structure. The shift tendency of the reflectivity peak was determined by the dominant factor d or n_{eff}. The calculation result shows that the bandgap position is red-shifted with the increase of the treating temperature if $n_{\mathrm{eff}} > 2$. But when n_{eff} is lower, the bandgap position will be shifted to the contrary tendency.

We assumed an extreme status: polystyrene spheres' deformation reached the maximum and the air void was infilled so that the volume of the air could be ignored, the inter-planar spacing $d = \frac{\sqrt[3]{2}\pi a}{\sqrt[3]{3}\sqrt{3}} = 200$ nm, $n_{\mathrm{eff}} = n_{\mathrm{sphere}} = 1.59$. The bandgap position λ is 634 nm. The calculation result shows that the peak is shifted to the short wavelength. But the measured value (622 nm) is smaller than the ideal calculation result. This could be caused by the error of microsphere size and the anisotropy in the shrinking process, more detailed analysis should be carried out in the future.

3 Conculsion

In summary, the polystyrene spheres' shape transforms to dodecahedron especially in the range from 80℃ to 100℃ with treating temperature increasing, and the peak of reflective spectra is shifted to the short wavelength because of the transformation, the shift in experiment is more obvious than that in the theoretical simulation.

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Geochemistry and petrogenesis of Jurassic high Sr/low Y granitoids in eastern China: Constrains on crustal thickness

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Abstract **The Jurassic high Sr/low Y granitoids in eastern China are characterized by high Sr/Y (27—166) and La/Yb (14—66) ratios, low abundance in Y (6—21 μg/g) and Yb (0.5—2.0 μg/g), comparable with those of adakites defined by Defant et al. Thus, they were recently considered as adakitic rocks by some researchers. Compared with the typical adakites in circum-Pacific margins, however, these high Sr/low Y granitoids have higher K_2O (–3.5%) but lower Al_2O_3 (–16.0%) as well as lower $Mg^{\#}$ (–38) and δSr_N (–1.23) values. Furthermore, they show relatively flat HREE patterns with Y/Yb values of –10 close to the chondritic value. These geochemical characteristics indicate a residue mineral assemblage of hornblende, garnet and plagioclase for these high Sr/low Y granitoids melt. Thus, they were generated by partial melting at 9—13 kbar (30—45 km in depth), similar to the Archaean high-Al TTG rather than the modern adakites. Generation of these high Sr/low Y granitoids cannot be considered as evidence for a thickened crust (>50 km) and/or the presence of the "Eastern China Plateau" in Jurassic.**

Keywords: granitoids, adakite, TTG, Jurassic, eastern China.

Defant et al.[1] had first proposed the term of adakites to describe some Na_2O-rich and K_2O-poor arc volcanic rocks, including calc-alkaline andesites, dacites, sodic rhyolites and their intrusive equivalents. Typical adakites are derived directly from partial melting of the subducted oceanic crusts, in contrast to the island-arc magmas[2] derived from partial melting of the underlying mantle wedges. In the process of partial melting, the garnets and amphiboles are residual and the plagioclases melt, which results in depletion in Y and HREE, but enrichment in Al_2O_3, Sr with high La/Yb and Sr/Y ratios in the typical adakites[1,3]. Additionally, the interactions between the ascending adakitic magma and the mantle wedge would increase the $Mg^{\#}$ values for the typical adakites[4,5]. For example, the adakite of Adak island in Aleutian islands (with $SiO_2 \approx 60\%$) contains 2366 ppm Sr, and their La/Yb and $Mg^{\#}$ are up to 48.9 and 72, respectively[6]. The typical adakites are mainly located in the Cenozoic circum-Pacific island arcs[3,7,8]. In general, only young and hot subducted oceanic crusts (<25 Ma) can reach the solidus temperature of hydrous tholeiite before it dehydrates, and melt to product adakitic magmas[1,3]. The process has been described in some places, such as Cook island of Chile[9], Mount St. Helens of North America[3] and so on. However, flat subduction of overthickened oceanic crusts (e.g. oceanic plateau) can also produce adakitic magmas, e.g. Peru and Ecuador, because the slabs have sufficient time to float on the upper mantle and gain enough heat to melt. In nature, of the 10 known flat subduction regions worldwide, eight are linked to occurrences of adakitic magmas[10]. Additionally, some older subducted slabs (>40 Ma) may be hot enough to melt in case of oblique convergent subduction or young subduction, such as the Adak and Komandorsky island of Aleutian[6,7,11], Mindanao of Philippines[12] and so on.

Adakites defined by Defant et al.[1] are rocks with distinct geochemistry and petrogenesis rather than particular petrographical characteristics. High Sr/Y (>20—40), La/Yb (>20) ratios and low Y ($\leqslant$18 μg/g), HREE (Yb$\leqslant$1.9 μg/g) contents are most important discriminating features of adakites. However, recent studies indicate that some rocks with similar geochemical features mentioned above were not generated by melting of subducted lithosphere[5, 13—15]. For example, Archaean high-Al TTG are characterized by high-Sr, low-Y and strongly fractionated REE patterns, and almost identical with typical adakites in composition. It is generally accepted that the Archaean high-Al TTG could have been generated from partial melting of either subducted oceanic crusts[4,16] or underplated basaltic rocks[5]. With plagioclase being as residual mineral, the TTG magmas were less or not affected by the mantle peridotite, which resulted in lower $\delta\,\mathrm{Sr_N}$ and Mg# ratios for the Archaean high-Al TTG relative to the typical adakites[4,5]. Furthermore, some Phanerozoic intermediate to felsic calc-alkaline rocks, such as Cordillera Blanca Batholith of Peru[13], Separation Point Batholith of New Zealand[14], also show geochemical affinity with the typical adakites with high Sr/Y and La/Yb ratios, although they were generated by partial melting of underplated basaltic rocks in the lower crust. According to the geochemical studies on high-silica lavas from island arcs of Philippines, Castillo et al.[15] presumed that some mantle-derived magmas could have high Sr/Y and La/Yb ratios through assimilation and fractional crystallization (AFC) processes. Actually, if adakites are loosely termed only by some geochemical parameters (e.g. high Sr/Y and La/Yb ratios, low Y and Yb contents), some mantle-derived shoshonitic rocks, high-Ba-Sr granitoids[17,18] and probably many other rock types could also be called adakites. Doing so, except indicating the residues of garnet and hornblende, adakites will not have other specific genetic applications any more.

A number of the Jurassic high-K calc-alkaline granitoids in eastern China are characterized by strongly fractionated REE patterns, high Sr/Y and $(\mathrm{La/Yb})_N$ ratios and low Y and HREE contents, comparable with the adakites defined by Defant et al.[1]. Thus, some researchers grouped these rocks into the "adakitic rocks"[19—22]. Furthermore, they suggested that a significantly thickened crust or "the Eastern China Plateau" might have existed in the Jurassic compared with the typical adakites that formed at high pressure (>15 kb) with garnet-bearing amphibolite or eclogite as residue[19, 20]. This paper provides a detailed comparison of geochemical characteristics and petrogenesis between the Jurassic high Sr/low Y granitoids in eastern China and the typical adakites located in the circum-Pacific margins, to explore whether these high Sr/low Y granitoids can provide constraints on the crustal thickness in eastern China.

1 Contrast on geochemical characteristics

We collected in this paper most of the published data of the Jurassic high Sr/low Y granitoids in eastern China in literatures, including Beipiao, Zhangwu and Fuxin volcanic rocks of Liaoning province[23, 24], Tiaojishan Formation in the Beijing area[25], some granitoids in the Yanliao area[20, 26], some granitoids in southern Dabieshan[27], and some intermediate-acid magmatic rocks in the middle-lower reaches of the Yangtze River (Shaxi and Tongling in Anhui)[21, 28]. Compared with the typical adakites of the circum-Pacific arcs, the high Sr/low Y granitoids display distinct differences in geochemistry as follows.

(1) K_2O contents. The high Sr/low Y granitoids contain 3.1%—5.2% Na_2O and 1.4%—4.5% K_2O with high K_2O/Na_2O ratios (average in 0.76, and a few$\geqslant$1), in contrast to the typical adakites that are sodic volcanic rocks characterized by Na_2O-rich (3.5%—7.5%) and K_2O-poor (0.57%—3.2%) with low K_2O/Na_2O ratios (average in 0.42[4]). In a K_2O vs. SiO_2 diagram (fig. 1(a)), the typical adakites are plotted in the tholeiitic to calc-alkaline fields, whereas the high Sr/low Y granitoids are mostly plotted in the high-K calc-alkaline field, with a few plotted in shoshonitic or calc-alkaline fields. Thus the high Sr/low Y granitoids in eastern China are significantly richer in K than the typical adakites.

(2) Al_2O_3 contents. Both of the high Sr/low Y granitoids and the typical adakites show decreasing trends of Al_2O_3 with SiO_2 increasing, indicating the fractional crystallization of plagioclase (fig. 1(b)). Overall, the average Al_2O_3 content of ~16.0% for the high Sr/low Y granitoids is similar to that of Archaean high-Al TTG (~15.7%[30]), but lower than that of the typical adakites (~17.1%). Furthermore, difference in Al_2O_3 is more pronounced at lower silica values between them.

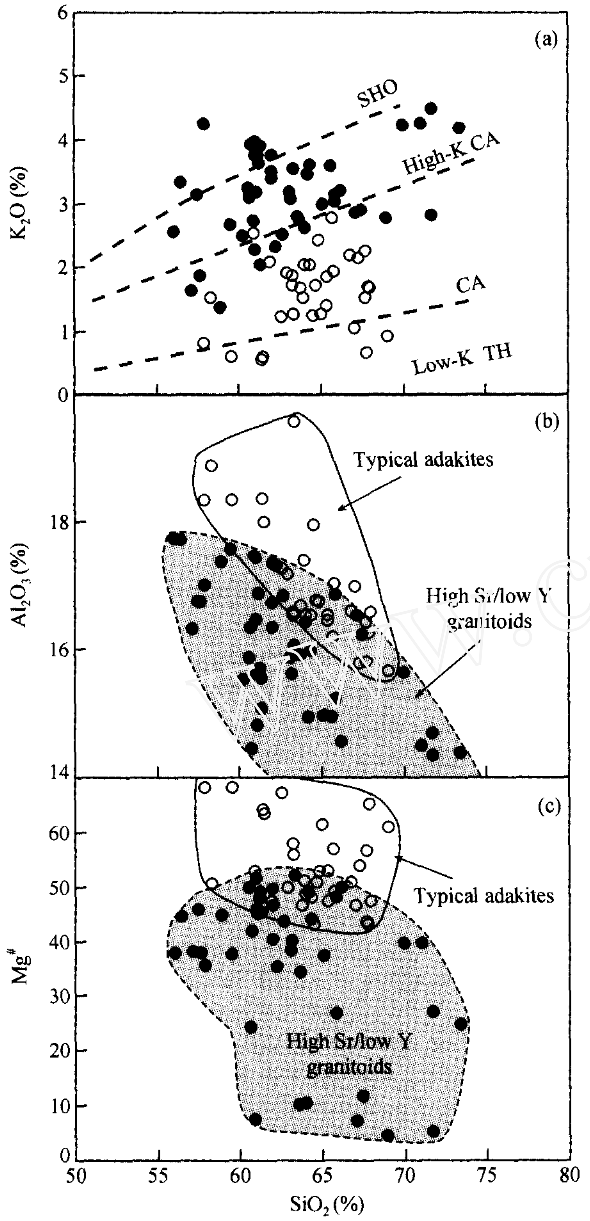

Fig. 1. Comparison of geochemical compositions bewteen the high Sr/low Y granitoids and the typical adakites. (a) K_2O vs. SiO_2; (b) Al_2O_3 vs SiO_2; (c) $Mg^\#$ vs. SiO_2. Data for the typical adakites (open circles) are from refs. [4, 8, 9, 29—33]; The high Sr/low Y granitoids in eastern China (filled circles) are from refs. [20, 21, 23—28] and 1).

(3) $Mg^\#$ values. Typical mid ocean ridge basalts (MORB) have $Mg^\#$ values [$=100\times Mg^{2+}/(Mg^{2+}+Fe^{2+})$] of about 60. Experimental results have shown that the apparent maximum $Mg^\#$ value is –45 for partial melts of MORB[34], but the addition of only –10% peridotite can increase the $Mg^\#$ value from –44 to –55[35]. Consequently, $Mg^\#$ value can provide a sensitive indicator of the contamination of peridotite[5]. The typical adakites have higher $Mg^\#$ values (average in 55 and up to 68, fig. 1(c)), which was interpreted by interactions between the ascending adakitic magma and the overlying mantle wedge[4, 5]. The high Sr/low Y granitoids have lower $Mg^\#$ values (average in 38), apart from a few latite samples from Zhangwu (up to –50, fig. 1(c)), indicating that the parental magmas of most high Sr/low Y samples might not have interacted with the peridotite mantle, similar to Archaean high-Al TTG[5].

(4) δSr_N ratios. Sr enrichment relative to LREE, expressed as the δSr_N value, is one of the diagnostic features for typical adakites, indicative of the lack of residual plagioclase (fig. 2). On the contrary, Archaean high-Al TTG have no any Sr positive anomaly (fig. 2), implying the plagioclase as a residue mineral[4]. The Sr contents and Sr/Y ratios of the high Sr/low Y granitoids (376—1535 μg/g and 27—166, respectively) are similar to those of the typical adakites (348—2003 μg/g and 32—443, respectively). However, they do not show obvious Sr positive anomaly due to strong enrichments of LREE, with a few samples even showing Sr negative anomaly (fig. 2). In general, the high Sr/low Y granitoids are similar to Archaean high-Al TTG, rather than the typical adakites, in δSr_N values. Although δSr_N values increase and decrease gently with Sr and SiO_2 increasing (fig. 3), possibly due to plagioclase fractionation, the distinct difference in δSr_N values between high Sr/low Y granitoids ($\delta Sr_N < 2$) and the typical adakites ($\delta Sr_N > 2$), however, is difficult to be interpreted solely by plagioclase fractionation.

(5) HREE contents. Unlike the typical adakite, the high Sr/low Y granitoids show nearly flat heavy REE patterns with Y/Yb ratios (—10) close to the chondrite value[38], except a few North Dabieshan samples displaying strongly fractionated HREE patterns with Y/Yb ratios of 14—18[39]. In addition, the depletion of heavy REE in the high Sr/low Y granitoids is insignificant compared with that of typical adakites. In the $(La/Yb)_N$ vs. Yb_N diagram (fig. 5)[16], the high Sr/low Y granitoids are plotted mainly in the transitional field of high-Al TTD (or adakite) and low-Al TTD, lying between partial melting curves of amphibolite restite and 10% garnet amphibolite restite. Whereas, most typical adakites lie between partial melting curves of 10% garnet amphibolite restite and eclogite restite.

2 Petrogenesis of the high Sr/low Y granitoids in eastern China

According to field geology, igneous rock associations and geochemical characteristics of the high Sr/low Y granitoids as well as the tectonic regime of eastern China in the Mesozoic, many researchers[20—23,25] suggest that the high Sr/low Y granitoids were likely generated by partial

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1) Wang, Q., Zhao, Z. H., Xu, J. F. et al., The adakite-like magmas in the eastern Yangtze Block and their geodynamic and metallogenetic significance, in press.

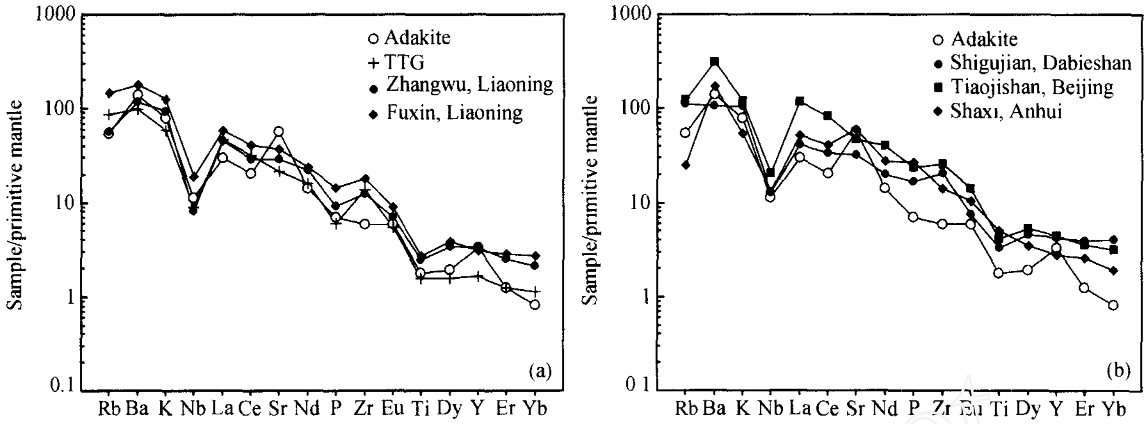

Fig. 2. Primitive mantle normalized trace elements diagram. Adakite from ref. [36], TTG from ref. [37], the high Sr/low Y granitoids from refs. [21, 23-25, 27], normalized primitive mantle abundances from ref. [38]

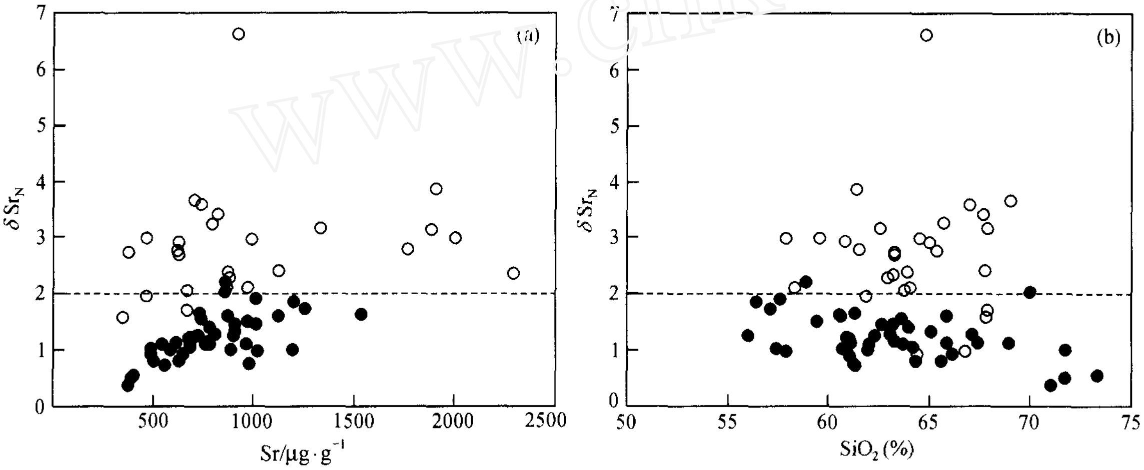

Fig. 3. The diagrams of δSr_N vs. Sr and δSr_N vs. SiO_2. $\delta Sr_N = 2Sr_N/(Ce_N+Nd_N)$, N, normalized to primitive mantle[38], data sources and symbols are the same as in fig. 1.

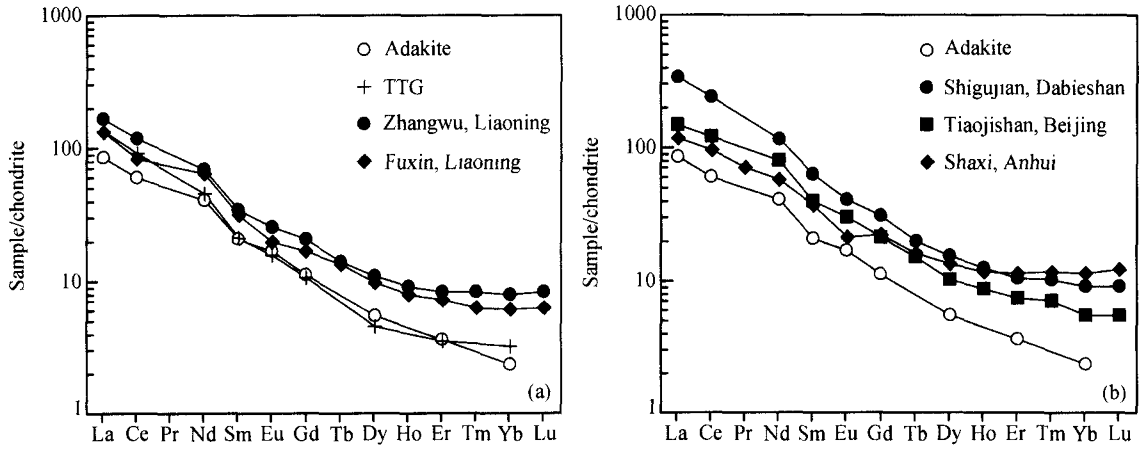

Fig. 4. Chondrite normalized REE patterns. Data sources and symbols are the same as in fig. 2, normalized values are from ref. [38].

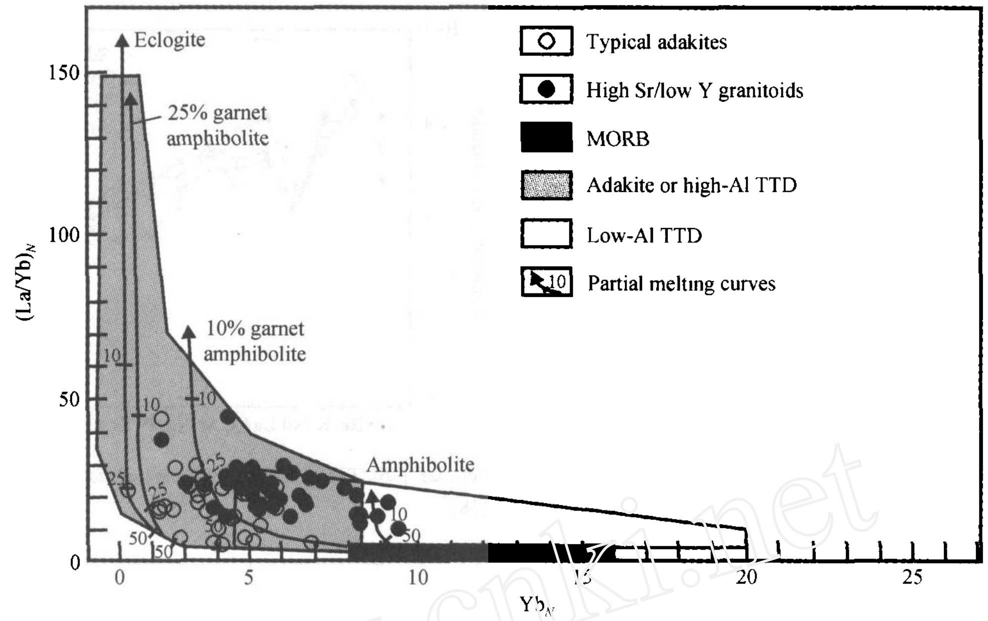

Fig. 5. $(La/Yb)_N$ vs. Yb_N diagrams[16]. N, Chondrite normalized, data sources are the same as in fig. 1.

melting of the basaltic lower-crust, rather than by melting of subducted paleo-Pacific oceanic crust, fractional crystallization of basaltic magma or magma mixing. This viewpoint is consistent with the field and geochemical characteristics of the high Sr/low Y granitoids; for example, high SiO_2 contains >56%, low $Mg^{\#}$ values of <50, rarely associated with basic rocks, no evolutional trends with basic rocks, and homogeneous and lower-crust-like Sr and Nd isotopic compositions in specific regions (for example, $\varepsilon_{Nd}(t)$ = −15.7—−15.0 and initial $^{87}Sr/^{86}Sr$ = 0.70575—0.70607 for 6 samples from Tiaojishan Formation volcanics[40]). However, the sources of the high Sr/low Y granitoids could also be composed of lower-crust mafic rocks and some other rock types (e.g. intermediate-acid rocks or metasedimentary rocks) in some areas. Addition of mantle-derived magmas cannot be totally ruled out for a few high Sr/low Y granitoids with high ε_{Nd} ratios.

The experimental petrological studies indicate that the potassium contents of source rocks would distinctively influence K_2O contents of derived-melts, and that high-K calc-alkaline magma should not be originated from partial melting of low-K tholeiite[41]. Very high K_2O (average in 3.15%), Sr, LREE contents, 56.02% SiO_2 in the most basic rocks and Sr, Nd isotopic data all suggest that the sources of the high Sr/low Y granitoids of eastern China should be lower-crust basaltic rocks derived from an enriched lithospheric mantle, but we also do not exclude some other possibilities, such as the mixture of depleted mantle and old crust.

The geochemical differences between the high Sr/low Y granitoids and the typical adakites indicate the different residual phases in source area. Since plagioclase is an important Al-rich mineral in igneous rocks and the Sr partition coefficient between plagioclase and melt is very high, Al_2O_3 and Sr contents are used to diagnose the role that plagioclase plays in the magma generation and evolution. Compared with the typical adakites, the high Sr/low Y granitoids in eastern China have lower Al_2O_3 contents and δSr_N values, indicating that plagioclase was likely the residual mineral during partial melting, resembling the Archaean high-Al TTG[4], because such significant differences could not be attributed to the plagioclase fractionation alone. Furthermore, amongst the HREE, Yb and Lu have the highest garnet-melt partition coefficients, whereas Dy and Ho have the highest hornblende-melt partition coefficients[42]. When garnet is the main residual phase, HREE will show strongly fractionated patterns with Y/Yb > 10 (up to 20). In contrast, when hornblende is the main residual phase, HREE will show flat patterns with Y/Yb ≈ 10. So the HREE patterns indicate that the typical adakites should have either garnet amphibolite or eclogite as residual phases[1, 3, 4, 16], in contrast to the high Sr/low Y granitoids with hornblende, garnet and plagioclase as main residual phases.

3 Constrains on the crustal thinkness in eastern China

Since the high Sr/low Y granitoids in eastern China are most probably generated by partial melting of the mafic lower crustal caused by basaltic underplating or intrusion, melting conditions, particularly the pressure of melting could provide constraints on the crustal thinkness as proposed by Zhang et al.[20] and Wang et al.[21].

Distinct from that of typical adakites, the residual mineral assemblage of the high Sr/low Y granitoids in eastern China was likely made up of hornblende + garnet + plagioclase, in which hornblende might be the major residual phase. Thus, the P-T conditions required for the production of these rocks should correspond to the stable ranges of garnet granulites (shadow area in fig. 6)[30]. Experimental studies indicate that dehydration partial melting of water-undersaturated basaltic rocks needs temperatures high than 850℃[30, 43, 44], and that the melting temperatures of lower-crust induced by basaltic underplating is generally lower than 950℃[45]. The pressure for the stability of garnet granulite is about 8—12 kbar at 850—950℃ (fig. 6)[30]. Experiments on dehydration melting of amphibolite show that the garnet appears at 850—990℃ and 10 kbar[46]. Compiling the experiment results of the stable range of garnet, Vielzeuf and Schmidt[47] considered that the garnet-in curve was located between 9 and 14 kbar in terms of the various compositions of basaltic sources at 800—1000℃. Furthermore, the geological and geochemical studies of the high-Al TTG indicate that they could have been generated at ~ 10 kbar. For example, the high-Al trondhjemite of Catalina island in southern California is generated at 9—11 kbar[48], and the Birbir TTG in Ethiopia is generated at 8—12 kbar[49]. Thus, it is not necessary to invoke high pressures of > 12—15 kbar[19—21, 23] interpreting the presence of garnet in the residues for those high Sr/low Y granitoids. In fact, because of the coexistence of hornblende, plagioclase and garnet in the residues and the dehydration reaction for H_2O-undersaturated melting (amphibole + plagioclase = garnet + melt ± clinopyroxene)[45], the melting pressure close to the reaction curve (garnet-in curve) may be more appropriate for hornblende, rather than garnet, being the major residue. Thus, the melting pressure of the high Sr/low Y granitoids in eastern China was likely at 9—13 kbar, the minimum pressure range for stabilizing garnet granulite, at temperature intervals of 800—1000℃. This pressure range corresponds to 30—45 km in depth.

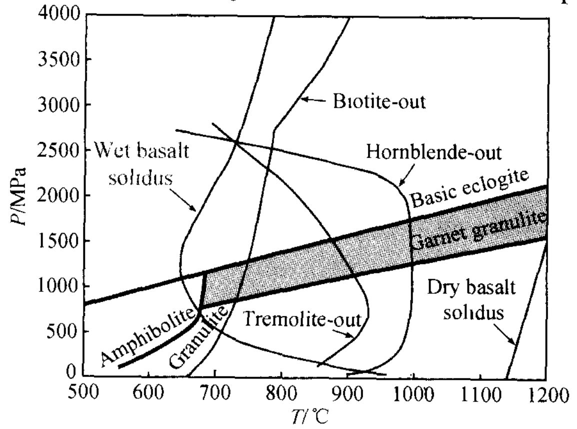

Fig. 6. P-T diagram depicting various metamorphic facies fields and potential melting conditions in concert with dehydration reactions[30].

Therefore, a distinctively thickened Jurassic crust or "the plateau of Eastern China" is not necessarily true based on the occurrences of these rocks.

4 Conclusions

The high Sr/low Y granitoids share some compositional features of adakite defined by Defant et al.[1], such as high Sr/Y, $(La/Yb)_N$ ratios and low Y, HREE concentrations. Nevertheless, compared with the typical adakites in circum-Pacific margins, the high Sr/low Y granitoids have lower δSr_N values and weaker depletions in Y and HREE. More importantly, there are some obvious differences in geochemistry between them. The high Sr/low Y granitoids have higher K_2O contents, lower Al_2O_3 contents and lower $Mg^\#$ values than the typical adakites. So it may be inappropriate to using the term of "adakitic rocks" to describe the high-K calc-alkaline granitoids which were not directly related to subduction. In other countries, there are also some high Sr/low Y intermediate-acid igneous rocks occurring in the intraplate environments or orogenic zones, such as Idaho batholith in northwestern USA[50] and granites of the Arunta Inlier in central Australia[51, 52]. Although they are similar to adakite with high Sr/Y ratios and strongly fractionated REE patterns, these igneous rocks have not been termed "adakite" or "adakitic rocks".

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