Neoproterozoic Adakitic Plutons and Arc Magmatism along the Western Margin of the Yangtze Block, South China

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ABSTRACT

Neoproterozoic adakitic plutons that crop out along the western margin of the Yangtze Block (South China) from Kangding on the north to Panxi on the south provide constraints on the origin of the giant Jinningian magmatic event of South China. Representative plutons include the Xuelongbao (750 Ma), Datian (760 Ma), and Dajianshan intrusions. The latter two bodies consist mainly of granodiorite with relatively high SiO_2 (51.0–73.4 wt%) and Mg#'s (0.36–0.55). They have fractionated rare earth element patterns, with $(La/Yb)_N$ ratios ranging from 2.6 to 101.8, and are characterized by high Sr (344–1018 ppm) and low Y (4.3–17.9 ppm), yielding Sr/Y ratios ranging from 27 to 111. On primitive mantle–normalized trace-element diagrams, these rocks show enrichment of large-ion lithophile elements and depletion of high-field-strength elements (Nb, Ta), with positive Zr-Hf and negative Ti anomalies, consistent with an arc-related setting. They have relatively constant initial whole-rock $^{87}Sr/^{86}Sr$ ratios (0.704308–0.705068) and εNd values (+0.66 to −0.92). From their geochemistry, these plutons are interpreted to have formed in an arc environment. The parental magmas were generated from partial melts of a subducted oceanic slab that were modified by interaction with the overlying mantle wedge. Therefore, we conclude that the western margin of the Yangtze Block was an active magmatic arc during the Neoproterozoic.

Online enhancement: table.

Introduction

Numerous Neoproterozoic plutons around the Yangtze Block consist of voluminous granitic and minor mafic-ultramafic rocks (fig. 1; Ministry of Geology and Mineral Resources 1990*a*; Zhou et al. 2002*a*, 2002*b*). The origin of these plutons and the source of heat required for the formation of this giant Neoproterozoic assemblage have long been debated (Li et al. 2007*a*, 2007*b*; Munteanu and Yao 2007; Zhou et al. 2007). Li et al. (1995, 1999) suggested that the igneous activity was related to a mantle plume that initiated the breakup of the supercontinent Rodinia. On the other hand, Zhou et al. (2002*a*, 2002*b*, 2006*a*, 2006*b*) and Zhao and Zhou (2007) argued that the arclike geochemistry of these plutons indicates formation at an active continental margin and that they define the Hannan-Panxi arc.

Granitic plutons in the western margin of the Yangtze Block include normal-arc granites and trondhjemite-tonalite-granodiorite (TTG) suites, as shown in various local geological maps (He et al. 1988; Ministry of Geology and Mineral Resources 1990*a*). The TTG suites are of particular importance because they are geochemically similar to adakites (Martin 1999). The adakitic affinity of the Xuelongbao granodioritic pluton was confirmed in a recent study by Zhou et al. (2006*b*). It is possible that all plutons of the TTG suite have adakitic affinities, but detailed geochemical data for these rocks are not available.

Adakites were originally thought to have been produced by partial melting of subducted oceanic slabs (Drummond and Defant 1990; Defant and Drummond 1993; Kay et al. 1993), but they can also be formed by fractionation of basaltic magma (e.g., Castillo et al. 1999; Macpherson et al. 2006) or partial melting of the lower crust (e.g., Petford and Atherton 1996; Chung et al. 2003). Slab melts are formed from subducted H_2O-bearing basaltic

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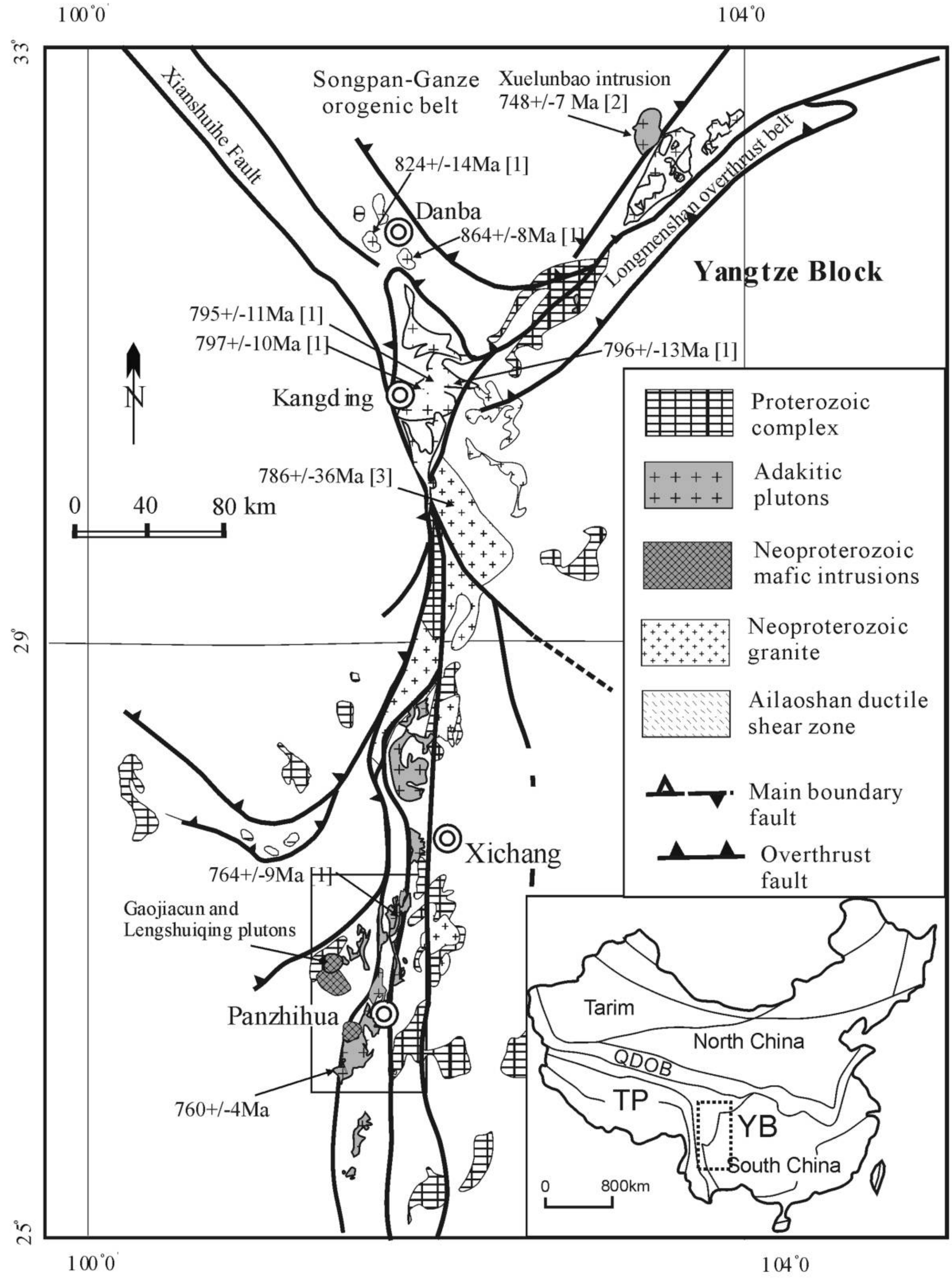


Figure 1. Sketch map showing the distribution of Proterozoic granodiorite plutons along the western margin of the Yangtze Block, China (modified from Ministry of Geology and Mineral Resources 1990*a*, 1990*b*). The age data are from Zhou et al. (2002*b*; [1]), Zhou et al. (2006*b*; [2]), Shen et al. (2000; [3], and this study). *QDOB* = Qinling-Dabie orogenic belt; *TP* = Tibetan Plateau; *YB* = Yangtze Block. Box indicates area of figure 2.

material and are therefore geochemically different from those formed by melting of anhydrous lower-crustal material under amphibolite- or eclogite-facies conditions (Peacock et al. 1994; Rapp and Watson 1995). Although Zhou et al. (2006*b*) proposed that the Xuelongbao pluton was produced by partial melting of a subducted oceanic slab, Li et al. (2007*a*) argued that it formed by melting of the lower crust. Thus, determining the petrogenesis, extent, and distribution of adakitic bodies in the western margin of the Yangtze Block is extremely important for deciphering the tectonic evolution of the region. In this article, we document the adakitic affinities of two additional plutons, the Datian and Dajianshan plutons, in the southern part of the region and conclude that the adakitic bodies formed by slab melting and that they define a Neoproterozoic paleoarc above a subduction zone.

Geological Background

South China comprises the Yangtze Block to the northwest and the Cathaysian Block to the southeast, which were welded together during Meso- to Neoproterozoic time (fig. 1; Chen et al. 1991; Li and McCulloch 1996). The Yangtze Block is separated from the North China Block to the north by the Qinling-Dabie orogenic belt, which was formed by closure of the easternmost part of the Paleotethyan ocean (Mattauer et al. 1985; Hsu et al. 1987). To the west, it is bounded by the Tibetan Plateau (fig. 1).

The eastern margin of the Tibetan Plateau is marked by the Songpan-Ganze Terrane, which is characterized by a thick (several to >10 km) sequence of the Late Triassic strata of deep marine origin (see review by Yin and Harrison [2000]). The Songpan-Ganze Terrane is separated from the Yangtze Block by the Longmenshan fault. Metamorphic core complexes in this terrane were unroofed by nearly east-west extension, possibly at 180–150 Ma (fig. 1; Zhou et al. 2002*b*; Yan et al. 2003).

The Yangtze Block consists of basement complexes overlain by a Neoproterozoic (Sinian) to Cenozoic cover. The basement complexes are composed mainly of Archean and Proterozoic strata, and the latter are intruded by numerous Neoproterozoic plutons in the western part of the block. These plutons, mainly silicic but with minor mafic-ultramafic components, occur over a north-south distance of more than 1000 km (fig. 1). The granitic plutons are locally accompanied by variable amounts of amphibolite and granulite, as well as minor migmatite, mica schist, graphite-bearing sillimanite-garnet gneiss (khondalite), marble, and quartzite.

The Neoproterozoic mafic-ultramafic intrusions occur mainly in the Hannan region to the north and the Panxi region to the south (fig. 1). In Hannan, the Wangjiangshan and Bijigou intrusions have SHRIMP zircon U-Pb ages of 820 and 780 Ma, respectively (Zhou et al. 2002*a*). In Panxi, the Tongde, Gaojiacun, and Lengshuiqing intrusions have similar ages of 810 Ma and intrude the Yanbian Group (Zhou et al. 2006*a*; Sun et al. 2007). In addition, the Dadukou intrusion has a SHRIMP zircon age of 745 Ma (Zhao and Zhou 2007).

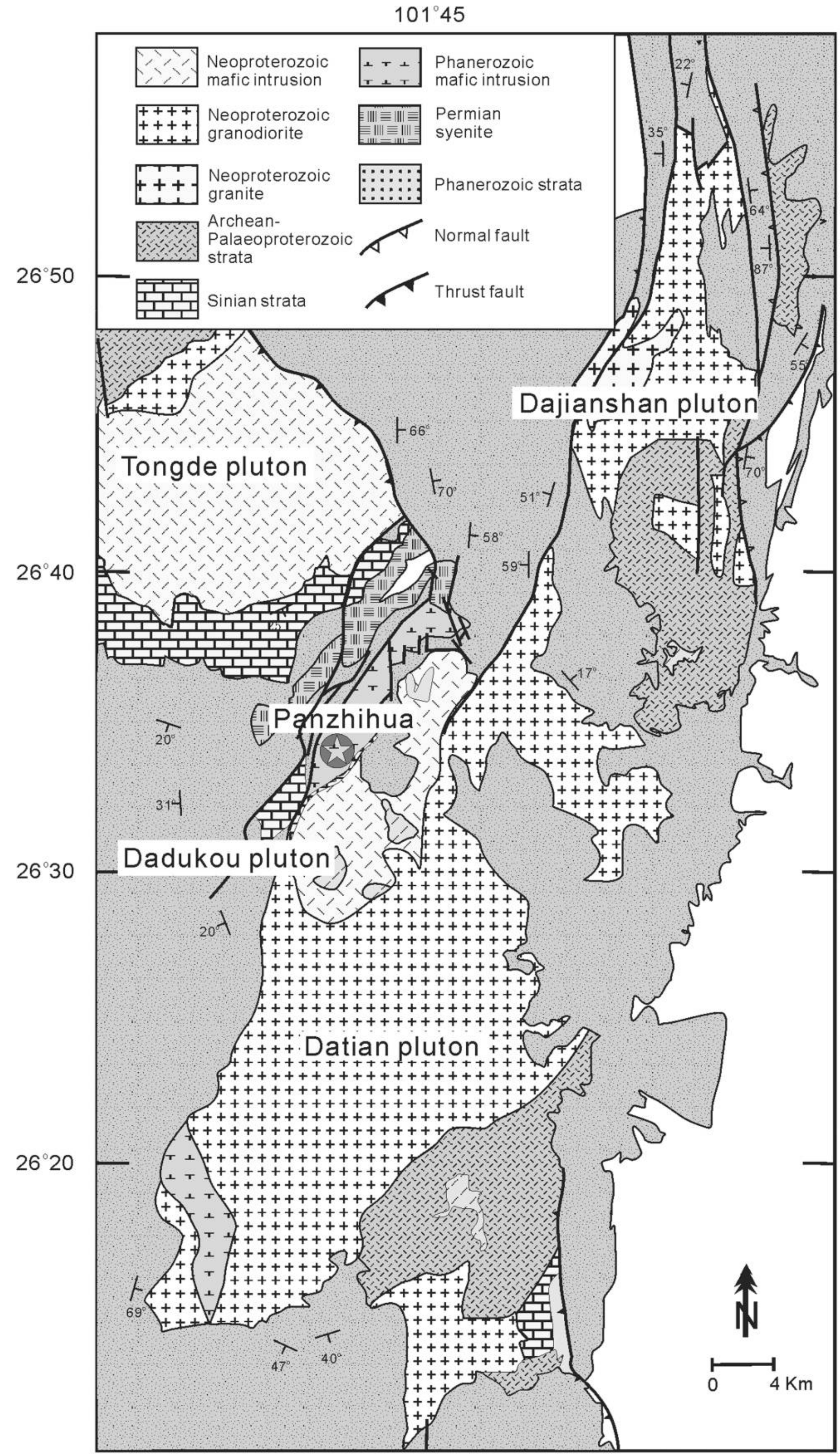
The Neoproterozoic sedimentary sequences associated with the plutons include the Yanbian Group in the Panxi region and the Bikou and Xixiang groups in the Hannan region. The Yanbian Group consists of pillow basalts in the lower part and a thick flysch sequence in the upper part. Detrital zircons from the upper flysch sequence give U-Pb ages as young as 840 Ma (Zhou et al. 2006*a*). The pillow lavas have a SHRIMP U-Pb zircon age of 782 $\pm$ 53 Ma (Du et al. 2005). Their arclike geochemical characteristics suggest formation in a back-arc setting (Sun et al. 2007). The Bikou Group has the same tectonostratigraphic features as the Yanbian Group and contains zircon as young as 720 Ma. Numerous mafic intrusions, including the Wangjiangshan and Bijigou intrusions, intrude the Xixiang Group, a sequence of volcanic and sedimentary rocks of possibly back-arc basin origin.

Another group of intermediate to silicic plutons, ranging from granodioritic to tonalitic in composition, has been mapped as a TTG suite. Representative of this group are the Xuelongbao, Datian, and Dajianshan intrusions, which were selected for detailed examination.

Adakitic Plutons

The Xuelongbao plutonic complex is composed of coarse-grained biotite tonalite in the center, mantled by finer-grained biotite granodiorite and then two-mica granodiorite. The major minerals in this complex include plagioclase (50%–70%), K-feldspar (<10%), quartz (20%–30%), and biotite (5%–10%). This pluton is dated at 750 Ma (Zhou et al. 2006*b*).

The Datian and Dajianshan plutons are located in Panxi, Sichuan Province (figs. 1, 2). They intrude a metamorphic complex of fine-grained amphibolite and amphibole-bearing gneiss. The Datian pluton is intruded by the Dadukou gabbro to the northwest (fig. 2), which has been dated at 745 Ma using


101°45
Neoproterozoic mafic intrusion
Neoproterozoic granodiorite
Neoproterozoic granite
Archean-Palaeoproterozoic strata
Sinian strata
Phanerozoic mafic intrusion
Permian syenite
Phanerozoic strata
Normal fault
Thrust fault
26°50
26°40
26°30
26°20
Tongde pluton
Dajianshan pluton
Panzhihua
Dadukou pluton
Datian pluton
22°
35°
64°
87°
55°
66°
70°
51°
58°
59°
70°
17°
20°
31°
20°
69°
47°
40°
N
0
4 Km

the SHRIMP zircon U-Pb technique (Zhao and Zhou 2007). Rocks of the Datian pluton are mainly medium- to coarse-grained granodiorite, composed of plagioclase (35%–45%), quartz (20%–30%), amphibole (10%–15%), biotite (10%–15%), and K-feldspar (<10%; fig. 3*a*). The amphibole crystals are subhedral to euhedral with resorbed edges and are surrounded by plagioclase, quartz, and biotite, suggesting that the amphibole was an early-crystallizing phase (fig. 3*b*). Rocks from the Dajianshan intrusion are diorites, composed of amphibole (40%–50%), plagioclase (20%–30%), and quartz (10%–20%), with minor biotite and K-feldspar.

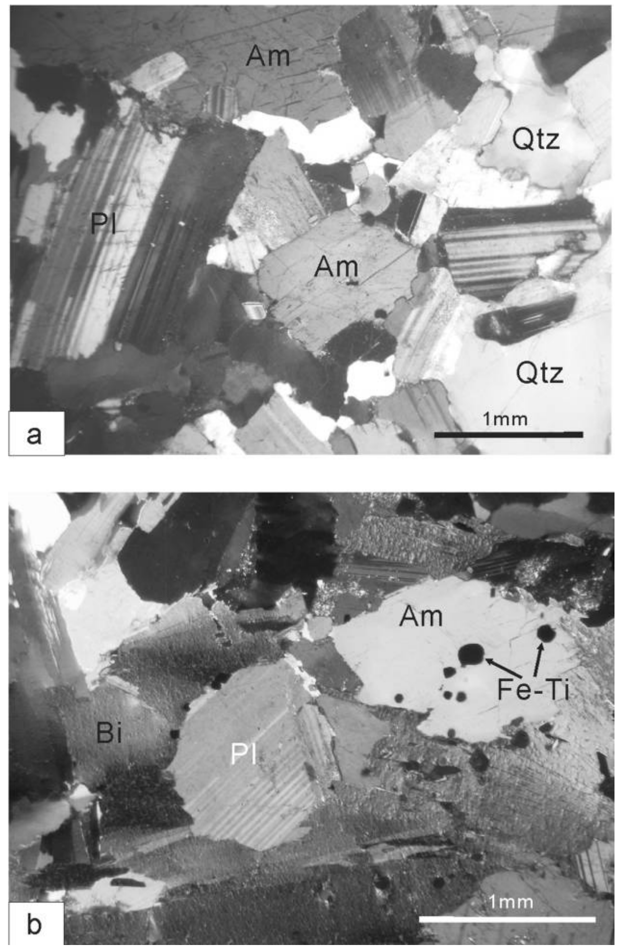


Figure 3. Photomicrographs of the granodiorite from the Datian pluton, Sichuan Province, China. *Am* = amphibole; *Bi* = biotite; *Fe-Ti* = Fe-Ti oxide; *Pl* = plagioclase; *Qtz* = quartz.

Analytical Methods

SHRIMP Zircon U-Pb Dating. Zircon grains were separated using conventional heavy-liquid and magnetic techniques, mounted in epoxy, polished, coated with gold, and photographed in transmitted and reflected light to identify grains for analysis. U-Pb isotopic ratios of zircon separates were measured using the SHRIMP II at the Institute of Geosciences, Chinese Academy of Geological Sciences. The $^{206}Pb/^{238}U$ ages given in table 1 and figure 4 are independent of the standard analyses. Detailed analytical procedures for SHRIMP zircon dating are described by Jian et al. (2003).

Whole-Rock Geochemical Analyses. Major-element abundances were obtained by x-ray fluorescence (XRF) analysis of fused glass beads at the University of Hong Kong. Trace elements, including rare earth elements (REEs), were analyzed on a VG PQ Excell inductively coupled plasma mass spectrometer (ICP-MS), also at the University of Hong Kong. Pure elemental standards were used for external calibration, and BHVO-1 and SY-4 were selected as reference materials. Detailed analytical procedures for the trace-element analyses are described by Qi et al. (2000). Accuracies of the XRF analyses are estimated to be 2% for major elements, whereas ICP-MS analyses for trace elements yield accuracies better than 5%.

Rb-Sr and Sm-Nd Isotopic Analyses. Rb-Sr and Sm-Nd isotopic analyses were performed on a VG-354 thermal ionization magnetic sector mass spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. The procedures for chemical separation and isotopic measurement are described by Zhang et al. (2001). Mass fractionation corrections for Sr and Nd isotopic ratios were based on $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$. Uncertainties in Rb/Sr and Sm/Nd ratios are less than $\pm 2\%$ and $\pm 0.5\%$ (relative), respectively.

Analytical Results

Zircon U-Pb Dating Results. Sample DT-29 from the Datian pluton was selected for zircon dating. All of the zircons recovered from this sample have

Figure 2. Simplified geological map of the Datian and Dajianshan granodioritic intrusions, Sichuan Province, southwestern China.

Table 1. SHRIMP Zircon U-Pb Analytical Results for the Datian Intrusion, Southwestern China

Spot	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	Age ± SE (Ma)		
					$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$
DT29.1	117	87	13.0	.77	760.3 ± 9.5	798 ± 43	774 ± 15
DT29.2	71	51	8.6	.75	797.0 ± 9.9	806 ± 57	797 ± 16
DT29.3	250	165	28.6	.68	794.3 ± 8.6	767 ± 25	808 ± 13
DT29.4	3801	502	334.0	.14	611.0 ± 6.2	739 ± 47	542 ± 42
DT29.5	3860	1939	433.5	.52	790.5 ± 6.6	753 ± 22	526 ± 20
DT29.6	151	152	17.1	1.04	771.2 ± 7.6	760 ± 50	775 ± 13
DT29.7	5640	3178	492.6	.58	625.3 ± 5.2	677 ± 10	416 ± 6
DT29.8, inner	302	142	32.3	.48	753.5 ± 6.8	774 ± 24	759 ± 11
DT29.8, outer	249	114	26.6	.47	748.2 ± 6.7	831 ± 18	777 ± 10
DT29.11, inner	160	94	17.8	.61	772.5 ± 9.1	829 ± 34	790 ± 15
DT29.11, outer	142	83	15.5	.60	751.5 ± 7.2	803 ± 37	773 ± 14
DT29.12	140	86	15.4	.64	756.8 ± 7.6	758 ± 54	760 ± 18
DT29.13	268	134	28.7	.52	751.0 ± 6.8	798 ± 26	766 ± 11
DT29.14	80	43	11.8	.56	742.2 ± 9.1	386 ± 292	626 ± 59
DT29.15	183	105	20.0	.59	763.8 ± 7.8	721 ± 38	764 ± 15
DT29.16	163	155	18.1	.98	769.2 ± 7.4	755 ± 35	775 ± 11
DT29.17	160	150	17.7	.97	765.8 ± 7.4	739 ± 37	766 ± 12
DT29.18	130	83	14.5	.66	767.7 ± 9.6	816 ± 26	796 ± 13
DT29.19	102	66	11.3	.66	766.8 ± 8.8	795 ± 48	765 ± 17
DT29.20	254	133	27.8	.54	765.4 ± 7.0	764 ± 29	771 ± 12
DT29.21	130	110	15.0	.88	782.4 ± 8.1	821 ± 35	808 ± 13
DT29.22	113	75	12.7	.68	761.7 ± 7.8	828 ± 27	794 ± 12
DT29.23	105	72	11.5	.71	755.4 ± 7.8	862 ± 40	767 ± 14
DT29.24	74	50	8.9	.70	769.1 ± 8.8	659 ± 98	772 ± 27
DT29.25	104	99	11.9	.98	767.1 ± 8.0	672 ± 63	760 ± 15

sector zoning, typical of igneous grains. A total of 25 spots were analyzed on 23 zoned crystals. Two crystals were analyzed from both the inner and outer parts of individual zoned grains. Twenty of the 25 analyses form a tight cluster with a weighted mean $^{206}Pb/^{238}U$ age of 760 ± 4 Ma (fig. 4), which is 10 m.yr. older than the Xuelongbao pluton (Zhou et al. 2006*b*).

Whole-Rock Elemental Data. Rocks from the Datian and Dajianshan plutons have SiO_2 contents ranging from 50.96 to 73.40 wt% and Al_2O_3 contents ranging from 14.27 to 20.96 wt%. All the samples are metaluminous, with an alumina saturation index (ASI; molar $Al_2O_3/(CaO + Na_2O + K_2O)$) of 0.69–1.10. Their K_2O contents range from 0.02 to 3.72 wt%, and their Na_2O contents range from 3.05 to 5.26 wt%, yielding low K_2O/Na_2O ratios of less than 1 for all samples. Most samples have relatively high MgO contents except the most siliceous, which have less than 1 wt% MgO content. On major-element variation diagrams (fig. 5), the samples plot along linear trends, suggesting that fractional crystallization played a major role in their evolution. The rocks from the Xuelongbao intrusion have relatively high SiO_2 and total alkalis but low MgO, Fe_2O_3, CaO, and Al_2O_3 contents (fig. 5).

Chondrite-normalized REE patterns of all the rocks show strong light REE enrichment and moderately negative to positive Eu anomalies (Eu/Eu* = 0.62–1.34; fig. 6). They have highly variable $(La/Yb)_N$ ratios ranging from 2.6 to 102. Their primitive mantle–normalized trace-element patterns are characterized by enrichment of large-ion lithophile elements (LILEs) and depletion of Nb and Ta, with negative Ti and positive Pb anomalies (fig. 7). Zr and Hf are variable and show both negative

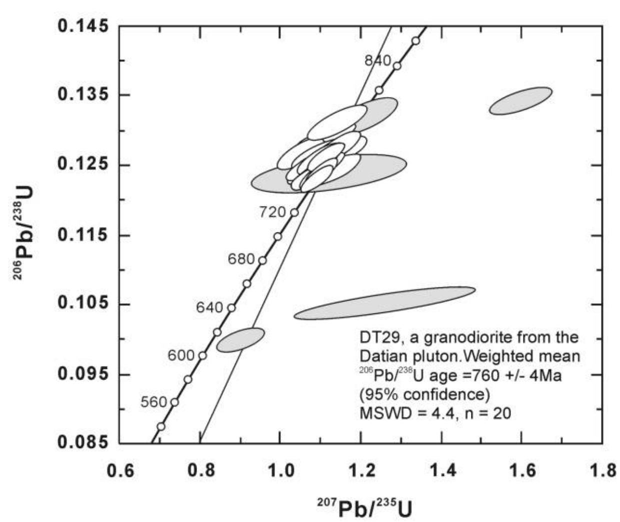


Figure 4. SHRIMP U-Pb zircon dates for the rock from the Datian intrusion, southwestern China.

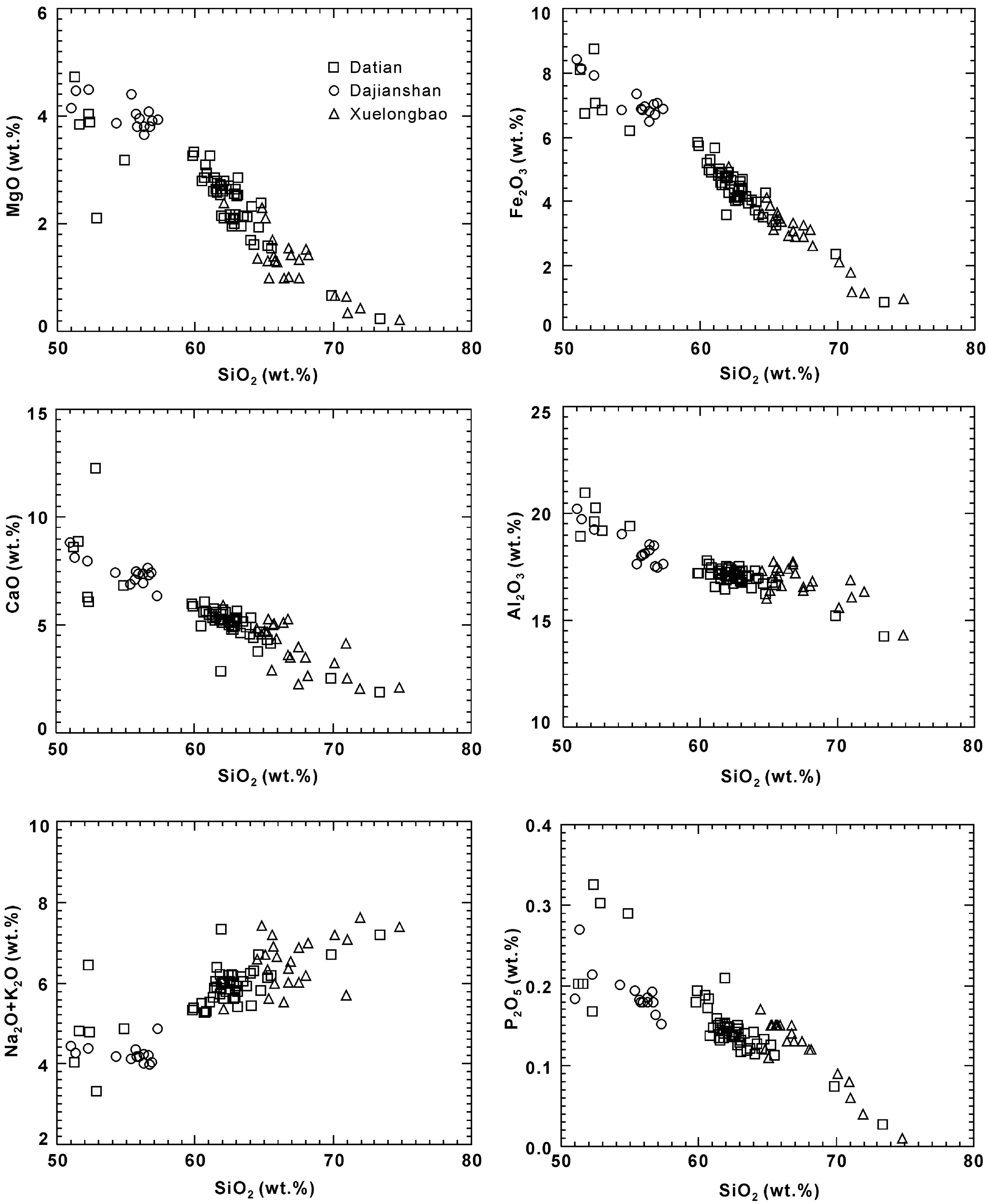


Figure 5. Major-element variation for the Datian and Dajianshan plutons, southwestern China. Rocks from the Xuelongbao pluton are also shown for comparison (Zhou et al. 2006*b*).

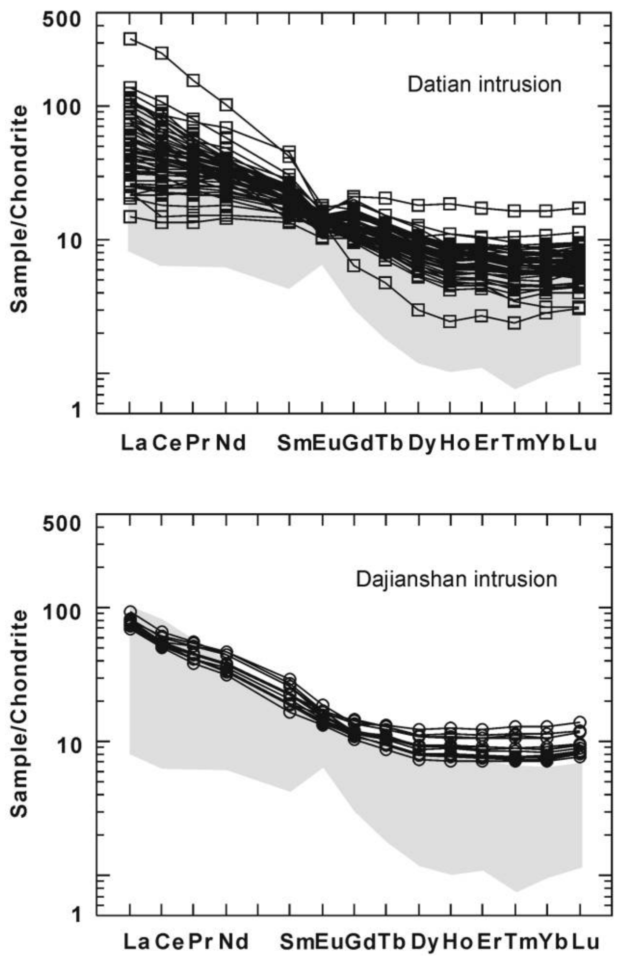


Figure 6. Chondrite-normalized rare earth element (REE) patterns for the rocks from the Datian and Dajianshan intrusions, Sichuan Province, China. The shaded area shows the range of REE patterns for the Xuelongbao pluton (Zhou et al. 2006*b*). Normalizing values are from Sun and McDonough (1989).

and positive anomalies, compared with neighboring elements. These geochemical features are similar to those of subduction-related arc rocks (fig. 7).

The rocks from these two plutons all have high Sr (344–1018 ppm) and low Y concentrations (4.3–17.9 ppm), resulting in high Sr/Y ratios ranging from 27 to 111. Thus, all samples plot in the adakite field in a Sr/Y versus Y diagram (fig. 8). In other tectonic discrimination diagrams (fig. 9), they all plot in the volcanic-arc fields.

Whole-Rock Isotopic Compositions. Rocks from the Datian and Dajianshan plutons have similar and relatively constant Sr-Nd isotopic ratios (table 2; fig. 10), with $^{87}Sr/^{86}Sr$ ratios ranging from 0.704308 to 0.705068 and $^{143}Nd/^{144}Nd$ ratios from 0.511611 to 0.511692. Their εNd values range from +0.66 to −0.92 (fig. 10). However, the rocks from the Xuelongbao pluton have relatively high $^{143}Nd/^{144}Nd$ ratios.

Discussion

Origin of the Adakitic Plutons by Slab Melting. The Datian and Dajianshan plutons are geochemically and petrologically similar to the Xuelongbao pluton, which has been shown to be adakitic in composition (Zhou et al. 2006*b*). Thus, we suggest that these two bodies are also adakitic in composition.

The adakitic rocks from the Datian and Dajian-

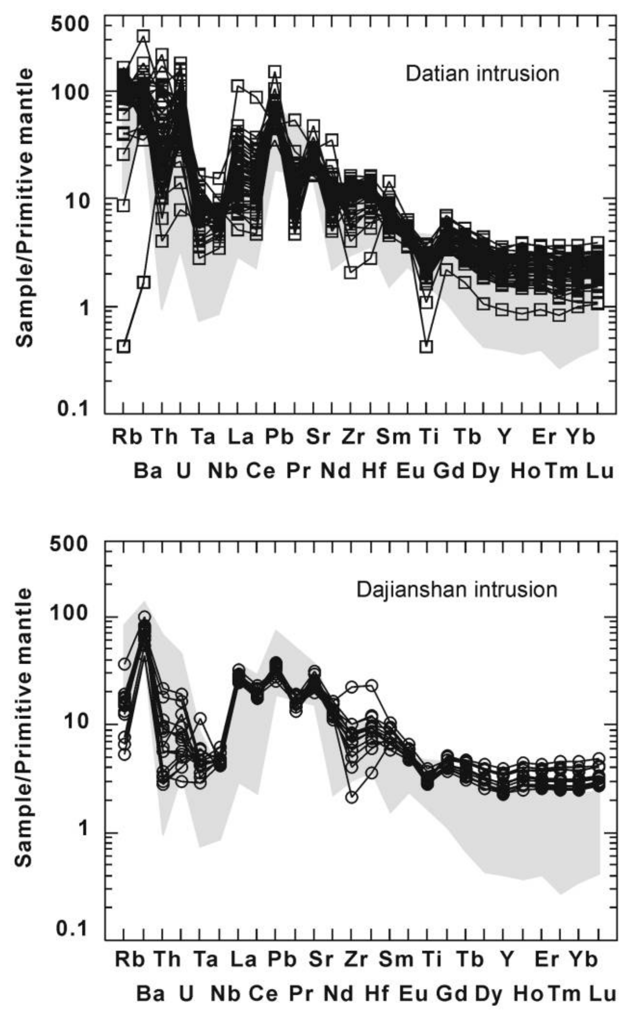


Figure 7. Primitive mantle–normalized trace-element patterns for the felsic rocks from the Datian and Dajianshan plutons, Sichuan Province, China. The shaded area shows the range for the Xuelongbao pluton (Zhou et al. 2006*b*). Normalizing values are from Sun and McDonough (1989).

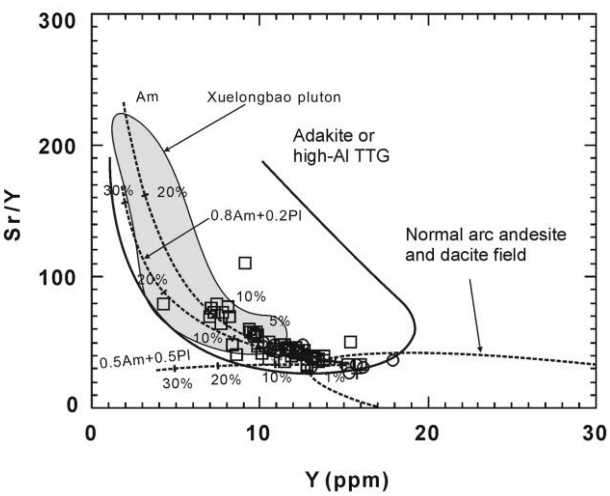


Figure 8. Sr/Y versus Y for granodiorites from the Datian (*squares*) and Dajianshan (*circles*) intrusions, Sichuan Province, China. The Xuelongbao intrusion is also shown for comparison (Zhou et al. 2006*b*). Fields for adakite, or high-Al trondhjemite-tonalite-granodiorite (TTG), and normal-arc andesite and dacite are from Drummond and Defant (1990). The dashed lines are fractional crystallization curves with different proportions of amphibole (Am) and plagioclase (Pl); numbers along the line are percentages of crystallization. Distribution coefficients are compiled from Nash and Crecraft (1985), Sisson (1994), and Icenhower and London (1996).

shan plutons all plot along well-defined linear trends on Harker variation diagrams (fig. 5), suggesting that differentiation may have played an important role in their evolution. The rocks are composed mainly of plagioclase and quartz, with no pyroxene or garnet, suggesting only low-pressure fractional crystallization (Macpherson et al. 2006). The rocks from the Datian pluton have obvious negative Eu anomalies (fig. 6), suggesting plagioclase fractionation. However, fractionation of plagioclase also reduces Sr and decreases Sr/Y ratios. Thus, the original magma may have had an even higher Sr content, consistent with magma of adakitic origin (fig. 8).

Adakitic melts can also be formed by low-pressure fractionation of amphibole from basaltic magma (e.g., Castillo et al. 1999), and such fractionation could also theoretically cause an increase in the Sr/Y ratios at a given Y concentration. Calculations show that more than 10% amphibole fractionation would be required to produce the observed Sr/Y versus Y covariation in these rocks (fig. 8). Because the rocks from these two plutons contain only minor amphibole, it is possible that their high Sr/Y ratios could have been produced by such a process (fig. 8). However, amphibole fractionation should produce rocks with U-shaped chondrite-normalized REE patterns and variable Dy/Yb ratios (Macpherson et al. 2006). Thus, the right-inclined REE patterns and constant Dy/Yb ratios of the rocks described here are inconsistent with an origin by fractional crystallization of amphibole (fig. 6). In addition, the relatively large proportions of silicic rocks relative to mafic rocks in the region do not support an origin of the adakitic plutons by fractionation from mafic magmas. The large volume of granitic rock could not have been produced by fractionation of the relatively small volume of basalt magma represented by the exposed mafic in-

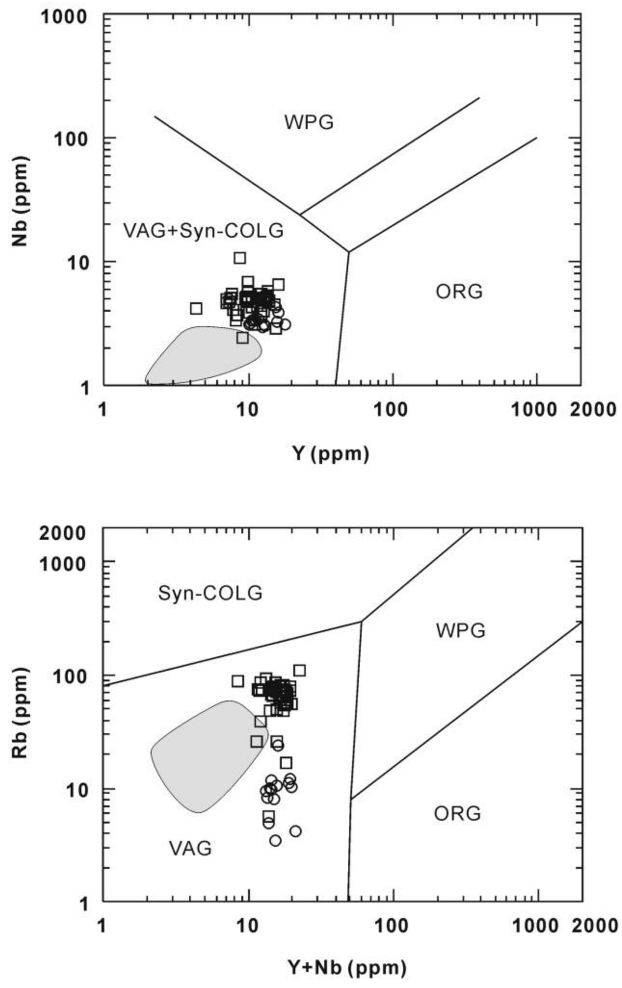


Figure 9. Nb versus Y and Rb versus Y + Nb discriminant diagrams for the Datian (*squares*) and Dajianshan (*circles*) adakites, showing the tectonic classification suggested by Pearce et al. (1984). The shaded area is for the Xuelongbao pluton (Zhou et al. 2006*b*). *ORG* = ocean ridge granite; *Syn-COLG* = syncollision granite; *VAG* = volcanic-arc granite; *WPG* = within-plate granite.

Table 2. Sr-Nd Isotopic Compositions for the Rocks from the Datian and Dajianshan Granitoid Intrusions, Sichuan Province, Southwestern China

Sample	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	$(^{87}Sr/^{86}Sr)_i$[a]	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	$(^{143}Nd/^{144}Nd)_i$[a]	εNd (T = 760 Ma)
Datian intrusion:							
DT-03	.711091	.568545	.704922 (12)	.512195	.112040	.511637 (12)	−.41
DT-10	.709303	.460319	.704308 (11)	.512244	.122756	.511633 (13)	−.49
DT-15	.709559	.413891	.705068 (10)	.512158	.104910	.511636 (14)	−.44
DT-25	.708677	.337893	.705010 (12)	.512365	.151303	.511611 (10)	−.92
DT-29	.709225	.401910	.704865 (12)	.512393	.153126	.511630 (12)	−.55
DT-35	.708450	.316211	.705018 (11)	.512347	.143037	.511635 (12)	−.45
HL-16	.704870	.029880	.704546 (14)	.512296	.121603	.511690 (10)	.62
HL-23	.705933	.104122	.704803 (12)	.512213	.111586	.511657 (12)	−.01
Dajianshan intrusion:							
HL-6	.705322	.058375	.704688 (14)	.512309	.123803	.511692 (11)	.66
HL-12	.705121	.046851	.704613 (10)	.512261	.116550	.511681 (13)	.45

[a] The "i" indicates initial value. Values in parentheses are 2σ errors (%).

trusions. Because the observed mafic plutons in the region, such as the Dadukou, Gaojiacun, and Lengshuiqing plutons, have different ages and different initial isotopic compositions than the granitic plutons (fig. 10), we rule out formation of these adakitic rocks by fractional crystallization of mafic magmas.

Zhou et al. (2006*b*) suggested that the Xuelongbao pluton was produced by melting of a subducted oceanic slab, but Li et al. (2007*a*) argued that such adakitic plutons were formed by partial melting of thickened lower crusts. These different origins can be distinguished on the basis of the available geochemical and isotopic data.

Adakites formed by melting of oceanic slabs have distinctly different major-element compositions from those derived from the lower crust (Smithies and Champion 2000), and the compositions of the studied plutons are compatible with derivation from a subducted slab. The Datian and Dajianshan adakitic plutons have higher MgO contents and Mg#'s and lower K_2O contents (0.02–1.40 wt%) than Cenozoic adakitic rocks in Tibet that have been interpreted as the products of lower-crustal melting (Chung et al. 2003; Hou et al. 2004; Wang et al. 2005). In a plot of SiO_2 versus Mg# (fig. 11), almost all of the samples plot in the field of adakites produced by melting of the oceanic crust. In addition, these three plutons have Mg#'s and SiO_2 contents similar to those of adakitic rocks from the Andean Austral Volcanic Zone, which were produced by melting of subducted oceanic crust (Stern and Kilian 1996).

Adakitic rocks formed by melting of oceanic crust also have incompatible-trace-element ratios distinctly different from those formed from lower continental crust. In particular, melts derived from oceanic crust have distinctly lower Th/La, Th/Zr, and Nb/Zr ratios than those derived from the lower continental crust. The plutonic rocks have distinctly lower Th/La and Th/Zr ratios than the adakites from Tibet (fig. 12), further arguing against lower-crustal involvement in their origin. The low concentrations of Th and U in slab-derived melts may reflect release of these fluid-mobile elements from the eclogitic slab before partial melting (Rollinson and Tarney 2005) or formation from the basaltic portion of subducting slabs (e.g., Plank 2005). The rocks from the Datian and Dajianshan plutons

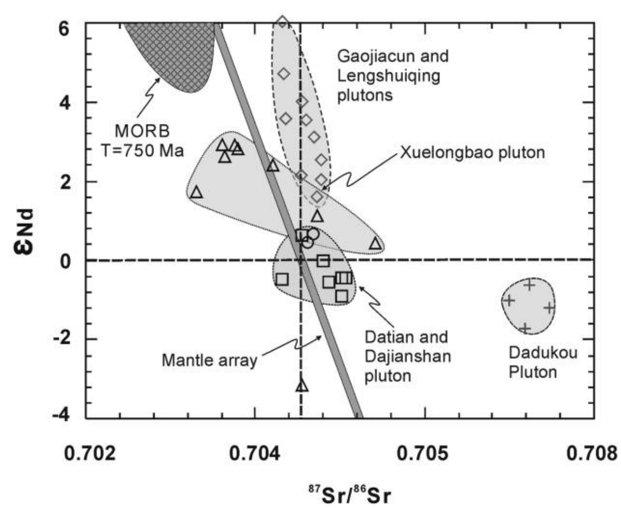


Figure 10. Plot of εNd versus $^{87}Sr/^{86}Sr$ for the Datian (*squares*) and Dajianshan (*circles*) plutons, Sichuan Province, southwestern China. Corrected mid-ocean ridge basalt (T = 750 Ma) range is from Zimmer et al. (1995). Data for the Xuelongbao pluton (*triangles*) are from Zhou et al. (2006*b*), those for the Dadukou gabbros are from Zhao and Zhou (2007), and those for the Gaojiacun and Lengshuiqing plutons are from Zhou et al. (2006*a*).

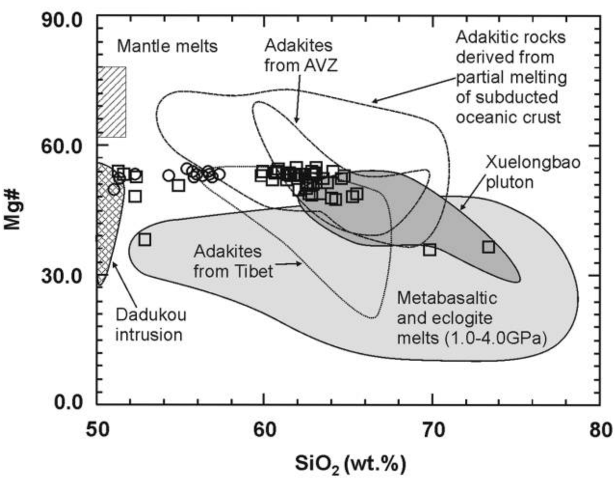


Figure 11. SiO_2 versus Mg# for the Neoproterozoic adakites from the western margin of the Yangtze Block; squares are for the Datian and circles for the Dajianshan plutons. The field for the Xuelongbao pluton is from Zhou et al. (2006*b*). The field for adakites produced from subducted oceanic crust is after Wang et al. (2006), and the field for metabasaltic and eclogite experimental melts (1.0–4.0 GPa) is from Rapp et al. (1999). Adakites from the Andean Austral Volcanic Zone (*AVZ*) are shown for comparison (Stern and Kilian 1996). The field for the Dadukou gabbroic pluton is from Zhao and Zhou (2007).

all have low Th/La, Th/Zr, and Nb/Zr ratios and plot within the field of adakitic rocks from the Andean Austral Volcanic Zone (fig. 12). In addition, these adakitic rocks have La concentrations as low as 3.56 ppm (table 3, available as both an Excel file and a tab-delimited ASCII file in the online edition or from the *Journal of Geology* office). Low La concentrations are thought to have resulted from partial melting of a subducted oceanic slab (e.g., Wang et al. 2007).

Slab-derived siliceous melts rise into and metasomatize the overlying mantle wedge because of their chemical disequilibrium (Beard et al. 1993; Sen and Dunn 1994). Such interaction will elevate the Mg, Fe, and Ca contents in the melt but lower its Na, K, and Si contents (Sen and Dunn 1994; Killian and Stern 2002), and it will also produce straight arrays in binary chemical and isotopic plots (Macpherson et al. 2006). Emplacement of the 740-Ma Dadukou pluton suggests that the lithospheric mantle was hot at that time (Zhao and Zhou 2007). Thus, interaction between the melt and the mantle was possible. The relatively high Mg#'s and low K_2O, Na_2O, and SiO_2 contents of the Yangtze plutons may reflect such interaction between slab melts and the overlying mantle wedge (fig. 11). The well-defined linear trends of the adakitic rocks evident in figures 8, 10, and 11 suggest that interaction/mixing between the slab melts and the mantle wedge occurred during their emplacement.

However, the rocks from the Datian and Dajianshan intrusions are chemically different from those of the Xuelongbao pluton: they have relatively low Sr/Y ratios (fig. 8) and high Nb and Y concentrations (fig. 9), which can be explained by accumulation of

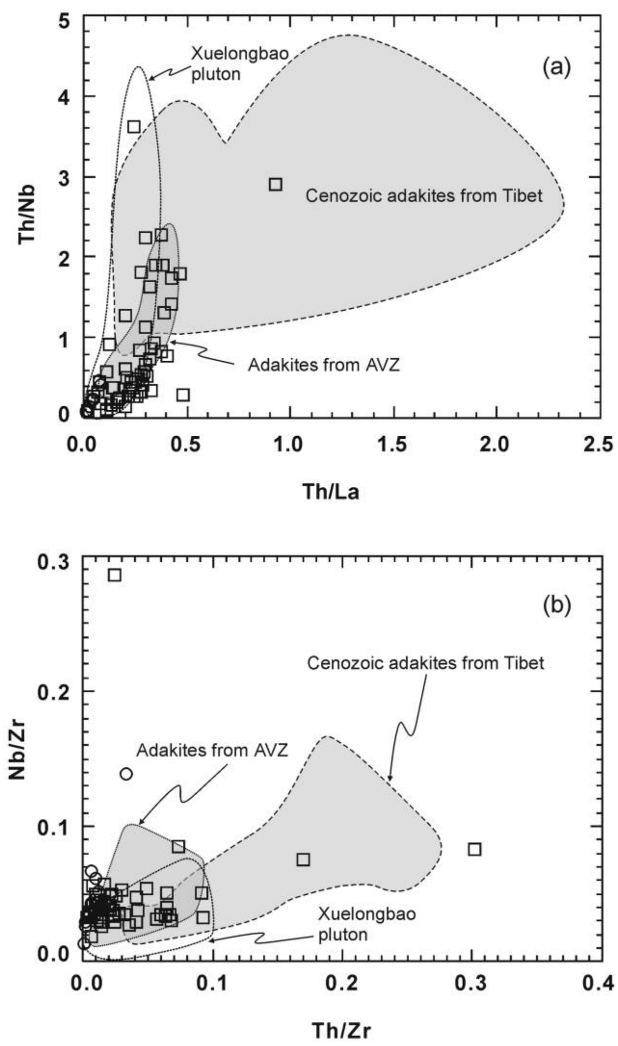


Figure 12. Th/La versus Th/Nb (*a*) and Th/Zr versus Nb/Zr (*b*) ratios for rocks from the Datian (*squares*) and Dajianshan (*circles*) plutons. Data for the Xuelongbao pluton is shown for comparison (Zhou et al. 2006*b*). Data for Cenozoic adakites from Tibet, produced by partial melting of the lower crust, are from Chung et al. (2003), Hou et al. (2004), and Wang et al. (2005). Adakitic rocks from the Andean Austral Volcanic Zone (*AVZ*) were formed by melting of the subducted oceanic slab (Stern and Kilian 1996).

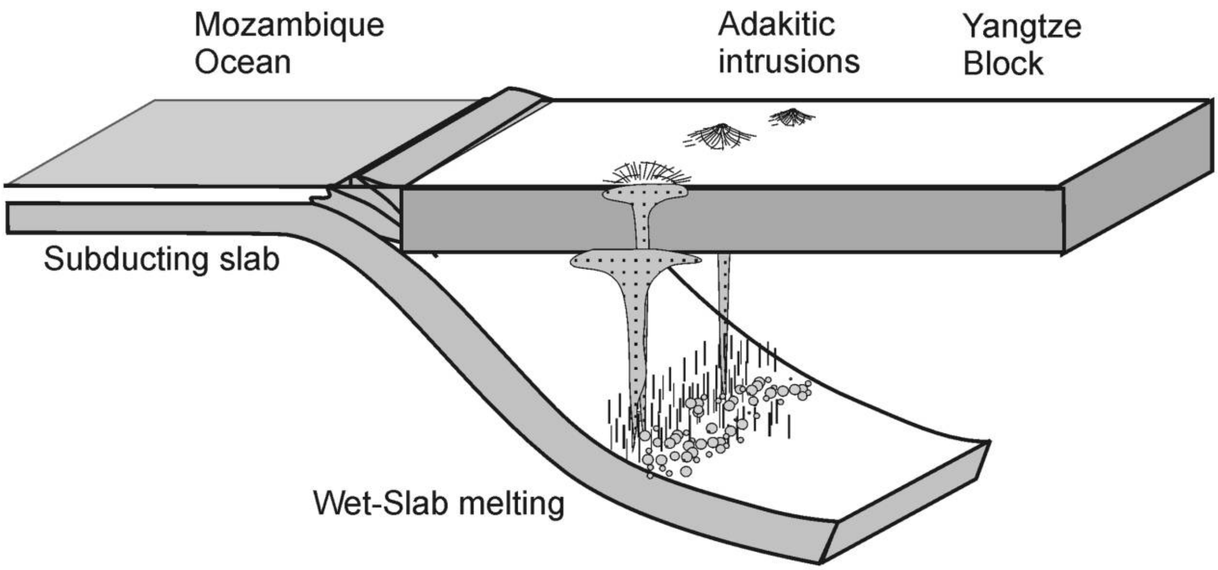


Figure 13. Neoproterozoic subduction beneath the western margin of the Yangtze Block, showing the formation of adakitic plutons along the western margin of the Yangtze Block during the Neoproterozoic from 860 to 740 Ma.

amphibole. In addition, the Datian and Dajianshan adakites have lower εNd values (fig. 10) but higher MgO than those of the Xuelongbao pluton, suggesting that they may have been significantly contaminated by mafic island arc magmas (figs. 8, 11). Positive Zr-Hf anomalies in the spider diagrams suggest that crustal contamination also existed during the magma emplacement (fig. 7).

Implications for the Neoproterozoic Hannan-Panxi Arc. The Neoproterozoic Xuelongbao, Datian, and Dajianshan granitic plutons define a belt of arc plutonic bodies that extends for more than 1000 km from north to south along the western margin of the Yangtze Block (fig. 1). These bodies coincide with the Hannan-Panxi arc defined by associated mafic intrusions (Zhou et al. 2002*a*, 2006*a*). The recognition of this adakitic belt strongly suggests that the western margin of the Yangtze Block was an active magmatic arc in the Neoproterozoic.

Ages for the mafic-ultramafic and granitic intrusions mainly range from 860 to 740 Ma (Li et al. 2003; Ling et al. 2006; Zhao and Zhou 2007). The Dadukou gabbroic intrusion in the Panxi region has been shown to have formed from a mantle source metasomatized by both subducted adakitic melts and fluids, confirming that subduction was still active in the region at 745 Ma (Zhao and Zhou 2007). The arclike geochemical features of the 810-Ma Gaojiacun and Lengshuiqing mafic-ultramafic intrusions in the same region also demonstrate a subduction-related origin (Zhou et al. 2006*a*, 2007). Farther north, both the 820-Ma Wangjiangshan and the 780-Ma Bijigou mafic-ultramafic intrusions also have arc-related compositions (Zhou et al. 2002*a*).

Normal granites temporally and spatially associated with the adakites also typically show arclike geochemical characteristics (Zhang et al. 1994; Li et al. 2003). For example, granitic rocks in the Kangding-Shimian area have U-Pb zircon ages of 786–864 Ma (Shen et al. 2000; Ling et al. 2001; Zhou et al. 2002*b*), and the Ershan pluton in the southernmost part of the western Yangtze Block has a date of 819 Ma (Li et al. 2003). Although these rocks formed by melting of continental crust, they all plot in the volcanic-arc region in tectonic discrimination diagrams (Ling et al. 2001; Li et al. 2003). A Neoproterozoic subduction zone along the western margin of the Yangtze Block is also consistent with the development of the back-arc basins in which sedimentary sequences of the Yanbian, Bikou, and Xixiang groups were deposited (Yan et al. 2004; Zhou et al. 2006*a*; Sun et al. 2007).

Thus, we propose a model for the formation of the adakitic rocks along the western margin of the Yangtze Block involving slab melting, melt-mantle interaction, and further melting of the overlying mantle wedge in a subcontinental arc. The subducted oceanic crust underwent partial melting and dehydration, and the resulting slab melts then interacted with the overlying mantle wedge to enrich the mantle sources. These modified slab melts then formed a belt of adakitic intrusions (fig. 13). Underplating by the adakitic and mantle melts caused partial melting of preexisting arc crust, forming the normal granites with arc signatures.

The Panxi-Hannan arc may have been part of a magmatic belt at the western margin of East Gondwana and Australia during assembly of the Gondwana supercontinent. In this model, the arc may have been formed by subduction of the Mozambique oceanic slab beneath the western margin of the Yangtze Block (Zhao and Zhou 2007). Voluminous slab melts were formed along the paleo–continental margin and added to the Yangtze Block. Thus, the Neoproterozoic was a period of major crustal growth along the margin of the Yangtze Block.

Conclusions

Voluminous Neoproterozoic granodiorite intrusions along the western margin of the Yangtze Block have adakitic characteristics. These adakitic plutons were produced from partial melts of a subducted oceanic slab during the Neoproterozoic, suggesting that the western margin of the Yangtze Block was active at 750 Ma. The combination of arc sedimentary sequences, normal-arc granites, arc-related mafic-ultramafic intrusions, and voluminous adakitic plutons described in this article strongly suggest that a Neoproterozoic subduction zone existed along the western margin of the Yangtze Block for a distance of at least 1000 km.

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