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Melting of Newly Formed Mafic Crust for the Formation of Neoproterozoic I-Type Granite in the Hannan Region, South China

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ABSTRACT

Neoproterozoic magmatism in the Hannan region at the northwestern margin of the Yangtze Block is characterized by numerous felsic plutons associated with minor mafic-ultramafic intrusions. The felsic plutons are either adakitic or normal-arc granitic in composition. The adakitic plutons are ∼735 Ma in age and are interpreted as having formed by partial melting of a thickened lower mafic crust. Among the normal-arc-related felsic plutons, the Tianpinghe pluton is the largest and has a SHRIMP zircon U-Pb age of 762 ± 4 Ma, older than the adakitic plutons in the region. Rocks from the Tianpinghe pluton have relatively high SiO₂ (67.1–70.1 wt%) and K₂O + Na₂O (7.8–8.6 wt%) and relatively low MgO (0.7–1.3 wt%) and Al₂O₃ contents (14.5–15.6 wt%), with Al₂O₃/(CaO + K₂O + Na₂O) {A/CNK} values ranging from 0.95 to 1.08. They have arc-affinity trace-element compositions that are characterized by enrichment of large-ion lithophile elements and depletion of high-field-strength elements [Nb, Ta], with strong positive Pb and negative Ti anomalies. They have a narrow range of εNd(t) values [+0.15 to −1.76] and relatively high zircon εHf values [+0.6 to +8.3]. These geochemical features are typical of I-type granites. The rocks from the Tianpinghe pluton have relatively young single-stage and two-stage Hf model ages [1.01–1.31 and 1.31–2.01 Ga, respectively], suggesting that the pluton was generated by partial melting of newly formed basaltic rocks. On the basis of its arc-related geochemical affinity and its emplacement before voluminous adakitic magmatism but after mafic-ultramafic intrusions, the Tianpinghe pluton is considered to be Neoproterozoic arc granite formed during a period of crustal growth and reworking. Generation of the later adakitic plutons suggests that the crustal thickness increased to more than 50 km by mafic magma underplating.

Online enhancements: color figures, tables.

Introduction

Calc-alkaline granitoids are the most abundant rock types in orogenic belts and can provide valuable information about the processes of continental crustal evolution and differentiation [e.g., Roberts et al. 2000; Ortega-Obregon et al. 2003; Kemp et al. 2007]. I-type calc-alkaline granitoids can be produced by melting of newly formed lower crust, fractional crystallization of mantle-derived mafic magmas, or mixing of mantle-derived magmas and continental felsic melts [e.g., Juster et al. 1989; Singer et al. 1992; Rudnick 1995; Soesoo 2000; Rajesh 2004; Cluzel et al. 2005; Kemp et al. 2007]. Thus, I-type calc-alkaline granitoids may provide information about the interaction between the mantle and the overlying continental crust [e.g., Kemp et al. 2007]. In addition, they can be used to discriminate tectonic settings and can help decipher the secular evolution of the continental crust [e.g., Pitcher 1993; Frost et al. 2001].

The Yangtze Block in South China, which is considered part of the supercontinent Rodinia (Li et al. 1995), is characterized by numerous Neoproterozoic I-type granitic plutons, with minor S-type granitic and mafic plutons along its western margin [e.g., Ling et al. 2001; Zhou et al. 2002a, 2002b, 2006a, 2006b; Li et al. 2003; Zhao and Zhou 2007a, 2007b, 2008a, 2008b]. Although their petrogenesis is not clear and remains controversial, the I-type granites are important for understanding the crust-mantle interaction, continental crustal growth, and reworking of the Yangtze Block. The most interesting problem in the region is the heat source neces-
sary for the formation of these plutons. Li et al. (2003) proposed that the felsic rocks were generated by an upwelling mantle plume; however, Zhou et al. (2002a) argued that they were formed at an active continental margin.

Numerous Neoproterozoic mafic-ultramafic, adakitic, and normal-arc-related felsic plutons crop out in the Hannan region, on the northwestern margin of the Yangtze Block (fig. 1). The mafic-ultramafic plutons are documented to have been produced by partial melting of lithospheric mantle above a subduction zone (Zhou et al. 2002a; Zhao and Zhou 2008a). The subsequent formation of the adakitic plutons probably reflects melting of a thickened lower crust (Zhao and Zhou 2008a). The normal-arc-related granitic plutons have not been examined in detail. This study focuses on the Tianpinghe pluton, the largest normal-arc-related felsic pluton in the region. As a representative example of arc-related magmatism, it is important for understanding the growth and reworking of continental crust in the region and for determining the tectonic setting in which it was emplaced along the northwestern margin of the Yangtze Block.

**Geological Background**

South China consists of the Yangtze Block to the northwest and the Cathaysia Block to the southeast (fig. 1), which were welded together during Meso- to Neoproterozoic time (Chen et al. 1991; Li and McCulloch 1996; Wang et al. 2007). The Yangtze Block is bounded by the eastern Tibetan Plateau to the west and is separated from the North China Block by the Qinling-Dabie orogenic belt, which was formed by closure of the easternmost part of Paleotethys (Mattauer et al. 1985; Hsü et al. 1987).

The Yangtze Block consists of Archean to Neoproterozoic basement complexes overlain by a Sinian to Cenozoic cover sequence. The basement complexes consist of arenaceous to argillaceous sedimentary strata that have been metamorphosed to low-grade greenschist facies assemblages. The Archean Kongling Terrane in the Yangtze Block consists of felsic gneisses, clastic metasedimentary rocks, and amphibolites (Gao et al. 1999). Mesoproterozoic rocks are also preserved along the margins of the Yangtze Block (Greentree et al. 2006; Li et al. 2007). The Neoproterozoic sequences along the western margin of the Yangtze Block consist of a lower sequence of volcanic rocks overlain by a thick

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**Figure 1.** Simplified geological map showing the distribution of Neoproterozoic plutons in the Hannan region at the northwestern margin of the Yangtze Block, South China (modified from BGMRS 1990). YB = Yangtze Block; TP = Tibetan Plateau; QDOB = Qinglin-Dabie orogenic belt.
flysch sequence (Yan et al. 2004; Zhou et al. 2006b). The thick cover sequence (>9 km) of upper Sinian to Permian strata consists of glacial deposits and clastic, carbonate, and metavolcanic rocks (Yan et al. 2003).

Neoproterozoic magmatism in South China is characterized by numerous granitic plutons, with less abundant mafic-ultramafic plutons. Both the mafic-ultramafic and the felsic plutons intrude Mesoproterozoic rocks and are unconformably overlain by Sinian strata (Zhou et al. 2002a, 2002b; Li et al. 2003; Zhou et al. 2006a, 2006b; Zhao and Zhou 2007a, 2007b).

In the Hannan region on the northwestern margin of the Yangtze Block (fig. 1), pre-Sinian (>750 Ma) rocks are exposed in a belt more than 1200 km long (Zhang 1991) and are divided into three tectonostratigraphic units: from the base upward, the Houhe complex, the Huodiya Group, and the Xixiang Group (Ling et al. 2003).

The Archean-Paleoproterozoic Houhe complex consists of trondhjemitic gneisses, amphibolites, and migmatites, with minor marbles. The Mesoproterozoic Huodiya Group unconformably overlies the Houhe complex and consists of metasedimentary rocks in the lower part and volcanic rocks in the upper part. The Neoproterozoic Xixiang Group is a metavolcanic-sedimentary succession with a total thickness of more than 4 km. It comprises a lower unit dominated by high-Mg andesite and low-Ti tholeiitic basalts and an upper unit composed of basalt, andesite, and dacite-andesite and low-Ti tholeiitic basalts and an upper unit composed of basalt, andesite, and dacite.

The Tianpinghe pluton consists of coarse-grained granites composed of alkali feldspar (mode 50%–55%), quartz (mode 30%–35%), plagioclase (mode 10%), and biotite (mode 10%). The alkali feldspar is mainly microcline, which forms anhedral, commonly embayed crystals up to 1.5 x 5 mm. Quartz is interstitial and fine grained, with a diameter generally less than 0.5 mm (rarely up to 1 mm). Plagioclase forms small, irregular grains. Biotite is the only mafic mineral present and generally forms small aggregates, but a few inclusions of biotite may also occur in the microcline. Common accessory minerals include titanite, magnetite, and zircon. Samples show only slight alteration, with minor amounts of carbonate, kaolinite, and chlorite.

Analytical Results

**SHRIMP Zircon U-Pb Dating.** The results of SHRIMP U-Pb zircon analyses are listed in table 1. Sample TPH14, a granite from the Tianpinghe pluton, contains euhedral, oscillatory-zoned, igneous zircons with variable U contents. The majority of the zircons have cores, patches, and thin rim overgrowths with high U, generally >250 ppm. A small proportion of zircons with similar crystal morphology (<10%) have lower U concentrations (<150 ppm). The high-U zircons give relatively young 206Pb/238U ages and appear to have suffered minor Pb loss. Analyses of spots TPH14-01 and TPH14-02 were not used because the analytical spots overlapped high-common-Pb inclusions. Eight low-U zircons, which form a coherent group on the concordia diagram, have a weighted mean 206Pb/238U age of 762 ± 4 Ma, which we interpret as the crystallization age of the intrusion (fig. 2).

**Major and Trace Elements.** On the basis of CIPW normative mineralogy, rocks from the Tianpinghe pluton fall mainly in the granodiorite field in the QAP diagram, whereas they all lie in the granite field in the Ab-An-Or diagram. In the plot of total alkaline versus SiO2 (fig. 3a), rocks from the Tianpinghe pluton plot in the same classification fields.
as quartz monzonite and granite. The Tianpinghe granites are alkali-calcic in composition, according to the classification scheme of Frost et al. (2001; fig. 3b). They are also metaluminous, with an alumina saturation index (ASI; molar Al₂O₃/(CaO + Na₂O + K₂O)) ranging from 0.95 to 1.08. The rocks from the Tianpinghe pluton range in SiO₂ from 67.1 to 70.1 wt%, in MgO from 0.67 to 1.25 wt%, and in Al₂O₃ from 14.5 to 15.6 wt%. They have high K₂O (3.2–4.1 wt%) and Na₂O (4.2–5.2 wt%) contents, giving low K₂O/Na₂O ratios ranging from 0.64 to 0.99. Fe₂O₃, MgO, Al₂O₃, CaO, TiO₂, and P₂O₅ all correlate negatively with SiO₂.

All of the analyzed rocks have slightly U-shaped chondrite-normalized rare earth element (REE) patterns with strong enrichment in light REEs (LREEs) and display slightly negative Eu anomalies (Eu/Eu* = 0.73–0.95; fig. 4a). All of the samples also have a relatively narrow range of (La/Yb)N ratios (11.8–16.5). In primitive-mantle-normalized trace-element diagrams, the rocks show enrichment of large-ion lithophile elements (Rb, Ba, Th, and U) and depletion of Nb and Ta, with negative Ti and positive Pb and Zr-Hf anomalies (fig. 4b). They have low Sr [204–328 ppm] and high Y [14.7–22.3 ppm] concentrations, yielding low Sr/Y ratios of 11.1–20.7. Compatible trace elements, such as Cr, Ni, and V, are relatively low in abundance (table 2, available in the online edition or from the Journal of Geology office).

Whole-Rock Sr-Nd Isotopes. Rocks from the Tianpinghe pluton have low and constant initial ⁸⁷Sr/⁸⁶Sr ratios ranging from 0.7037 to 0.7053 and constant but slightly negative εNd values (+0.15 to −1.76; table 3). In the diagram of initial ⁸⁷Sr/⁸⁶Sr versus εNd(t), the samples plot near the mantle array (fig. 5). Their εNd(t) values are slightly lower than those of the Neoproterozoic mafic-ultramafic intrusions in the Hannan region (figs. 5, 6).

Zircon Lu-Hf Isotopes. Lu-Hf isotope analyses of zircons from four granite samples are presented in table 4, available in the online edition or from the Journal of Geology office, and are plotted in figures 7 and 8. Grain TPH14-19 has extremely low ¹⁷⁶Lu/¹⁷⁷Hf (0.000778) and ¹⁷⁶Hf/¹⁷⁷Hf ratios (0.281718), yielding a very low εHf value of −20.9, different from those of the other analyses (figs. 7, 8). It is characterized by very old single-stage (2.14-Ga) and two-stage (3.92-Ga) model ages. The other analyses yielded ¹⁷⁶Lu/¹⁷⁷Hf ratios ranging from
0.000977 to 0.003058 and present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282334 to 0.282575 (79 points). Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios vary from 0.282314 to 0.282532, with an average of 0.282412 (fig. 7, top). The $\varepsilon$Hf values range from +0.6 to +8.3, with an average of 4.1. Single-stage model ages range from 1.01 to 1.31 Ga and two-stage model ages from 1.31 to 2.01 Ga. The weighted means of the single-stage and two-stage model ages are 1.17 ± 0.01 and 1.74 ± 0.07 Ga, respectively (fig. 7, bottom).

Discussion

Classification of the Tianpinghe Pluton as an I-Type Granitoid. Granitoids were originally divided into I- and S-type granites [White and Chappell 1983], which are different in petrography and geochemical composition [e.g., Collins et al. 1982; White and Chappell 1983]. I-type granites normally have high Na$_2$O and CaO and low K$_2$O and alumina saturation (A/CNK) compared to S-type granites [Chappell and White 2001]. In addition, I-type granites display more regular compositional variations than S-type granites because of their relatively homogeneous source regions [Chappell and White 2001].

Rocks from the Tianpinghe pluton form relatively linear trends in compositional-variation diagrams. They have moderate Na$_2$O and K$_2$O contents, with high Na$_2$O + K$_2$O contents and low K$_2$O/Na$_2$O ratios (table 2). The rocks are metaluminous, with A/CNK ranging from 0.95 to 1.08.

Figure 3. Total alkalis versus SiO$_2$ [Middlemost 1994; a] and Na$_2$O + K$_2$O – CaO versus SiO$_2$ [Frost et al. 2001; b] for the rocks from the Tianpinghe pluton in the Hannan region, South China.

Figure 4. Chondrite-normalized rare earth element patterns [a] and primitive-mantle-normalized trace-element patterns [b] for the rocks from the Tianpinghe pluton in the Hannan region, South China. Normalizing values are from Sun and McDonough (1989).
<table>
<thead>
<tr>
<th>Sample</th>
<th>Rb [ppm]</th>
<th>Sr [ppm]</th>
<th>$^{87}$Rb/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr ± 2σ</th>
<th>$^{87}$Sr/$^{86}$Sri</th>
<th>Sm [ppm]</th>
<th>Nd [ppm]</th>
<th>$^{147}$Sm/$^{144}$Nd</th>
<th>$^{143}$Nd/$^{144}$Nd ± 2σ</th>
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<tr>
<td>TPH1</td>
<td>87.5</td>
<td>241</td>
<td>1.0534</td>
<td>.715147 ± .000013</td>
<td>.703686</td>
<td>3.29</td>
<td>19.6</td>
<td>.1013</td>
<td>.512109 ± .000013</td>
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<td>310</td>
<td>.7457</td>
<td>.713462 ± .000010</td>
<td>.705349</td>
<td>3.92</td>
<td>23.9</td>
<td>.0990</td>
<td>.512100 ± .000011</td>
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<td>86.0</td>
<td>312</td>
<td>.7987</td>
<td>.713179 ± .000013</td>
<td>.704489</td>
<td>4.17</td>
<td>24.4</td>
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<td>.512133 ± .000012</td>
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<td>TPH10</td>
<td>66.5</td>
<td>306</td>
<td>.6279</td>
<td>.712138 ± .000011</td>
<td>.705306</td>
<td>3.63</td>
<td>21.9</td>
<td>.1005</td>
<td>.512118 ± .000013</td>
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<td>315</td>
<td>.8159</td>
<td>.712882 ± .000010</td>
<td>.704005</td>
<td>4.24</td>
<td>24.8</td>
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<td>THP17</td>
<td>89.7</td>
<td>314</td>
<td>.8267</td>
<td>.713142 ± .000010</td>
<td>.704148</td>
<td>4.26</td>
<td>26.1</td>
<td>.0987</td>
<td>.512128 ± .000022</td>
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<tr>
<td>THP20</td>
<td>82.2</td>
<td>328</td>
<td>.7249</td>
<td>.712485 ± .000009</td>
<td>.704599</td>
<td>4.29</td>
<td>24.9</td>
<td>.1042</td>
<td>.512183 ± .000012</td>
<td>.15</td>
</tr>
<tr>
<td>TPH26</td>
<td>97.6</td>
<td>273</td>
<td>1.0342</td>
<td>.715590 ± .000012</td>
<td>.704338</td>
<td>3.88</td>
<td>23.5</td>
<td>.0998</td>
<td>.512081 ± .000013</td>
<td>−1.42</td>
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</table>
and Al₂O₃/(K₂O + Na₂O) from 1.06 to 1.20. These geochemical features suggest that they are more likely to be I-type than S-type granites.

I-type granites can also be distinguished from A-type granites by their associated rock types, mineralogy, and bulk-rock chemistry (Bonin 2007). A-type granites are characterized by high Fe₂O₃/MgO (>16), (Na₂O + K₂O)/CaO (>10), 10000Ga/Al (>2.6), and Zr + Nb + Ce + Y (>350 ppm; Whalen et al. 1987). However, the rocks from the Tianpinghe pluton have relatively low Fe₂O₃/MgO (2.08–3.75), (Na₂O + K₂O)/CaO (3.41–9.39), and 10000Ga/Al ratios (1.84–2.18). They also have low concentrations of high-field-strength elements and REEs. Their Nb contents range from 9.27 to 14.3 ppm, their Zr from 170 to 236 ppm, and their Zr + Nb + Ce + Y from 258 to 346 ppm. These geochemical compositions are significantly different from those of A-type granites but similar to those of I-type granites (Whalen et al. 1987). The Tianpinghe granites have less than 1 wt% normative corundum and have slightly negative εNd (+0.15 to −1.76) and positive zircon εHf values (+0.6 to +8.3). Therefore, the rocks from the Tianpinghe pluton are interpreted as I-type granites, as defined by Chappell and White (2001).

Origin of the Tianpinghe Pluton. Calc-alkaline I-type granites can be generated by various processes. Among these are differentiation of basaltic magmas (e.g., Soesoo 2000), mixing of basaltic magma with felsic crustal components (e.g., Juster et al. 1989; Singer et al. 1992; Kemp et al. 2007), and melting of basaltic crust (e.g., Chappell and White 2001; Wu et al. 2005).

Partial Melting of Ancient Crustal Rocks. The basement of the Yangtze Block is mainly composed of the Paleoproterozoic and Archean rocks (Gao et al. 1999; Qiu et al. 2000; Zhang et al. 2006a, 2006b; Zheng et al. 2006). The Archean rocks, i.e., the Kongling Terrane, consist of dioritic-tonalitic-trondhjemitic and granitic gneiss (DTTG), metapelites, and amphibolites. Both whole-rock Nd model ages and zircon U-Pb dating reveal several episodes of crustal growth in this terrane from 3.8 to 3.2 Ga (Gao et al. 1999; Qiu et al. 2000; Zhang et al. 2006a, 2006b). Multistage episodic reworking of the Archean crust occurred during the Paleoproterozoic to Neoproterozoic (Zhang et al. 2006b). It is therefore possible that the Tianpinghe granitic pluton represents one episode of reworking of the Yangtze basement.

As discussed in “Analytical Results,” the Tianpinghe granites have a narrow range of chemical compositions and relatively constant εNd values that are much higher than the negative εNd values...
Involvement of Mantle-Derived Magmas. It is generally accepted that I-type granites can be produced by differentiation of mafic magmas (White and Chappell 1977; Eggins and Hensen 1987; Soesoo 2000). Neoproterozoic mafic-ultramafic intrusive and extrusive rocks are widely distributed in the Hannan region (Zhou et al. 2002a; Ling et al. 2003). These contemporaneous mafic rocks are the only mantle-derived materials that could possibly represent the protolith of the Tianpinghe granites (fig. 1). However, there are significant compositional gaps between the Tianpinghe granites and the mafic rocks. The rocks from the Tianpinghe pluton have relatively high and uniform SiO$_2$ contents (67–70 wt%), and their incompatible-trace-element ratios, such as Cr/Th (0.04–0.64), Sm/Nd (0.17–0.20), and Sr/Ba (0.27–0.39), are very different from those of the mafic plutons (Cr/Th = 0.67–11.600; Sm/Nd = 0.2–0.38; Sr/Ba = 0.61–47.3; fig. 9). In order to illustrate the trace-element variation relative to fractional crystallization, Sm, La, Th, and Sc were used to model fractional crystallization. The results show that fractional crystallization of mafic magmas cannot explain the high La and Th concentrations of the Tianpinghe granites. For example, the values of La and Th for the Tianpinghe granites (fig. 10) cannot be reached even with 80% removal of any mafic mineral from the assumed parental magma. Alternatively, fractional crystallization of mineral assemblage, including olivine, orthopyroxene, clinopyroxene, alkaline feldspar, and plagioclase, may have evolved the mafic parental magma into the Tianpinghe granite. Removal of plagioclase and alkaline feldspar increase Sc but does not modify Th, whereas fractional crystallization of mafic minerals strongly decreases Sc and slightly increases Th (fig. 10). Olivine is the strongest incompatible mineral among the mafic minerals (table 5); therefore, fractional crystallization of olivine is more effective for increasing Th in the melt than is the fractional crystallization of the mineral assemblage of variable proportions. After removal of 80% of olivine, Th in the melt is lower than that in the Tianpinghe granites. Thus, the Tianpinghe pluton was not generated by simple fractionation of mafic magma.

Alternatively, the I-type granites may have been generated by crustal contamination or mixing of mafic magma with crustally derived felsic magma (e.g., Lackey et al. 2005; Kemp et al. 2007). Granites generated by these processes are normally characterized by abundant mafic enclaves and a wide range of chemical compositions (e.g., Chappell 1996; Janousek et al. 2004). The granitic rocks from the Tianpinghe pluton have SiO$_2$ contents much higher and εNd values (+0.15 to −1.76) notably lower than those of the mafic rocks (εNd = 3.5–5.9; figs. 5, 6), suggesting that voluminous crustal assimilation would have been required to produce their high SiO$_2$. However, their narrow

![Figure 7. $^{176}$Lu/$^{177}$Hf versus initial $^{176}$Hf/$^{177}$Hf (top) and histogram of single-stage model Hf ages (bottom) for rocks from the Tianpinghe pluton in the Hannan region, South China.](image-url)
range of SiO$_2$ and $\varepsilon$Nd values (figs. 3, 5) and the similar initial $^{176}$Hf/$^{177}$Hf ratios of their zircons and the mafic rocks in the region (fig. 8) suggest that only minor crustal material was involved in their petrogenesis. Therefore, mafic magma differentiation, crustal contamination, and magma mixing cannot explain the geochemical features of the Tianpinghe pluton.

Partial Melting of Newly Formed Mafic Crust. Melting of basaltic rocks is another way in which I-type granitic magmas may be formed (Chappell and White 2001). The Tianpinghe granites have a minimum single-source-region age of 0.93 Ga, defined by the intersection between the depleted-mantle curve and the dashed horizontal line in figure 8 ($^{176}$Lu/$^{177}$Hf = 0). The rocks from the Tianpinghe pluton have single- and two-stage model ages of 1.01–1.31 and 1.31–2.01 Ga, respectively (table 4). With minor crustal contamination taken into consideration, the youngest two-stage model age of the 1.31 Ga represents the maximum resident time of their source rocks, suggesting that the Tianpinghe granites were more likely produced by melting of newly formed mafic rocks.

In the Hannan region, Neoproterozoic mafic intrusions with ages of 780–820 Ma (Zhou et al. 2002a) are common. Thus, it is possible that the Tianpinghe granites were produced by melting of mafic rocks geochemically similar to these mafic intrusions. An experiment of metabasalt dehydration melting reveals that the silicon concentration of melt decreases with an increasing degree of partial melting (Rapp and Watson 1995). A low degree of melting (<10%) produces melts that are highly silicic (Rapp and Watson 1995). To model such a melting process, we use the Neoproterozoic mafic-ultramafic rocks as the parental source of the Tianpinghe pluton (table 5). The source mineralogy

Figure 8. Initial Hf isotopic compositions at the crystallization age of the zircons for the Tianpinghe granites. Reference lines representing meteoritic Hf evolution and depleted mantle are from Blichert-Toft and Albarede (1997) and Griffin et al. (2000), respectively. The basement of the Yangtze Block is defined on the basis of zircon Hf isotopes for the Precambrian strata (Zhang et al. 2006a, 2006b) and the felsic granulite xenolith from Neoproterozoic rocks (Zheng et al. 2006) at assumed $^{176}$Lu/$^{177}$Hf ratios of 0.015 and 0.009, respectively. The initial $^{176}$Hf/$^{177}$Hf ratios for the Neoproterozoic mafic-ultramafic plutons in the Hannan region [HNM] are also shown for comparison (Zhao and Zhou 2008b).
The rocks from the Tianpinghe pluton have \( \varepsilon \)Nd values slightly lower than those of the Neoproterozoic mafic rocks [fig. 5], suggesting minor

is obtained from the CIPW calculation of the average bulk-rock compositions of the Bijigou, Wangjiangshan, and Beiba mafic plutons (fig. 1). Trace-element concentrations of the source region are obtained from the average concentrations in these three plutons. Calculation procedures and partition coefficients used for trace-element modeling are given in table 5. Batch melting calculations reveal that less than 5% partial melting of the mafic rocks will produce a melt with a chemical composition equivalent to that of the Tianpinghe pluton (fig. 10). The mantle-normalized trace-element patterns (fig. 11) also suggest that 5% melting of mafic rocks could have produced the Tianpinghe granites. Therefore, we suggest that the Tianpinghe granites were formed by low-percentage melting of newly emplaced mafic rocks.

The rocks from the Tianpinghe pluton have \( \varepsilon \)Nd values slightly lower than those of the Neoproterozoic mafic rocks (Zhou et al. 2002a; Zhao and Zhou 2008b) and the Archean basement (Gao et al. 1999) are also shown for comparison.

Figure 9. Sm/Nd versus Cr/Th (top) and Sr/Ba versus Rb/Sr (bottom) for rocks from the Tianpinghe pluton. Neoproterozoic mafic rocks (Zhou et al. 2002a; Zhao and Zhou 2008b) and the Archean basement (Gao et al. 1999) are also shown for comparison.

Figure 10. Sm versus La (top) and Th versus Sc (bottom) for the rocks from the Tianpinghe pluton. Data for mafic rocks from the Neoproterozoic intrusions in the Hannan region are from Zhou et al. (2002a) and Zhao and Zhou (2008b). Data for the Archean basement, represented by the Kongling Terrane, are from Gao et al. (1999). The thick lines represent partial-melting curves for the average compositions of the mafic rocks in the Hannan region and are drawn according to table 5, and the numbers along the curves are percentages of partial melting. The thin dashed lines represent calculated trends of fractional crystallization. Numbers in parentheses represent the degree of mineral fractionation. Rayleigh fractionation

\[ C_L/C_O = F^{D-1} \]

is used, where \( C_L \) is concentration of a trace element in the liquid, \( C_O \) is concentration of a trace element in the parental liquid, \( F \) is the fraction of melt remaining, and \( D \) is the partitioning coefficient. Values of \( D \) for amphiboles are collectively from Villemant et al. (1981) and Higuchi and Nagasawa (1969); \( D \) data for other minerals are shown in table 5.
involvement of old crustal material during emplacement. One zircon analysis has an exceptionally low $\varepsilon$Hf value of $+20$, which plots in the field of the basement of the Yangtze Block (fig. 8). Its old single- (2.14 Ga) and two-stage model ages (3.92 Ga) indicate that the zircon is a relict of Archean crustal material. The basement rocks have high Hf concentrations and low $^{177}$Hf/$^{176}$Hf values (Zhang et al. 2006a, 2006b; Zheng et al. 2006; fig. 8), so that the addition of small amounts of old crustal material can significantly lower the $^{177}$Hf/$^{176}$Hf ratio of the magma. The variable $\varepsilon$Hf values ($+0.6$ to $+8.3$) of zircons from the Tianpinghe pluton suggest that assimilation of old crust played an important role in determining the magma composition. The highest $\varepsilon$Hf value of $+8.3$ may represent the initial $\varepsilon$Hf value of the melts, whereas the lowest $\varepsilon$Hf value of $+0.6$ reflects contamination by older crustal components.

**Implications for Neoproterozoic Arc-Related Magmatism.** Zircon saturation temperatures calculated from bulk-rock compositions provide minimum estimates of initial magma temperature at the source (Miller et al. 2003). The Tianpinghe granites have Zr contents ranging from 170 to 237 ppm, corresponding to zircon saturation temperatures of about 1050°C–1080°C (Miller et al. 2003). This conclusion is consistent with experimental results showing that tonalitic to granitic calc-alkaline magmas are normally generated by dehydration melting of fertile portions of the continental crust at temperatures above 780°C (e.g., Rapp 1995; Rapp and Watson 1995). Anatectic of continental crust under temperatures in excess of 780°C within continental collision zones requires advective input of heat from the mantle (e.g., Huppert and Sparks 1988; Roberts and Clemens 1993; Miller et al. 2003) accompanied by slow exhumation (Patino and McCarthy 1998). Such high temperatures are generally considered to have occurred in the deep crust and to have required significant heat input through under- or intraplating by mantle-derived basaltic magmas (e.g., Clemens 1990; Vielzeuf et al. 1990). Intraplating of basaltic magmas is thought to be responsible for the melting of refractory mafic rocks by fluid-absent breakdown to produce hot, water-undersaturated, calc-alkaline silicic magmas in an active continental margin. The 762-Ma Tianpinghe

<table>
<thead>
<tr>
<th>Table 5. Trace Elements Used in the Modeling</th>
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<tr>
<td>D&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Anorthite</td>
</tr>
<tr>
<td>Albite/orthoclase&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Clinopyroxene</td>
</tr>
<tr>
<td>Orthopyroxene</td>
</tr>
<tr>
<td>Olivine&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Apatite</td>
</tr>
<tr>
<td>Ilmenite</td>
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<td>Magnetite</td>
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<th>Composition (ppm):</th>
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<tr>
<td>Initial&lt;sup&gt;d&lt;/sup&gt;</td>
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<tr>
<td>Under partial melting&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>1%</td>
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<td>30%</td>
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<td>40%</td>
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<sup>a</sup> Partitioning coefficients are from Bacon and Druitt (1988), except as noted.
<sup>b</sup> Partitioning coefficients for albite and orthoclase are assumed to be the same and are from Nash and Crecraft (1985).
<sup>c</sup> Partitioning coefficients for olivine are from Mahood and Hildreth (1983), Villemant (1988), and Mahood and Stimac (1990).
<sup>d</sup> The Neoproterozoic mafic plutons are assumed to be a protolith of the Tianpinghe granites. Initial trace-element concentrations reflect the average composition of the rocks from the Neoproterozoic mafic plutons exposed in the Hainan region (Zhou et al. 2002a; Zhao and Zhou 2008b).
<sup>e</sup> Batch partial melting model is calculated by $C_L/C_O = 1/[D_O + F(1 - D_O)]$, where $C_L$ is the weight concentration of a trace element in the liquid, $C_O$ is the weight concentration of a trace element in the original unmelted solid, $D_O$ is the bulk distribution coefficient of the original solids, and $F$ is the fraction of melt already removed from the source.
pluton was generated at a time when the lithospheric mantle was hot, suggesting that intraplapping and underplating of mantle-derived magmas were the main heat sources for generating the Tianpinghe pluton.

The 735-Ma adakitic plutons in the Hannan region are explained by melting of a thickened lower mafic crust (Zhao and Zhou 2008a). This mechanism requires that the crust be more than 50 km thick, the minimum depth for producing adakitic melts in the eclogitized lower crust (e.g., Rapp et al. 1991; Kay and Kay 2002). No older adakitic plutons have been found in the region, suggesting that the thickness of the continental crust gradually increased to more than 50 km at around 735 Ma by underplating of the mantle-derived magma (Zhao and Zhou 2008a). The rocks from the 762-Ma Tianpinghe pluton all plot within the volcanic-arc granite field in the Nb versus Y and Rb versus Y + Nb diagrams (fig. 12, VAG), indicating that they were formed in a collisional environment. The Tianpinghe pluton was therefore the product of continental crustal differentiation that resulted from crustal thickening at an active continental margin during the Neoproterozoic (fig. 13).

According to the arc signatures of the Xixiang volcanic rocks in the Hannan region, subduction of oceanic lithosphere beneath the western margin of the Yangtze Block started no later than 950 Ma (Ling et al. 2003). The mafic-ultramafic intrusions in the Hannan region have SHRIMP zircon U-Pb ages ranging from 820 to 746 Ma and show arclike geochemical compositions, suggesting that they were produced by partial melting of a mantle wedge above a subduction zone (Zhou et al. 2002a). In addition to the Tianpinghe granites, I-type calc-alkaline Neoproterozoic granites are widely distributed in the western margin of the Yangtze Block (Ling et al. 2001; Zhou et al. 2002b; Chen et al. 2005). Subduction is therefore a reasonable explanation for the long span of arc magmatic activities. The active continental margin persisted for more than 200 m.yr. along this margin, an environment similar to the eastern margin of the Eurasian continent above the subduction zone of the I-Ianian/Pacific oceanic plate since the Triassic (Maruyama et al. 1997).

Figure 11. Primitive-mantle-normalized patterns for selected modeled trace elements. The gray area represents the field of the rocks from the Tianpinghe pluton. The numbers represent percentages of partial melting. Normalizing values are from Sun and McDonough (1989).

Figure 12. Nb versus Y (top) and Rb versus Y + Nb (bottom) discrimination diagrams for the Tianpinghe granites, showing the tectonic classification suggested by Pearce et al. [1984]. Syn-COLG = syn-collisional granite, VAG = volcanic-arc granite, WPG = within-plate granite, ORG = ocean ridge granite.
The presence of a long-lived magmatic arc, the so-called Panxi-Hannan arc (Zhou et al. 2002b), at the western margin of the Yangtze Block rules out the Rodinian-reconstruction model proposed by Li et al. (2003), in which South China was located in the center of the supercontinent. Instead, the Panxi-Hannan arc may have been part of the Neoproterozoic Andean-type arc that has been defined by volcanic and plutonic rocks in Madagascar, Seychelles, and northwestern India (Tucker et al. 2001). Therefore, South China was most probably located along the margin of the Neoproterozoic supercontinent (Zhou et al. 2006a). The Neoproterozoic granites at the western margin of the Yangtze Block are part of the Andean-type arc assemblage at the northwestern margin of Rodinia.

**Conclusions**

The rocks from the 762-Ma Tianpinghe pluton are I-type granites that were generated by partial melting of newly formed basaltic rocks in the lower crust. This mafic lower crust formed by intraplaeting of mantle-derived magma during crustal thickening. The Neoproterozoic was an important period of continental growth and reworking in the Yangtze Block.
Block. The northwestern margin of the Yangtze Block was an active continental arc for a period of 200 m.yr., similar to the present-day eastern margin of the Eurasian continent. Reworking of the newly formed continental crust may have been the main mechanism of crustal differentiation in the Yangtze Block. The long-lasting Neoproterozoic arc at the western margin of the Yangtze Block suggests that it was a continuation of the Andean-type arc at the northwestern margin of the Rodinia.

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