformation of the compressional and extensional tectonics in this region approximately 128 Ma obviously lags behind that in the mid-segment of the Jiangnan Uplift (135 Ma), but occurred earlier than the MLYDZ (126 Ma). The Pengshan ore field extends from the mid-segment of the Jiangnan Uplift to the MLYDZ. Although the tectonic stress field is constrained by the combination of the two secondary tectonic units, the time of tectonic system transformation is closer to the MLYDZ because the spatial orientation of the area is enclosed in the MLYDZ. Relevant geophysical and drilling data confirm the rationality of Pengshan–Ao’xia as a multi-center vertical zoning ore field, and show the scientificity of the prospecting idea of abutting joint between the north-west of Pengshan area and the south-east of Ao’xia area.

Key words: zircon dating, S-type granite, Early Cretaceous, syn-collisional, dynamics, Pengshan Sn-polymetallic ore field

1 Introduction

The Middle-Lower Yangtze Metallogenic Belt (MLYMB) and the Mesozoic Tungsten–Copper–Molybdenum Polymetallic Metallogenic Belt are important components of the main metallogenic belts in Eastern China (Xiang et al., 2012a, 2015a, b; Zhou et al., 2017; Wang et al., 2018). The Pengshan Sn-polymetallic ore field is located at the transitional junction of the two and is a typical metallogenic type in this region (Zhou, 1983, 1988; Ma, 1989; Bi, 1992). A series of large, medium and small deposits, such as the Zengjialong tin deposit, the Jianfengpo tin deposit, the Zhangshiba lead-zinc deposit, the Huangjinwa tin deposit, the Baoshan antimony–gold deposit, and the Xiangxi fluorite deposit, have been discovered in this ore field (Fig. 1). The discovered reserves of tin are over 100,000 tons, and the reserves of lead and zinc are approximately 700,000 tons. This field has become one of the most important resource producing areas for tin (lead and zinc) polymetallic ores in eastern China (Lu et al., 2004a, b, c, 2005a). The available dating shows that the Sn-polymetallic metallogenesis in the ore field is related to the intrusion of acid magma in the Early Cretaceous (128 Ma, Luo et al., 2010a, b; Xu et al. 2015). The metallogenesis types are mainly skarn-type Sn–Zn–Cu mineralization and quartz glutenite-type Sn–Zn–Pb mineralization. The Sn–Zn–Pb polymetallic metallogenic events in this area have attracted much attention from researchers, who have studied the chronology of the typical deposits (Luo et al., 2010a, b; Xu et al. 2015; Xiang et al., 2016), geological structure (Ma, 1989; Lu et al., 2004a), mineralogy (Luo et al., 2011), stable isotopes (Lu et al., 2005b), exploration and prospecting models (Zhou, 1983, 1988; Ma, 1989; Bi, 1992; Xiang et al., 2017), and magma evolution characteristics (Lu et al., 2004b, c, 2005a; Xiang et al., 2016) leading to a relatively rich theoretical understanding. However, research on the petrogenesis of acid intrusive rocks related to metallogenesis in the Early Cretaceous is weak, and there is no consensus regarding the petrogenesis type. There is
no relevant research on the mechanism of the Early Cretaceous metallogenic dynamics in the Pengshan Sn-polymetallic ore field. For magmatic metallogenic systems, scientific determination of the metallogenic dynamic mechanism can not only reveal the details of metallogenic processes, such as the driving force, time evolution and spatial distribution, but also direct and expand the understanding of these processes in aid of prospecting and exploration.

Compared with other ore fields, the metallogenic characteristics of this field are distinct. As revealed by field exploration and the evaluation of existing data, the Early Cretaceous granite in this area has characteristics indicative of multiple intrusions. For example, there are biotite adamellite batholiths (main unit) emplaced in earlier stages of non-ore formations. In addition, muscovite granite stock (the complement unit) has intruded into biotite adamellite batholith and strata in later stages closely related to metallogenesis, and there are post-metallogenic granite-porphyry intrusions (vein unit) cutting off Sn-polymetallic ore bodies. We speculate that the metallogenic muscovite-granite, non-ore-forming
biotite adamellite and granite-porphyry have some common features (for example, they belong to high-K calc-alkaline series rocks, have the same petrogenesis types, and are basically similar in emplacement time). At the same time, it is likely that there are some differences in the initial material source composition and in their respective evolutionary processes, but determination of these differences requires reliable chronological evidence and detailed geochemical data for comparative studies to determine their respective specific petrogenesis and geodynamic evolution mechanisms during emplacement. The determination of the limitation period for the transformation of the Mesozoic tectonic deformation field in the Pengshan area is of great significance to develop a comprehensive understanding of the emplacement mechanism for acid magma and the evolutionary regularity of regional metallogenic dynamics in Pengshan and its adjacent areas. In this paper, zircon LA-ICP-MS U–Pb isotopic dating is assembled for muscovite-granite related to metallogenesis and for non-ore-forming granite (biotite adamellite and granite-porphyry) in the area. The whole-rock geochemistry of the rocks is compared and analyzed, providing chronological constraints for acid granites closely related to the metallogenesis in the Pengshan ore field. This paper discusses their respective origins, evolutionary processes, and tectonic backgrounds as well as the tectonic significance of their emplacement and provides a basis for rationalizing the overall determination of Pengshan–Ao’xia as a multicenter vertical zoning ore field. This paper also provides new evidence allowing a deeper understanding of the metallogenic dynamic background of the field and the Early Cretaceous tectonic deformation at the junction of the northern edge of the middle Jiangnan Uplift and the southeast edge of the Middle–Lower Yangtze Depression Zone (MLYDZ).

2 Geological Background

The Pengshan Sn-polymetallic ore field is located in the mid-eastern part of De'an County, Jiangxi Province, China, at the junction of the MLYMB in the lower Yangtze metallogenic province and the Mesozoic Tungsten–Copper–Molybdenum Polymetallic Metallogenic Belt of the Jiangnan Block. The ore field is located in the southeastern part of the Yangtze Plate, spanning the southeast edge of the MLYDZ and the northern edge of the mid-segment of the Jiangnan Uplift (Fig. 1a), and on one side of the MLYDZ (JBGME, 2007). Since the formation of the epimetamorphic fold basement of the Shuangqiaoshan Group in the Pengshan area, the field shows evidence of ascending and descending movement in the Caledonian and Hercynian, and after that, the formation of gentle and open folds. In the Mesozoic, the continental margin activity stage was dominant, forming tectonic-magmatic anomaly metallogenic tectonic convergence fields, such as Mesozoic crust folds and faults, which controlled the magma intrusion and deposit location, accompanied by many diagenetic and metallogenic events with different intensities (Pei and Xiong, 1999; Pei et al., 2001; Zhao et al., 2018). Except for the part of the Neoproterozoic epimetamorphic series exposed in the core of the Pengshan anticline, the lithology of the strata distributed on the surface is mostly sedimentary caprocks from the Nanhua to the Lower Triassic. The Yanshanian NNE-trending Pengshan short-axis anticline and NE-trending Fushan and Dachongjian faults are superimposed on NEE-trending caprock folds developed in the Indosinian (Fig. 1b). Yanshanian granite-porphyry, diabase, diorite and lamprophyre veins are scattered on the surface (Zhou, 1983, 1988; Ma, 1989; Bi, 1992; Lu et al., 2004a, b, c, 2005a, b).

As a component of a Pengshan hidden granite body, the metallogenic muscovite-granite gradually changes from medium-grained to fine-grained structure from the inside of the rock body to the edge, and the muscovite content also shows a gradual increase to the outside. Muscovite-granite is greyish-white (Fig. 2a) and has a massive structure and a medium-grained granitic texture. Muscovite-granite is mainly composed of plagioclase, potassium feldspar, quartz, muscovite and other minerals (Fig. 2a'). Apatite and zircon are seen as accessory minerals. The phenocryst contents of potassium feldspar, plagioclase, quartz and muscovite account for approximately 30 wt%, 32 wt%, 26 wt% and 12 wt%, respectively. The non-ore-forming biotite adamellite is greyish-white (Fig. 2b'), with a medium-grain granitic texture and massive structure. The rock has a typical discontinuous unequal crystal grain texture. The phenocryst and matrix are observably separated between localized intergranular grains. The matrix is phanerocrystalline and mainly consists of plagioclase, potassium feldspar, quartz, biotite and muscovite (Fig. 2b'). Zircon is the main accessory mineral; magnetite and monazite are occasionally produced. The phenocryst content of potassium feldspar, plagioclase, quartz and biotite accounts for approximately 25 wt%, 30 wt%, 30 wt% and 15 wt%, respectively. The post-metamorphic granite-porphyry is one of the most exposed dykes in the area and is mainly produced as dike (or apophysis) and mainly NNE striking. The post-metallogenic granite-porphyry cuts off the tin orebody in the Honghuajian tin deposit. The granite-porphyry is greyish-brown (Fig. 2c') and porphyry textured with a massive structure and is mainly composed of potassium feldspar and quartz, containing a small amount of muscovite (Fig. 2c'), with apatite and other accessory minerals, such as zircon and pyrite, occasionally occurring. Plagioclase, potassium feldspar and quartz are the main components of phenocryst, accounting for 42 wt% of the total rock. The matrix accounts for 48 wt% of the total rock and has a microcrystalline inlaid texture, with microcrystalline feldspar and quartz as its main components.

3 Analytical Methods

In this study, 15 samples were collected from typical deposits in the Pengshan Sn-polymetallic ore field. Among these samples, five muscovite-granite samples, ZJL-1, ZJL-2, ZJL-3, ZJL-4 and ZJL-5, were collected from the PD163 adit of the Zengjialong tin deposit and

five biotite adamellite samples, TLX-1 (ZK0001, 1094.8 m), TLX-2 (ZK0001, 1078.1 m), TLX-3 (ZK0001, 1062.5 m), TLX-4 (ZK0001, 1040.2 m) and TLX-5 (ZK0001, 999.1 m), were collected from a borehole into the Tanlixia deposit, while HHJB-1, HHJB-2, HHJB-3, HHJB-4 and HHJB-5 were all collected from a borehole into the Honghuajian deposit.

Monomineral separation of zircon from three dated rock samples (ZJL-5, TLX-5, HHJB-5) was performed using heavy-fluid and magnetic methods. Cathodoluminescence (CL) images were taken by Gaonian Pilot Technology Co., Ltd. (Beijing), and U–Pb (LA–ICP–MS) chronological analysis was completed in the LA–ICP–MS Laboratory, Analysis and Testing Center, College of Resource and Environmental Engineering, Hefei University of Technology. The test laser was a 193 nm ComPex102 ArF, and He was used as the carrier gas to send laser denudation materials to Neptune. The beam spot diameter was set at 35 μm, and the signal receiving time was 40 s. The isotopic fractionation calibration was performed using a 91500 standard zircon sample. For every 5 zircon sites tested, 91500 standard samples were continuously tested twice (Liu et al., 2010). Glitter 4.4 was used for data processing (Griffin et al., 2008). Normal Pb correction was performed according to the steps described in Andersen (2002). IsoplottEx 2.49 was used to draw the U–Pb concordia diagram (Ludwig, 2001). The age analysis test results are presented in Table 1.

4 Analytical Results

4.1 Zircon U–Pb chronology

The U–Pb isotope data are presented in Table 1, and representative zircon CL images are shown in Figure 3. Zircon has a complete crystal form and a high euhedral degree in the shape of a long column. Three dating samples, muscovite-granite ZJL-5, biotite adamellite TLX-5 and granite-porphyry HHJB-5, were tested at 19, 22 and 15 points, respectively. The U–Pb concordia diagram is shown in Figure 3. The test points of the three samples are all concentrated on or near the concordia line. In addition, the euhedral growth zone is clearly displayed in the CL images, and the magmatic oscillatory zoning texture is clearly visible. During the experimental test, the test beam spot was reliably located within the oscillatory zoning region, resulting in data with a good concordant degree that accurately represent the age of crystallization. The weighted average age was calculated based on the test points (the 206Pb/238U age ranges from 122 Ma to 135 Ma). The determined ages of the three samples correspond to the Mesozoic, taking into account the common Pb correction. The 206Pb/238U age data can be used to calculate their crystallization ages (Griffin et al., 2004), with an age error of 2S. The weighted average values for the 206Pb/238U ages were 127.6 ± 1.7 Ma (MSWD = 0.74), 126.9 ± 1.6 Ma (MSWD = 0.60) and 126.6 ± 2.0 Ma (MSWD = 0.60), representing the diagenetic ages of these three groups of rocks, namely, muscovite-granite, biotite adamellite and granite-porphyry, respectively. These results indicate that the three groups of rocks are relatively close in age (approximately 127 Ma). They are similar to
the Rb-Sr isochronous age (126.2 ± 2.6 Ma) of the fine-biotite granite from the Xianglushan tungsten deposit, where is on the north margin of Jiangnan Uplift, Xiushui County (Zhang et al., 2008). Therefore, they are the products of Early Cretaceous magmatism both.

<p>| Table 1 LA-ICP-MS zircon U-Pb dating data of rocks in the Pengshan Sn-polymetallic ore field |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|</p>
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<th>U (ppm)</th>
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<th>207Pb/235U</th>
<th>208Pb/232U</th>
<th>206Pb/238U</th>
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4.2 Geochemical characteristics
4.2.1 Major element features
The major and trace elements compositions of 12 samples of muscovite-granite (ZJL-1, ZJL-2, ZJL-3, ZJL-4), biotite adamellite (TLX-1, TLX-2, TLX-3, TLX-4) and...
Table 2 Major (wt%) and trace (ppm) element compositions of rocks in the Pengshan Sn-polymetallic ore field

<table>
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<tr>
<th>Sample No</th>
<th>Muscovite-granite</th>
<th>Biotite adammellite</th>
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Table 2 Major (wt%) and trace (ppm) element compositions of rocks in the Pengshan Sn-polymetallic ore field

- **Table 2**: The table presents the major (wt%) and trace (ppm) element compositions of rocks in the Pengshan Sn-polymetallic ore field. The data includes a range of elements such as SiO₂, Al₂O₃, Fe₂O₃, FeO, CaO, MgO, K₂O, Na₂O, MnO, TiO₂, P₂O₅, LOI, K, Ca, Mg, Sc, Ho, Gd, Cu, Th, Cs, Sc, Er, V, and Zr. The table compares the compositions across different samples, categorized as Muscovite-granite, Biotite adammellite, and Granite-porphyry. The elements are listed in various columns, with concentrations expressed in weight percent (%) and parts per million (ppm). The data is presented in a tabular format, allowing for easy comparison and analysis of the compositions across different samples.
granite-porphry (HHJB-1, HHJB-2, HHJB-3, HHJB-4) are presented in Table 2. Their major element features include high silicon (SiO$_2$ = 72.82 wt%–75.97 wt%), high Al$_2$O$_3$ (12.24 wt%–14.20 wt%), low titanium (TiO$_2$ = 0.04 wt%–0.12 wt%), A/CNK = Al$_2$O$_3$/\((\text{Na}_2\text{O} + \text{CaO} + \text{K}_2\text{O})\) (1.06–2.11, average value 1.36), and they belong to peraluminous (or strongly peraluminous) series rocks; the K$_2$O/Na$_2$O values range from 0.89 to 59.70, with high potassium (K$_2$O = 3.47 wt%–5.97 wt%) and low MgO (0.04 wt%–0.60 wt%). In summary, the major elements of the muscovite-granite, biotite adamellite and granite-porphry in Pengshan, Jiangxi, reflect the characteristics of high silicon and rich alkali and belong to high-potassium, calc-alkaline, peraluminous (or strongly peraluminous) granite (Table 2, Figs. 4a–b).

4.2.2 Trace element characteristics

The test results for the trace elements from the 12 granite samples are presented in Table 2. The SREE content is 13.13–108.33 ppm. The muscovite-granite has a lower SREE content than the other two samples (Fig. 5a). LREE is richer than HREE, the \((\text{La}/\text{Yb})_n\) normalized ratio is 1.54–15.90 (Fig. 5a), Eu depletion is relatively strong (Eu/Eu$^*$ = 0.09–0.29, with an average of 0.17), and the LREE/HREE (and Eu/Eu$^*$) ratio decreases with the increase in the differentiation index DI. The increase in the DI is due to the process of magma fractional crystallization, which enhances and increases acidity (Table 2), indicating that the fractional crystallization of monazite, allanite (LREE-enriched minerals) and plagioclase (Eu-enriched minerals) may have occurred during diagenesis. The chondrite-normalized REE distribution patterns of the muscovite-granite and biotite adamellite samples exhibit a small-angle right-inclined pattern, while the REE distributions patterns of the granite-porphyry exhibit a large-angle right-inclined pattern (Fig. 5a). All three groups of samples show strong Eu depletion indicative of highly evolved granite. The TE$_{1,3}$ value (intensity index of the REE tetrad effect) of the three groups of samples is between 1.10 and 1.41 (please refer to Irber (1999) for the details of calculating TE$_{1,3}$), indicating that the tetrad effect is relatively easy to observe (the TE$_{1,3}$ values are greater than 1.10). The La/Yb ratio of the 12 samples shows a trend of partial melting and fractional crystallization with increases in the La content (Fig. 4c).

Figure 5b and Table 2 indicate that the granites in this area are characterized by the enrichment of LILE (large ion lithophile elements such as Rb, Th and U, etc.) and the strong depletion of barium (Ba), strontium (Sr) and titanium (Ti), basically consistent with Yanshanian peraluminous granites in Dahutang, northern Jiangxi (Xiang et al., 2012a, b). Generally, Eu, Sr and Ba are more easily enriched in plagioclase. When plagioclase remains in a magma source region during the partial melting process or when plagioclase that crystallized in the later magma fractional crystallization process is separated from magma, Eu, Sr and Ba in magma will be strongly depleted. In addition, the positive anomaly of Rb may be caused by the dehydration and melting of Rb-rich mica in the magma source region. In the process of magma evolution, rutile retention in the source region may be an important cause of Ti loss.
5 Discussions

5.1 Diagenetic and metallogenic age

Based on field observations and borehole cores, muscovite-granite stock is closely related to metallogenesis and intrudes into the non-ore-forming biotite adamellite batholith and strata, while granite-porphyry veins cut off tin orebodies and are post-metallogenic granite. Muscovite-granite and biotite adamellite are important components of the Pengshan hidden granite body. The Pengshan diapir dome structure and the related acidic magmatism control the distribution of the Sn-polymetallic metallogenic series in this area, constituting the basic outline of the "halo-type" distribution in the Pengshan Sn-polymetallic ore field.

Table 1 and Figure 3 indicate that the zircon U–Pb ages of the muscovite-granite, biotite adamellite and granite-porphyry are 127.6 ± 1.7 Ma, 126.9 ± 1.6 Ma and 126.6 ± 2.0 Ma, respectively. These dating data are basically in accordance with the evolution rule from the biotite adamellite to the muscovite-granite, to Sn-polymetallic orebody and to granite-porphyry in this area in terms of the space-time relationship. This result is basically consistent with the Rb–Sr isochron age of 127 ± 4 Ma obtained by Ma (1989), the SHRIMP and LA–ICP–MS zircon U–Pb ages of the Pengshan granite body (128 ± 1 Ma and 129 ± 2 Ma, respectively) obtained by Luo et al. (2010a, b), and the cassiterite LA–MC–ICP–MS U–Pb age of 129 ± 2.5 Ma obtained by Xu et al. (2015) from the Jianfengpo deposit. The granite in the Pengshan ore field has a relatively narrow age of consolidated diagenesis and is the product of Early Cretaceous magmatism.

The Pengshan ore field has multiple ore species and multiple deposit types. In terms of spatial relationships, deposits with industrial value all occur in a relatively limited area near the contact zone between the Pengshan
hidden granite body and the favorable strata for metallogenesis and have a mineralized zonation (tin mineralization to lead–zinc mineralization zoning) away from the granite body, suggesting that they are magmatic hydrothermal deposits. On the time scale, the cassiterite metallogenic age of the Jianfengpo deposit is 129.7 ± 2.5 Ma (Xu et al., 2015), earlier than the post-metallogenic granite–porphyry age of 126.6 ± 2.0 Ma measured in this study, and conforms to the geological facts of the region. Therefore, we believe that the Pengshan Sn-polymetallic metallogenesis occurred close in time to the emplacement age of the Pengshan hidden granite body and that the diagenesis and metallogenesis of the field belong to the Jurassic–Cretaceous diagenesis and metallogenesis system. As a consequence, the formation of the Pengshan Sn-polymetallic ore field simultaneously corresponds to the Yanshanian tungsten–tin large-scale metallogenesis (Hua et al., 2005).

5.2 Classification of petrogenesis types

Luo et al. (2010a, b) classified Pengshan granite as I-type granite according to its low $P_2O_5$ content and ACF diagram. $P_2O_5$ decreases with increases in $SiO_2$ in Early Cretaceous granites in this area (Table 2), contrary to the evolutionary trend of typical I-type granites, and exhibits a negative evolutionary trend consistent with S-type granites. Furthermore, the REE distribution patterns of the 12 samples from the three groups of rocks are of the seagull-type, with a small-angle right inclination (Fig. 5a), different from the characteristics of no Eu loss (or weak Eu loss) in I-type granite. In terms of the trace element characteristics, the $10^4 \times Ga/Al$ value of the 12 granites is relatively high ($10^4 \times Ga/Al = 2.84–4.28$, with an average of 3.25), exhibiting some characteristics of A-type granite (the lower limit ratio of $10^4 \times Ga/Al$ of A-type granite is 2.6, Whalen et al., 1987). However, their $10^4 \times Ga/Al$ values (average 3.25) are low compared with typical A-type granites (3.75, Whalen et al., 1987), which may be related to the increase in aluminum content caused by the relatively high differentiation degree of the rocks, which all have relatively high differentiation indexes (DI) (DI = 87.6–94.6, average 92.1, Table 2). In addition, the total contents of Zr, Nb, Ce and Y in the rocks are all lower than the corresponding contents of A-type granites, and the content ratio of $K_2O + Na_2O$ to $Ca$ in the rocks is also lower than the corresponding lower limit value for A-type granites (Fig. 4d), so they are not A-type granite. In addition, the zircon saturation temperature ($T_{Zr} = 662–787^\circ C$, average 740°C, calculated from Watson and Harrison, 1983) is lower than that of A-type granite and is close to the $T_{Zr}$ value of 764°C (King et al., 1997) for S-type granite.

In summary, the rocks in this area are characterized by a high silicon content and are rich in alkali. The rocks belong to high-potassium, calc-alkaline, peraluminous (or strong peraluminous) granite and have a high degree of differentiation (the average DI was 92.1). The REE distribution patterns of the rocks are characteristic of seagull-type patterns (Fig. 5a). In addition, the spider diagram of the trace elements is generally high on the left and low on the right with a gradual decrease (Fig. 5b). The petrographic characteristics mentioned above have been described and combined with field and laboratory microscopic observations. Hornblende and sphen are not found within the granite, but some aluminum-rich minerals, such as muscovite, garnet and topaz, have appeared, reflecting the observation that silica-aluminous crust material plays a very important role in magma composition. Therefore, the Yanshanian muscovite-granite, biotite adamellite and granite–porphyry in the
Pengshan Sn-polymetallic ore field are all highly fractionated S-type granite.

5.3 Origin and evolution of magma

The REE of the three groups of rock samples all show right-inclined distributions patterns with a strong Eu depletion (Fig. 5a), and the LREE/HREE and Eu/Eu* values decrease with increases in the differentiation index DI (Table 2), indicating that fractional crystallization of monazite, allanite (LREE-enriched minerals) and plagioclase (Eu-enriched minerals) may have occurred during magma evolution. The three groups of rocks are highly evolved granites. Ba, Eu and Sr tend to be enriched in plagioclase, and the trace element characteristics indicate a strong depletion of Ba and Sr (Fig. 5b). This finding implies the fractional crystallization of plagioclase and indicates that the rock is partially melted from crust-derived materials (Harris and Inger, 1992). The La/La/Yb magma evolution trend diagram (Fig. 4c) shows that both fractional crystallization and partial melting contributed to the magma evolution process (Chung et al., 2009). The Eu/Eu*(La/Yb) source region discrimination diagram (Fig. 6a, Wang et al., 1989) shows the characteristics of crustal origin. Taylor and McLennan (1985) believe that during the evolution of the crust-mantle separation, Rb is continuously enriched in the silicon-aluminum layer, increasing the Rb/Sr and Rb/Nb ratios. The Rb/Sr ratios (4.56–41.72, with an average of 20.56) and Rb/Nb ratios (19.75–38.95, with an average of 26.64) of the 12 granites are much higher than those typical of the upper crust. The averages of 0.32 and 4.48 (Taylor and McLennan, 1985), respectively, suggest that the 12 granites may have evolved from highly mature continental crust materials. The La/Ta ratio (0.15–8.87, averaging 4.10) of the rocks in this area is obviously smaller than that of magma originating from a mantle source (or part of the mantle source) (>25, Lassiter et al., 1997), so there is no contribution of mantle source materials to the formation of the granites in this area. In addition, the rocks in this area have a relatively high Rb/Ba ratio (Fig. 6b, Sylvester, 1998), and the data points for muscovite-granite and biotite adamellite all fall within the clay-rich sources region, near the pelite-derived rock end-member (Fig. 6b); the data for the other four post-metamorphic granite-porphries are far from the pelite-derived end-member and close to the psammitic-derived end-member (Fig. 6b), showing that the Pengshan muscovite-granite and biotite adamellite mainly originated from the partial melting of metapelites with high maturity, while the post-metamorphic granite-porphries originated from arenaceous rocks. Of course, this result is also supported by the presence of the major elements CaO and Na₂O. The ratio of CaO to Na₂O in muscovite-granite and biotite adamellite is from 0.12–0.27 (average 0.16), which is less than 0.3. However, the ratio of CaO to Na₂O of the post-metamorphic granite-porphry is from 0.10–2.70 (average 2.02), basically greater than 0.3 (Sylvester, 1998). The data show that the two-stage model age TDM2 for the zircon Hf isotopes of the Pengshan granite body is mainly concentrated in the range of 1.2–1.5 Ga (Luo et al., 2010a), which is lower than the spilite age of the Shuangqiaoishan Group in the Pengshan area by 1515 ± 24 Ma, showing that the muscovite-granite and biotite adamellite in the Pengshan Sn-polymetallic ore field mainly originated from the partial melting of metapelites of the Shuangqiaoishan Group, while the post-metamorphic granite-porphries originated from meta-arenaceous rocks of the Shuangqiaoishan Group. The difference in the source rock properties may be one of the main factors leading to metallogenesis. Therefore, the high Sn content of the metapelites in the Shuangqiaoishan Group may be the initial source of Sn in the Pengshan Sn-polymetallic ore field.

Admittedly, if the Pengshan hidden granite body only formed by the partial melting of the abovementioned metapelites with high maturity and high differentiation, it is difficult to explain the fractionation phenomenon of Nb–Ta and Zr–Hf, which have similar chemical habits. Černý et al. (1986) believe that the two groups of trace elements Nb–Ta and Zr–Hf will be fractionated and that their ratios will decrease under the conditions of the fluid-melt interaction during the melting process of crust-
derived type granites (Green, 1995). The Nb/Ta ratios (2.14–7.50) and Zr/Hf ratios (15.50–29.76) of the 12 granites in this area are lower than those of normal granites, which have ratios of 11 and 33–40, respectively (Dostal and Chatterjee, 2000); therefore, the characteristics of elemental fractionation are obvious and suggest that the metapelites with high maturity experienced a strong fluid-melt interaction during the evolution of partial melting. This finding is also supported by the evidence of granite TE_{1.3} (intensity index of REE tetrad effect). The TE_{1.3} values of the samples range between 1.10 and 1.41, which are greater than 1.10. The "seagull-type" quadruple distribution of REE is shown in Figure 5a, confirming the existence of the REE tetrad effect (Irber, 1999). Whitney (1988) believes that when the interaction between fluid and melt is sufficient, a selective complexation between REE and fluid occurs, thus forming the REE tetrad effect (Irber, 1999). In addition, the Nb/Ta ratio (2.14–5.66, with an average of 3.90) and Zr/Hf ratio (15.50–20.00, with an average of 17.81) of the metallogenic muscovite-granite are both lower than those of the non-ore-forming granite (biotite adamellite, granite-porphyry) (Nb/Ta = 5.24–7.50, average 6.60; Zr/Hf = 27.32–29.76, average 28.39). The TE_{1.3} values of the metallogenic muscovite-granite (1.28–1.41, average 1.35) are generally higher than those of the non-ore-forming granite (1.10–1.16, average 1.14), suggesting that the fluid-melt interaction intensity of the metallogenic muscovite-granite is higher than that of the non-ore-forming granite. In fact, in the late stage of magma evolution, the ore-bearing fluid extracted after the relatively sufficient interaction between melt and fluid makes it a necessary condition for the occurrence of later metallogenesis (Xiang et al., 2015a, b, c). As a result, the muscovite-granite intruded in the Early Cretaceous and has a lowSREE content (Fig. 5a), a higher degree of differentiation (the DI average value is as high as 93.54, greater than the other two DI values, which have an average of 91.44), more sufficient evolution (with a high strength of fluid-melt interaction), and more ore-rich source rocks (the Sn-rich source bed of metapelites in the Shuangqiaoshan Group) than other non-ore-forming granites. These factors are the basic conditions to induce tin concentration and mineralization in the Pengshan Sn-polymetallic ore field.

5.4 Discussion on metallogenic dynamics mechanism

Pearce et al. (1984) attributed the formation and emplacement of the parent magma of S-type granite (or strongly peraluminous granite) to the collision and compression environment, but the important contribution of extensional tectonics to granite genesis was supported by many other researchers (Pearce, 1996; Healy et al., 2004). Some researchers think that all granites formed in a late stage of magma evolution of partial melting. This finding is also supported by the evidence of granite TE_{1.3} (intensity index of REE tetrad effect). The TE_{1.3} values of the samples range between 1.10 and 1.41, which are greater than 1.10. The "seagull-type" quadruple distribution of REE is shown in Figure 5a, confirming the existence of the REE tetrad effect (Irber, 1999). Whitney (1988) believes that when the interaction between fluid and melt is sufficient, a selective complexation between REE and fluid occurs, thus forming the REE tetrad effect (Irber, 1999). In addition, the Nb/Ta ratio (2.14–5.66, with an average of 3.90) and Zr/Hf ratio (15.50–20.00, with an average of 17.81) of the metallogenic muscovite-granite are both lower than those of the non-ore-forming granite (biotite adamellite, granite-porphyry) (Nb/Ta = 5.24–7.50, average 6.60; Zr/Hf = 27.32–29.76, average 28.39). The TE_{1.3} values of the metallogenic muscovite-granite (1.28–1.41, average 1.35) are generally higher than those of the non-ore-forming granite (1.10–1.16, average 1.14), suggesting that the fluid-melt interaction intensity of the metallogenic muscovite-granite is higher than that of the non-ore-forming granite. In fact, in the late stage of magma evolution, the ore-bearing fluid extracted after the relatively sufficient interaction between melt and fluid makes it a necessary condition for the occurrence of later metallogenesis (Xiang et al., 2015a, b, c). As a result, the muscovite-granite intruded in the Early Cretaceous and has a lowSREE content (Fig. 5a), a higher degree of differentiation (the DI average value is as high as 93.54, greater than the other two DI values, which have an average of 91.44), more sufficient evolution (with a high strength of fluid-melt interaction), and more ore-rich source rocks (the Sn-rich source bed of metapelites in the Shuangqiaoshan Group) than other non-ore-forming granites. These factors are the basic conditions to induce tin concentration and mineralization in the Pengshan Sn-polymetallic ore field.

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The Pengshan ore field extends from the mid-segment of the Jiangnan Uplift to the MLYDZ. Although the tectonic stress field is constrained by the combination of the two secondary tectonic units, the time of tectonic system transformation is closer to the MLYDZ because the spatial orientation of the area is enclosed in the MLYDZ. The area including Pengshan (128 Ma), Dongping (133 Ma, Hu et al., 2018) and Xianglushan (126 Ma, Zhang et al., 2008), lies at the transition belt between the Jiangnan Uplift and the MLYDZ northern Jiangxi Province, and forms a tertiary tungsten–tin metallogenic belt controlled by a boundary fracture (Jiangnan Deep Fracture) of the two secondary structural unit (Fig. 1a).

It is worth mentioning that recently in the Ao’xia area, located approximately 50 km NW of the Pengshan ore field, boreholes have revealed a hidden granite body under the Ao’xia area. The zircon LA–ICP–MS age of the biotite adamellite collected is 128.6 ± 0.9 Ma. The main and trace element characteristics are similar to those of the granite in the Pengshan Sn-polymetallic ore field, and the ore-forming element assemblage is also highly consistent (reported in another paper). Therefore, the compression-extension transformation of the tectonic stress field at approximately 128 Ma simultaneously dominated the geodynamic evolution of the Ao’xia area, and the metallogenic regularity of the Pengshan area occurred in the transition period of orogenic compression-extension on the continental margin at the junction of the Middle–Lower Yangtze Depression Zone and the Jiangnan Uplift. It is a positive response to magmatic events accompanied by lithospheric thickening and thinning at the turn of the Jurassic–Cretaceous Period in eastern China.

6 Conclusions

(1) The zircon U–Pb ages of the muscovite-granite, biotite adamellite and granite–porphyry in the Pengshan Sn-polymetallic ore field are 127.6 ± 1.7 Ma, 126.9 ± 1.6 Ma and 126.6 ± 2.0 Ma, respectively. The compression-extensional tectonic transformation in Pengshan Sn-polymetallic ore field occurred approximately 128 Ma, the diagenesis and metallogenesis of the Pengshan area occurred in the transition period of orogenic compression-extension on the continental margin at the junction of the Middle-Lower Yangtze Depression Zone and the Jiangnan Uplift. It is a positive response to magmatic events accompanied by lithospheric thickening and thinning at the turn of the Jurassic–Cretaceous Period in eastern China.

(2) The granites in Pengshan are characterized by a high silicon content and are rich in alkali. They belong to high-potassium, calc-alkaline, peraluminous (or strong peraluminous) granite and are all highly fractionated S-type granite.

(3) The muscovite-granite has a low SREE content, a higher degree of differentiation, more sufficient evolution, and more ore-rich source rocks than other non-ore-forming granites. These factors are the basic conditions to induce tin concentration and mineralization in the Pengshan Sn-polymetallic ore field.
(4) The area including Pengshan (128 Ma), Dongping (133 Ma) and Xianglushan (126 Ma), lies at the transition belt between the Jiangnan Uplift and the MLYDZ northern Jiangxi Province, and forms a tertiary tungsten–tin metallogenic belt controlled by a boundary fracture (Jiangnan Deep Fracture) of the two secondary structural unit.

(5) The compression-extension transformation of the tectonic stress field at approximately 128 Ma simultaneously dominated the geodynamic evolution of the Ao’xia area, and the metallogenic regularity of the Pengshan ore field was not the single-center "halo-type" horizontal zoning assumed previously but a multicenter vertical zoning including the Ao’xia area, which validates the prospecting idea of an abutting joint between the north-west Pengshan area and the southeast Ao’xia.

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