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Mineralogical feature and geological significance of muscovites from the Longyuanba Indosinian and Yanshannian two-mica granites in the eastern Nanling Range

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Emplacement *P*-*T* condition estimations using granites are important for understanding metamorphic and erosional processes of orogenic belt. Granites are widespread in South China and a majority of them are peraluminous. Particularly, over 91% of the Indosinian granites exposed in the region are peraluminous in composition. It is extremely hard to determine the pressure of intrusion of these peraluminous granites due to the absence of amphibole, a good mineral barometer commonly identified in metaluminous granites. Muscovite is a common mineral in peraluminous granites, certain kind of it could be used as a mineral barometer to constrain the emplacement pressure of peraluminous granites. In this paper, results of petrographic and geochemical studies of muscovites from the Indosinian and early Yanshanian two-mica granites at the Longyuanba in the eastern Nanling Range are reported. Based on petrographic studies, the primary muscovite can be discriminated from the secondary muscovites. Muscovites from the Indosinian two-mica granites are enriched in Ti, Al, Mg, and Na, and depleted in Fe and Mn. Geochemically, these muscovites were considered as primary, whereas those from the Yanshanian two-mica granites fall into the area of secondary muscovite on discrimination diagrams. Barometer estimations show that pressures calculated for primary muscovites are accurate, but those calculated for secondary muscovites are overestimated. The average pressure of emplacement of the Longyuanba Indosinian two-mica granites is 5.9 kbar, corresponding to ~19 km in depth, suggesting that the Indosinian granitic magmas were probably generated by partial melting of a thickened crust root in a compressional tectonic setting.

emplacement depth, muscovite, peraluminous granites, Longyuanba complex, Nanling Range

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Estimating emplacement *P*-*T* conditions for the granites is an important method for understanding metamorphic and erosion process of orogeny (Anderson, 1996; Anderson et al., 2008). The Indosinian peraluminous granites (over 91% of the Indosinian granitoids are peraluminous, Zhou et al., 2006), associated with the intensive Triassic intracontinental orogeny, are widespread in south China. However, the intrusive pressure of these peraluminous granites is hard to determine due to the absence of a decent barometer, e.g., Al-in-amphibole barometer commonly used for metaluminous granites.

Muscovite ($KAl_2[AlSi_3O_{10}](OH)_2$) is one of the characteristic minerals of peraluminous granites. Its A/CNK value (=moles Al_2O_3/[moles($CaO+Na_2O+K_2O$)]) is 1.5 in the peraluminous granites (Clarke, 1981). There are primary and

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*Corresponding author (email: liwx@gig.ac.cn) secondary muscovites. The former refer to those crystallized directly from granitic melt, whereas the latter include all those transformed from other minerals by hydrothermal alteration under subsolidus conditions (Miller et al., 1981). Similar to some amphibole, primary muscovites can also be used to constrain depth of magma emplacement. Eleven km is considered as the minimum formation pressure for the primary muscovites (Anderson et al., 1981). Velde proposed a phengite barometer, based upon the fact that Si content in the muscovite increases with pressure (Velde, 1965, 1967).

The following petrographic features are important criteria for distinguishing primary muscovites from secondary ones: primary muscovites are generally subhedral to euhedral; they have comparable grain size to those of other rock-forming minerals; they are not enclosed by and do not enclose any other minerals. These petrographic features are different from those of the secondary muscovites (Velde, 1965, 1967; Miller et al., 1980, 1981; Speer, 1984; Ham et al., 1988; Gomes et al., 2000; Sun et al., 2002; Wang et al., 2006). However, uncertainty exists for the discrimination between primary muscovite and secondary muscovites using petrographic method. As a result, chemical criteria have been proposed to discriminate primary muscovites from secondary muscovites (Miller et al., 1981). Recently, Zhang et al. (2010) showed that some muscovites react with biotite. They proposed that these muscovites are metasomatic in origin, suggesting that they were formed by the replacement of early crystallized biotite at the late stage of magma evolution. These muscovites could be discriminated as secondary, though they are primary as they were formed in magma environment.

The Longyuanba complex, located in the eastern Nanling Range, is composed of the Indosinian granites and Yanshanian granites. Although products of the two-stage magmatism are different in mineral assemblage, petrological geochemistry, and tectonic setting, they both contain two-mica granite. There are obvious geochemical differences in the muscovite between the two-stage granites. In this paper, geochemistry of these muscovites is studied and the formation pressure is estimated. We discuss the application of muscovite barometry, too. In general, muscovite barometry provides a useful way for constraining depth of crystallization of the peraluminous granite.

1 Granite complex description

The Longyuanba granite complex crops out in the Town Longyuanba of Longnan County in southern Jiangxi Province, and has an outcrop area of about 500 km^2. It is a complex composed of the Indosinian and Yanshanian granites (Figure 1).

The Indosinian granites contain biotite granite and two-mica granite, both of which are peraluminous (Zhang et al., 2006; He et al., 2010). The coarse-grained massive biotite granite is porphyritic in texture. The oriented K-feldspar occurs as megacryst. Rock-forming minerals include K-feldspar (20%–40%), plagioclase (30%–35%), quartz (20%–30%), biotite (5%–10%), and minor magmatic epidote (~1%). The accessory minerals include zircon, titanite, apatite, allanite and Fe-Ti oxides. Two-mica granite is massive, showing fine- to medium-grained porphyritic texture with K-feldspar being the main phenocryst. The main rock-forming minerals include K-feldspar (25%–40%), plagioclase (20%–30%), biotite (5%–10%) and muscovite (3%–7%). Accessory minerals include zircon, apatite and Fe-Ti oxides.

The Yanshanian granites are highly evolved I-type granites (Tao et al., 2013). Biotite granite and two-mica granite are the major rock types. Biotite granite is characterized by massive coarse-grained, porphyritic or granitic textures; the main rock-forming minerals include quartz (20%–30%), K-feldspar (30%–50%), plagioclase (15%–40%), and biotite (~5%). Some potassic feldspars occur as megaphenocrysts, and contain inclusions of plagioclase and chloritized biotite. All plagioclase suffered varying degrees of sericitization. The biotite has been mostly chloritized. Carbonatization can be found occasionally in these rocks. The accessory minerals include zircon, apatite, and Fe-Ti oxides. Two-mica granites show massive, fine- to medium-grained granitic textures. They are composed of quartz (30%–40%), potassic feldspar (30%–50%), plagioclase (25%–30%), biotite (~7%), muscovite (~3%), and accessory minerals zircon, apatite, and Fe-Ti oxides. Quartz is anhedral and interstitial. K-feldspar is anhedral and has been locally altered to sericite. Plagioclase occurs as subhedral to anhedral grains with strong sericitization. Biotite grains are red-brown and brownish yellow and part of them has been chloritized and sericitized. The accessory minerals include zircon, apatite, and Fe-Ti oxides.

2 Petrographic feature of muscovite

Based upon petrographic observation, the Longyuanba Indosinian two-mica granites and Yanshanian two-mica granites contain 3%–7% and ~3% muscovites respectively. They can be subdivided into primary muscovites and secondary muscovites according to the textural criteria (Miller et al., 1981; Speer, 1984; Sun et al., 2002; Roycroft, 1991).

The primary muscovites sampled from the Indosinian two-mica granites are coarse in size. They are cleanly terminated and are euhedral-subhedral in crystal form (Figure 2(a)), and some of them are enclosed by K-feldspar. Secondary muscovites, however, show metasomatic relations with biotites, and seem to be uncleanly terminated (Figure 2(b)). It is noteworthy that no zoned muscovite can be found under microscope.

The primary muscovites in the Yanshanian two-mica granites are coarse in size. They are cleanly terminated, euhedral to subhedral and have similar size to the other

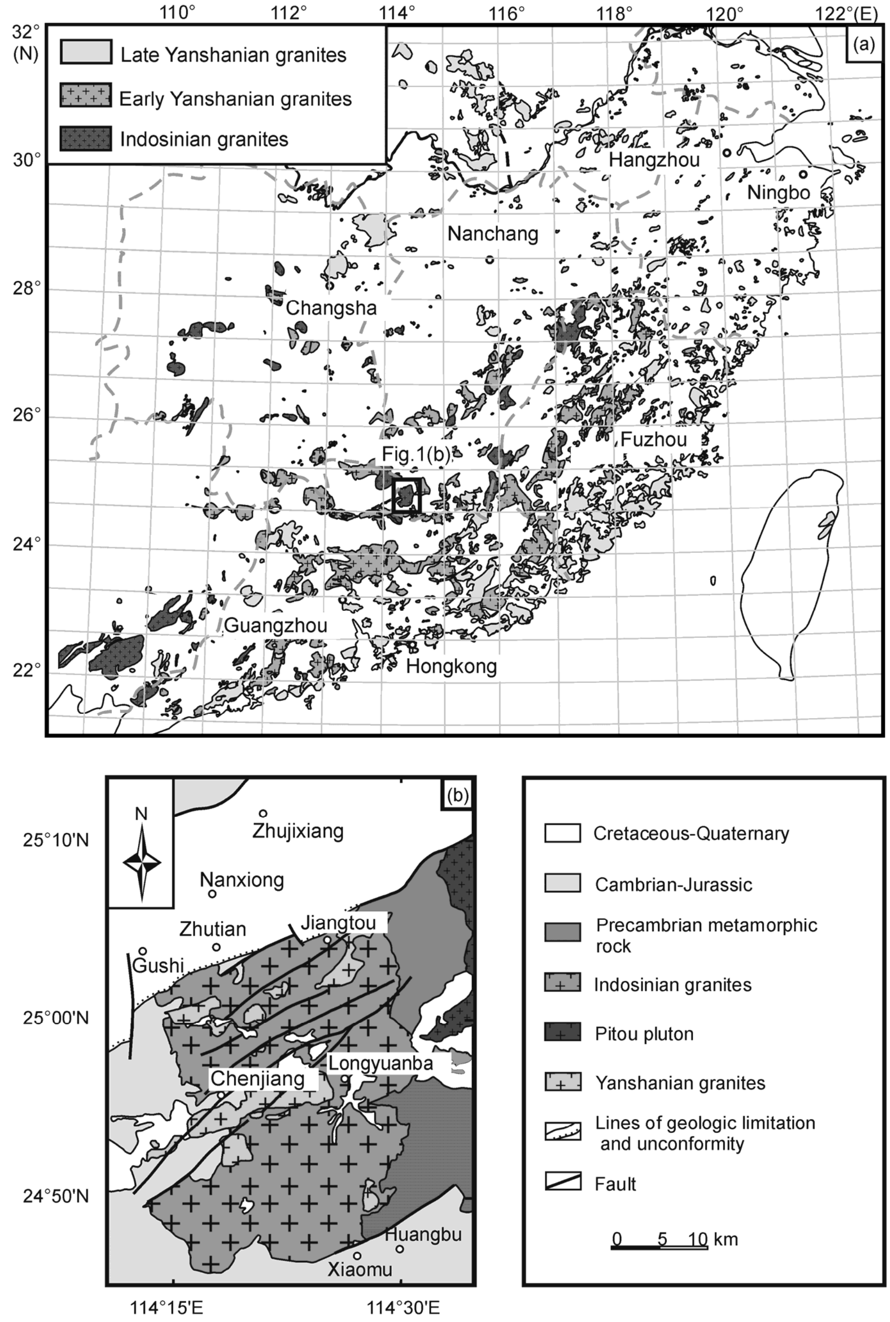

Figure 1 (a) A sketch map showing distribution of Mesozoic granitoids in southeast China (after Li et al., 2007); (b) a simplified geological map of the Longyuanba complex (modified from Zhang et al., 2006; footnote 1)).

rock-forming minerals. The muscovites are interstitial between feldspar and quartz, suggesting that they were crystallized later than feldspar and quartz (Figure 2(c)). Differently, secondary muscovites appear as fine lamella and scatter randomly. They have metasomatic relations with biotites, and are uncleanly terminated (Figure 2(d)). No zoning is observed in the muscovites.

Although both types of muscovites described above have fine sericite grains formed from early crystallized K-feldspars and plagioclase, we will discuss them further.

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1) Heavy Industry Bureau of Jiangxi Province and Geological Bureau of Guangdong Province. 1970. Report of Region Geology and Mineral Resource of Longnan, 1∶200000 (in Chinese).

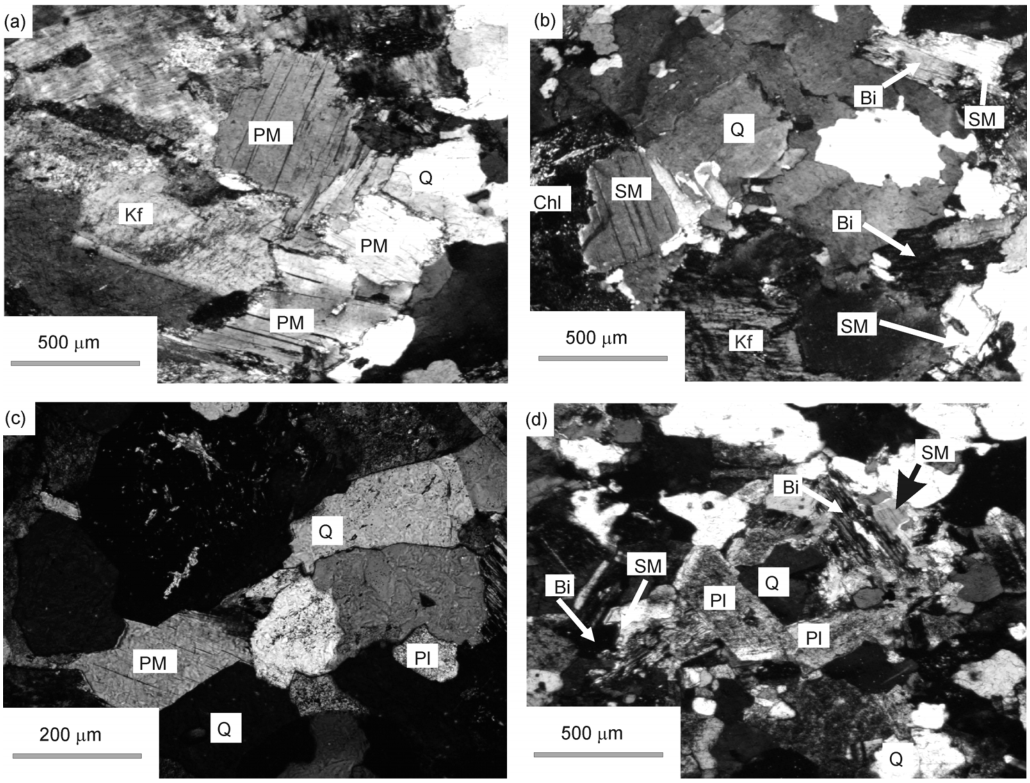

Figure 2 Micrograph of primary and secondary muscovites from the Indosinian ((a), (b)) and Yanshanian ((c), (d)) two-mica granites of the Longyuanba complex. Q-quartz; Pl-plagioclase; Kf-K-feldspar; Bi-biotite; PM-primary muscovite; SM-secondary muscovite.

3 Microprobe analyses

Chemical compositions of muscovites from the Longyuanba Indosinian and Yanshanian two-mica granites were analyzed on well-polished thin sections using electron-microprobe (EPMA). The analytical results are available in Supplemental Table (Table S1), and cations were calculated based on 22 oxygen atoms.

Based on data in Table S1 (http: link.springer.com; http: earth.scichina.com), the calculated average crystallochemical formulas for primary muscovites and secondary muscovites from the Longyuanba Indosinian two-mica granites are depicted as follows: $K_{1.77}Na_{0.13}Fe_{0.31}Mg_{0.21}Al_{3.46}[Al_{1.73}Si_{6.22}]O_{20}(OH)_4$ (primary muscovites), $K_{1.71}Na_{0.12}Fe_{0.29}Mg_{0.19}Al_{3.49}[Al_{1.75}Si_{6.20}]O_{20}(OH)_4$ (secondary muscovites). The average crystallochemical formulas of primary muscovites and secondary muscovites in the Longyuanba Yanshanian two-mica granites are demonstrated as follows: $K_{1.85}Na_{0.07}Fe_{0.86}$-$Mg_{0.14}Al_{3.27}[Al_{1.64}Si_{6.26}]O_{20}(OH)_4$ (primary muscovite) and $K_{1.80}Na_{0.07}Fe_{0.74}Mg_{0.10}Al_{3.42}[Al_{1.71}Si_{6.20}]O_{20}(OH)_4$ (secondary muscovites). Not all muscovites in the Longyuanba Indosinian and Yanshanian two-mica granites are pure muscovites ($KAl_2[AlSi_3O_{10}](OH)_2$) in composition, but invariably contain substitutions such as celadonitic (KAl(Fe, Mg) ($Si_4O10)(OH)_2$) and paragonitic ($NaAl_2[AlSi_3O_{10}](OH)_2$) components (Figure 3). It can be seen in Figure 3 that paragonitic substitution is common for muscovites from the Indosinian granites, whereas more common celadonitic substitution is found in those from the Yanshanian granites.

4 Discussion

4.1 Discrimination between primary and secondary muscovites

Primary and secondary muscovites can be distinguished easily based on petrographic features, but there is no significant compositional difference between primary and secondary muscovites from the coeval two-mica granites. However, significant compositional differences have been documented for muscovites of different origins. In other words, muscovites from the Indosinian two-mica granites, both primary and secondary, have higher contents of Ti, Al, Mg and Na, and lower contents of Fe and Mn than muscovites of the Yanshanian two-mica granites. As a result, primary and secondary muscovites of a rock fall in the same fields in discrimination diagrams. It is noteworthy that all muscovites from the Indosinian two-mica granites are plotted as primary muscovites, whereas those from Yanshanian two-mica granites are plotted as secondary (Figure 4(a), (b)). The chemical criteria seem to be contradict to the textural criteria, and may be a result of that: (1) whole-rock composition acts as a controlling factor on the composition of muscovites (Monier et al., 1986; Zane et al., 1999); (2)

muscovites that coexist with biotite and exhibit metasomatic Structure may not be secondary, but actually was formed from biotite in the process of crystallization as physical-chemical conditions changed and biotite became unstable (Zhang et al., 2010).

Studies suggest that compositions of muscovite are affected not only by physical-chemical conditions at the time of crystallization but also by the whole-rock composition (Ham et al., 1988; Monier et al., 1986; Zane et al., 1999; du Bray et al., 1994), Al content in particular, as muscovites in strongly peraluminous granite commonly have higher Al contents (Zane et al., 1999). Therefore, we compare whole-rock composition and muscovite composition between the Indosinian and Yanshanian two-mica granites (Figure 5). The results show positive correlations in Ti, Al and Mg contents between muscovites and whole-rock compositions, and negative correlations in Fe, Na and K. The whole-rock composition does not correlate perfectly with the composition of muscovite, suggesting that whole-rock composition does affect the composition of muscovites, but is not a controlling factor. Miller et al. (1981) noted that petrographic discrimination is sometimes uncertain. Therefore, they proposed a set of geochemical discrimination diagrams tested using compositions of primary and secondary muscovites from granites of different ages and compositions. Sun et al. (2002) proposed another set of discrimination diagrams using the same method. Because the studied muscovites were sampled from rocks with different whole-rock compositions, it means to cancel the effect of whole-rock composition. On the discrimination diagrams, all muscovites from the Indosinian granites fall into the field for primary muscovites. We also find that secondary muscovites, discriminated using petrographic criteria, coexist and interact with biotites. Zhang et al. (2010) suggested that muscovites like these are in fact primary and were formed by replacement of biotite in supersolidus conditions. They concluded that as the crystallization temperature of the biotite (~800°C) is higher than that of the muscovite (~700°C), the muscovite could have formed by replacement of previous biotite in supersoildus conditions (Zhang et al., 2010). In contrast, all muscovites from the Yanshanian granites are plotted into the field for secondary muscovites, confirming that they belong to secondary muscovites. It is interesting that all studied Yanshanian two-mica granites show tetrad effects with their REE patterns. Our previous studies suggested that granites with Lanthanide tetrad effects were probably subjected to the hydrothermal alteration by magmatic fluids (Tao et al., 2013). Therefore, muscovites from the Yanshanian two-mica granites are most likely secondary.

4.2 Geological implications

The Mesozoic granitoids in South China are dominated by peraluminous biotite granites with their A/CNK>1.0. Al-in-amphibole barometer is not available for these peraluminous granites, making it difficult to constrain the intrusion depth of the granites. As 91% of the Indosinian granitoids are peraluminous (Zhou et al., 2006), making this problem

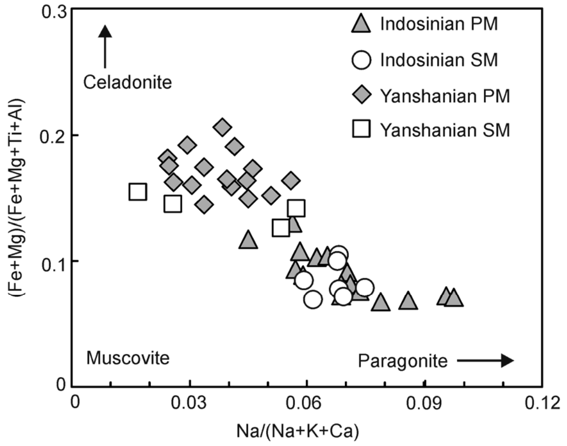

Figure 3 Chemical composition diagram of the muscovites from the Longyuanba Indosinian and Yanshanian two-mica granites (after Clarke, 1981).

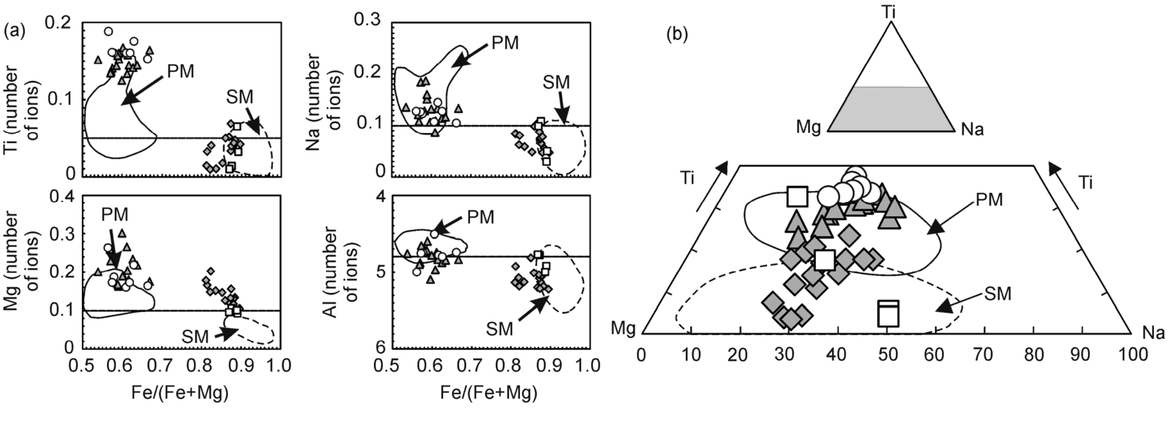

Figure 4 Geochemical discrimination diagrams of primary and secondary muscovites from the Longyuanba Indosinian and Yanshanian two-mica granites. (a) After Sun et al., 2002; (b) after Miller et al., 1981. Symbols are as in Figure 3.

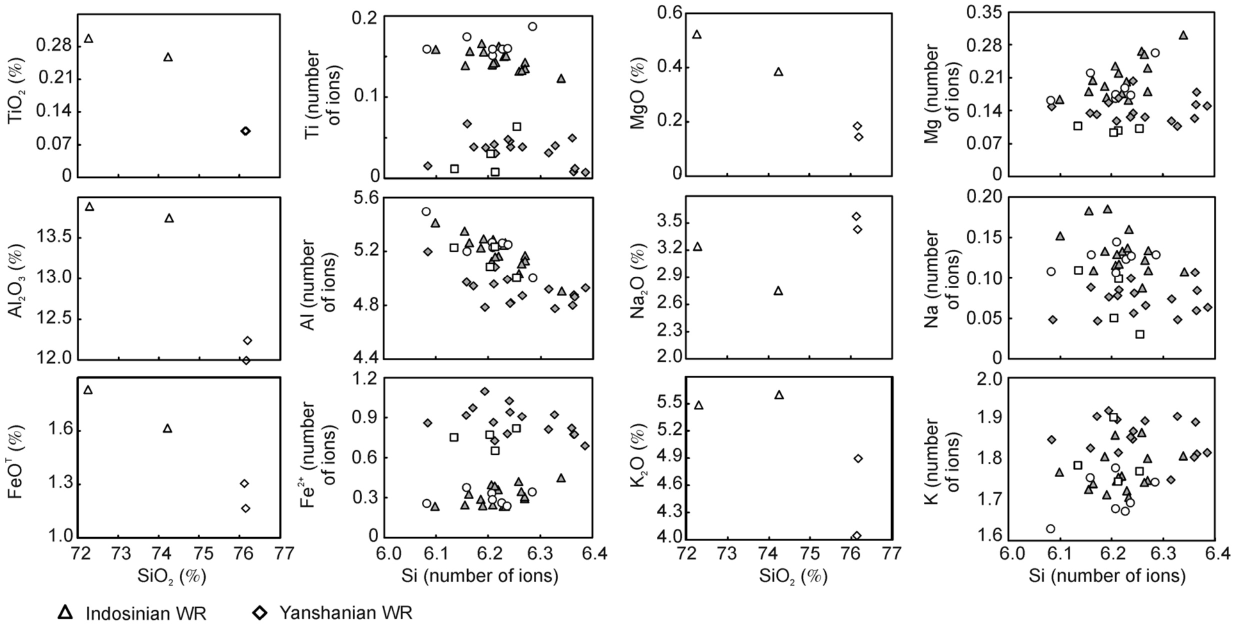

Figure 5 Comparison of whole rock and muscovite composition from the Longyuanba Indosinian and Yanshanian two-mica granites. Major elements data of the whole rock are from Zhang et al., 2006; He et al., 2010. Symbols are as in Figure 3.

even greater. Muscovite as a characteristic mineral of these peraluminous granites, however, could be used to estimate the formation pressure of the granites. The muscovite barometer was first proposed by Velde (1965). Based on new experimental data, Massonne et al. (1987) presented their calibration equation using the Si content as a function of P and T:

$$P\ (\text{kbar})=-2.6786\text{Si}^2+43.975\text{Si}+0.01253T(^\circ\text{C})-113.9995.$$

Muscovite commonly coexists with biotite, K-feldspar, and quartz in peraluminous granites, making it appropriate as a barometer (Anderson, 1996). The studied muscovites from the Indosinian two-mica granites are high in TiO_2 (0.97%–1.47%, average value of 1.20%), suggesting that they are primary muscovites (TiO_2>0.4%, Anderson, 1996). According to the equation presented above, another important parameter needs to be constrained before we could use it to constrain the intrusion pressure. The temperature of the Indosinian two-mica granites constrained using zircon-saturation thermometer is ~800°C (Watson et al., 1983; Miller et al., 2003) (calculation based on the data of Zhang et al., 2006 and He et al., 2010), which is obviously overestimated due to the presence of inherited zircons in the granites. In addition, the temperature (~800°C) is also higher than the crystallization temperature (~700°C) of muscovite inferred from experiments (Althaus et al., 1970). As the crystallization temperature of the muscovite is close to the solidus of the melt, we consider 700°C as a better formation temperature of the muscovite. The results are listed in Table S1, among them, spots 54-4-3, 54-4-4, 54-4-11, 54-4-15, 54-1-3 and 54-4-20 have low Si contents of 3.1 (Number of ions on the basis of 11 oxygens), lower than the values of muscovites which were analyzed in the barometry experiments. Moreover, the pressure values calculated from these spot data are clearly lower than those from the others, so these data were excluded. Pressures calculated from the rest data vary from 5.2 to 6.5 kbar, with an average of 5.8 kbar, corresponding to a depth of ~19 km. Based upon petrographic observation, primary muscovites from the Indosinian two- mica granites are cleanly terminated. They are coarse in size, comparable to other rock-forming mineral such as quartz, K-feldspar and plagioclase, suggesting that they all crystallized at the same time. As a result, these muscovites should be crystallized at high pressures ($\geqslant$4 kbar, Bumham, 1967). In addition, we find magmatic epidote in some coeval biotite granites. As epidote commonly formed at pressure of 4–6 kbar, its crystallization indicates that the formation pressure of the granites was also higher than 4–6 kbar (Anderson, 1996). Therefore, as noted above, the calculated pressure using muscovite barometry is consistent with petrographic observations, suggesting that the pressure of 5.8 kbar (~19 km depth) is a reasonable estimate.

The formation temperature of the Yanshanian two-mica granites is 730°C, estimated using zircon saturation thermometry (Watson et al., 1983; Miller et al., 2003) (calculation based on the data of Zhang et al., 2006 and He et al., 2010). It is very close to the temperature of the Indosinian two-mica granites (700°C). If we also use 700°C to calculate the formation pressure of the Yanshanian two-mica granites (Table S1), excluding the spots of 58-2-3, 60-2-6, 60-2-9, 58-2-5 (their Si contents are less than 3.1), the calculated results are in the range of 5.3 to 7.9 kbar (Anderson, 1996; Massonne et al., 1987) with pressure averaged at 6.4 kbar, corresponding to a depth of ~21 km. The pressure is higher than that for the Indosinian two-mica granites. We consider that the result is unreasonable for the following reasons: (1) TiO_2 contents of muscovites from the Yanshanian granites are mostly less than 0.4%. In addition, these muscovites are plotted in the area for secondary muscovites in all discrimination diagrams, suggesting that they are secondary/metasomatic muscovites; (2) The studied Yanshanian two-mica granites exhibit a tetrad effect with their REE patterns. Furthermore, most of these muscovites have high F contents (0.20%–1.51%), suggesting that they have undergone alteration. Alteration processes may change the composition of muscovites, particularly the Si atomic number of this mineral, making the pressure estimation inaccurate; (3) No evidence shows that an orogenic thickening took place after the Indosinian Orogeny in the South China Block. Therefore, the emplacement depth of the Yanshanian granites that intruded into the Indosinian granites is unlikely to be higher than that of the Indosinian granites.

Because the Mesozoic Nanling granites show a middle belt plutons texture feature which regarded as formation in depth of 6.5–13 km, in combination with the thickness of today's crust of Nanling Range being about 33–40 km, Sun et al. (2005) presumed that the crustal thickness of South China was $\leqslant$50 km in the Indosinian period. Using the similar logic, if the emplacement depth of the Indosinian granites was formed at ~19 km, we can presume that crustal thickness in the Indosinian period was likely more than 50 km. The prominent feature of the Indosinian orogeny in South China is the existence of a 1300 km wide intracontinental fold-thrust belt in association with a granitic magmatic province (Li et al., 2007), similar to the Laramide Orogeny in North American. It has been suggested that a 50–60 km thick crustal welt, combined with a coeval two-mica granite belt were existed behind the fold-thrust belt of the Laramide Orogeny (Coney et al., 1984). The fact that a thickening crust ($\geqslant$50 km) existed in the eastern Nanling Range further supports that a Laramide-type intracontinental orogeny probably existed in South China during the Indosinian period (Li et al., 2007). The anatexis of the thickened crustal root was likely the reason of the two-mica granites generation (Coney et al., 1984).

In general, the Mesozoic granitoids in South China are characterized by most granites being peraluminous granites and absence of amphibole that is often being used as a mineral barometry. However, these peraluminous granites usually contain muscovites, which can be used as a barometer to constrain formation depth of the peraluminous granites, particularly the two-mica granites. The calculated pressures using primary muscovites discriminated by chemical criteria are consistent with petrography and field geological constraint, whereas the calculated pressure based on the secondary muscovites discriminated by chemical criteria, such as the Yanshanian highly evolved two-mica granites, is overestimated. Therefore, it is not suitable to use the secondary muscovite barometer to constrain emplacement depth of the peraluminous granites.

5 Conclusions

(1) The muscovites from the Longyuanba Indosinian and Yanshanian two-mica granites are not ideally pure muscovites ($KAl_2[AlSi_3O_{10}](OH)_2$) in composition. Rather, they are composed of a series of substitutions including celadonitic ($KAl(Fe, Mg)(Si_4O10)(OH)_2$) and paragonitic ($NaAl_2[AlSi_3O_{10}](OH)_2$) components. The muscovites in the Indosinian granites are enriched in paragonitic content, whereas those in the Yanshanian granites contain high content of celadonitic components.

(2) Petrographically, both the Indosinian and Yanshanian granites contain primary and secondary muscovites. However, all muscovites from the Indosinian two-mica granites have high contents of Ti, Al, Mg, and Na, and low contents of Fe and Mn in composition, and should be considered as primary based on chemical criteria. In contrast, muscovites from the Yanshanian two-mica granites fall into the secondary muscovite field in all discrimination diagrams.

(3) The Mesozoic granitoids in South China are characterized by the widespread peraluminous biotite granites, and the intrusive pressure of these peraluminous granites are hard to determine due to the absence of a decent barometer, e.g., Al-in-amphibole barometer. Fortunately, these peraluminous granites usually contain muscovites, which can be used as a barometer to constrain depth of magma emplacement. However, the calculated pressure using primary muscovites discriminated by chemical criteria is a reasonable estimation, whereas the calculated pressure based on the secondary muscovites is an unreasonable estimation.

(4) The pressure estimated for the intrusion of the Longyuanba Indosinian two-mica granites is in the range of 5.2 to 6.5 kbar (5.8 kbar on average), corresponding to a depth of 17–21 km (the average is ~19 km), suggesting that a thickened crust likely presented in Triassic (Indosinian period) and that the Indosinian two-mica granites were probably formed by partial melting of the thickened crust root at a compressional tectonic setting.

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