

A-type granite and adakitic magmatism association in Songpan–Garze fold belt, eastern Tibetan Plateau: Implication for lithospheric delamination

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Abstract

The Songpan–Garze fold belt covers a huge triangular area (>200,000 km²), confined by the South China (Yangtze), North China and Tibetan Plateau continental blocks. In the Songpan–Garze fold belt, Triassic adakitic granitoids have been identified. However, whether there are Triassic A-type granites is unclear. Here, we report our first finding of an A-type granite (Nianbaoyeche), which occurs in the central part of the Songpan–Garze fold belt. The Nianbaoyeche granite (~820 km²) is characterized by arfvedsonite in its mineral assemblage. Using both LA-ICPMS and TIMS U–Pb zircon dating methods, we obtain a magma crystallization age of 211±1 Ma, which is slightly younger than Triassic adakitic granitoids (216–221 Ma) in the Songpan–Garze fold belt. The Nianbaoyeche granite is enriched in Si, K, Na, Rb, REE, HFSE (Nb, Ta, Zr, Hf), with elevated FeO^{tot}/(FeO^{tot}+MgO) and Ga/Al ratios, but is depleted in Al, Mg, Ca, Ba and Sr. The REE compositions show moderately fractionated patterns with (La/Yb)_N=2.67–7.54 and Eu*/Eu=0.09–0.34. These geochemical characteristics indicate that the Nianbaoyeche granite has an A-type affinity. Geochemical data and U–Pb zircon age, combined with regional studies, show that the Nianbaoyeche granite formed in a post-collisional tectonic setting. Sr–Nd isotopic data for the granite exhibit $I_{Sr}=0.7090–0.7123$ and $\epsilon_{Nd}(t)=-2.72$ to -4.26 with $T_{DM}=1.15–1.51$ Ga, suggesting that the magma has a dominantly crustal source, though a minor contribution from the mantle cannot be ruled out. Melting to produce an A-type granite may have resulted from Triassic lithospheric delamination after Triassic crustal thickening of the Songpan–Garze fold belt due to convergence between the Yangtze, North China and North Tibet continental blocks. The lithospheric delamination model also helps to explain the Triassic adakitic magma generation in the Songpan–Garze belt. We conclude that association of A-type granite and adakitic granitoids in post-collisional environment could be a useful indicator of lithospheric delamination.

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Keywords: A-type granite; U–Pb age; Magmatism association; Post-collision; Lithospheric delamination; Songpan–Garze fold belt, West China

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1. Introduction

Lithospheric delamination can lead to extensional collapse of mountains, basin formation and associated magmatism (Bird, 1979; Sacks and Secor, 1990; Nelson, 1992; Kay and Kay, 1993; Gao et al., 1998; Manley et al., 2000; Gao et al., 2004). In continental settings, crustal thickening results from collision between continental plates. The thickened lower crust and upper mantle would be characterized in part by high grade metamorphic rocks, resulting in an increased density, which could lead to lithospheric delamination (Kay and Kay, 1991; Rudnick and Fountain, 1995; Jull and Kelemen, 2001). In post-collisional (or post-orogenic) settings, lithospheric delamination and asthenospheric upwelling, accompanied by extensional tectonics, are often invoked to explain the origin of post-collisional granites (Jung et al., 1998; Wu et al., 2002; Chung et al., 2003; Ilbeyli et al., 2004; Chung et al., 2005; Wu et al., 2005). Magmatism in post-orogenic settings can provide insights into the composition of the lower crust and processes involving crustal thickening and lithospheric extension. Adakitic magmas in continental settings can be a fingerprint of crustal thickening (Xu et al., 2002a; Chung et al., 2003; Hou et al., 2004; Wang et al., 2005, 2006), and in some cases, high Mg adakite may be linked directly to lithospheric delamination (Xu et al., 2002a; Gao et al., 2004). A-type granitic magma is generally accepted to reflect lithospheric extension (Collins et al., 1982; Whalen et al., 1987; Sylvester, 1989; Rogers and Greenberg, 1990). Adakitic and A-type granitic magmas may therefore be closely associated or coeval in this tectonic context. A linked association between adakite and A-granite magmatism could potentially provide a strong evidence for regional lithospheric delamination, but unfortunately, the adakite and A-granite magmatism association in the same tectonic regime is uncommon or rare.

In the Songpan–Garze fold belt of the eastern part of the Tibetan Plateau, granitoids are widespread. Recent U–Pb zircon dating shows that most granitoids in the Songpan–Garze fold belt formed in the Triassic (Roger et al., 2004; Hu et al., 2005; Zhang et al., 2006; Xiao et al., 2007) with minor granitoids formed in Early Jurassic time (Roger et al., 2004; Hu et al., 2005). Published studies show that most Triassic granitoids are adakitic (Zhang et al., 2006; Xiao et al., 2007), though A-type granitoids also occur but are as yet undated. In this paper, we report geochemical, Sr–Nd isotope and U–Pb dating evidence for a Triassic A-type granite in the Songpan–Garze fold belt, and we use these data to discuss a geodynamic process for their formation.

2. Geological background and A-type granite description

The Songpan–Garze fold belt is located in the eastern part of the Tibetan Plateau. The belt, covering a huge triangular area with an area of more than 200,000 km², is a folded Triassic flysch basin, which formed during closure of the Paleo-Tethys ocean (Xu et al., 1992; Mattauer et al., 1992; Sengör and Natalin, 1996; Brugier et al., 1997). The belt is also a tectonic junction between three major continental blocks (South China, North China and Tibetan Plateau) (Fig. 1). To the east, the Longmenshan thrust-nappe belt separates the Songpan–Garze belt from the Sichuan basin. The northern limit of the belt is marked by the A’imaque–Mianlue suture zone, which is considered to be a Paleo-Tethys oceanic subduction zone dipping to the north in Late Paleozoic (Li et al., 1996; Xu et al., 2002b; Elena et al., 2003). To the southwest, the Songpan–Garze belt is bounded by the Jinshajiang suture zone, which is also considered to be a Late Paleozoic Paleo-Tethys oceanic subduction zone dipping to the west (Sengör, 1985; Wang et al., 2000; Reid et al., 2005).

In the Songpan–Garze belt, the sediments are almost exclusively marine Triassic flysch deposits, which reach a thickness of 5–15 km (Xu et al., 1992; Calassou, 1994). The pre-Triassic strata, forming an antiform with a core of Neoproterozoic sediments, are distributed in the Danba area of the southern Songpan–Garze belt. These pre-Triassic strata have experienced metamorphism of greenschist to upper amphibolite-facies conditions (Huang et al., 2003). In contrast, the Triassic flysch sediments have only experienced greenschist-facies metamorphism but they were intensively folded during the Indosinian (Late Triassic) compressional tectonism due to convergence between the North China, Yangtze and Tibetan continental blocks (Xu et al., 1992; Brugier et al., 1997; Reid et al., 2005). The Triassic flysch sediments are separated from the Paleozoic sedimentary cover and the crystalline basement of the Yangtze block by a large-scale décollement near the eastern and southeastern margin of the Songpan–Garze basin (Xu et al., 1992; Mattauer et al., 1992; Calassou, 1994). Based on new U–Pb chronological study of detrital zircons (870 zircon grains) from the Triassic sediments (Weislogel et al., 2006), the provenance of the Triassic sediments includes the Qinling–Dabie orogen, North China block and Yangtze block.

Widespread granitoids in the Songpan–Garze belt intrude the folded Triassic sediments, implying that they are post-orogenic or post-collisional granitoids. In the northeastern part of the belt, the Yanggon and Maergai

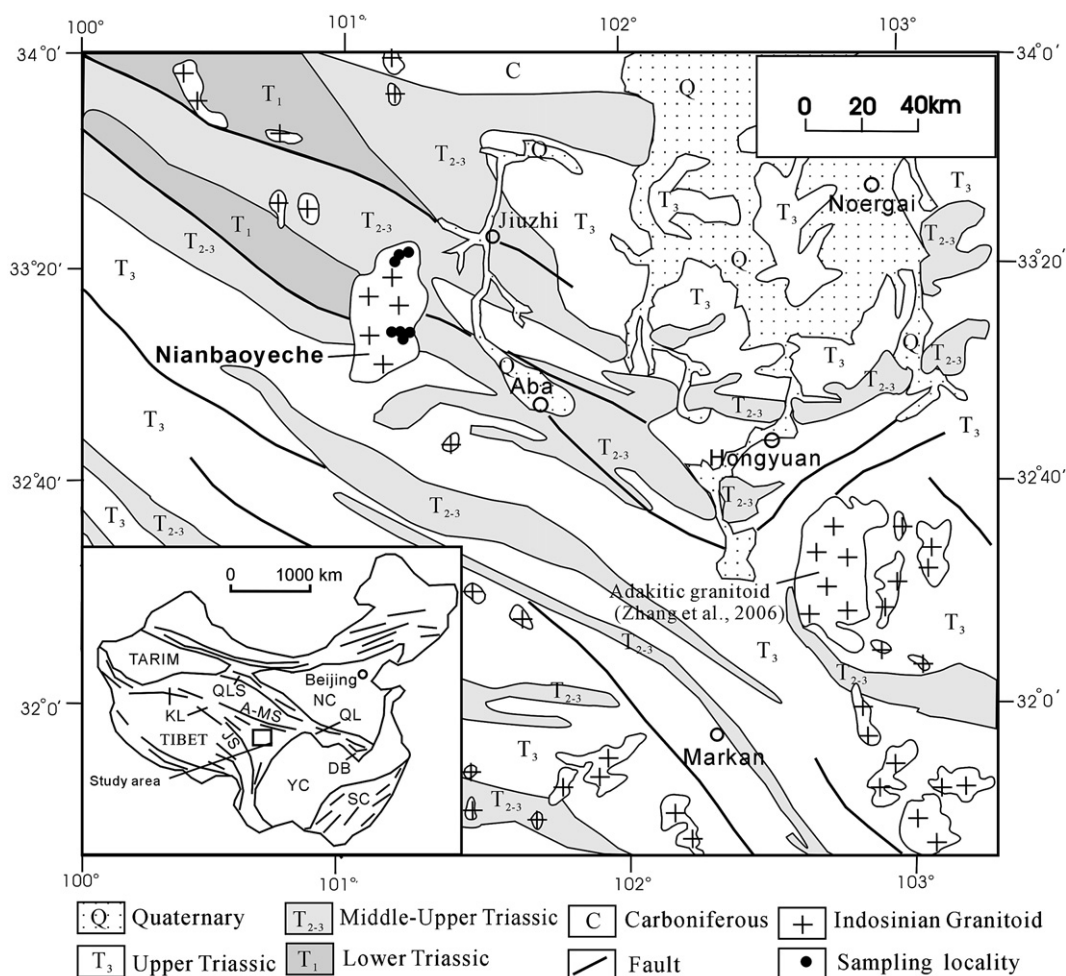


Fig. 1. Simplified geological map of the northeastern part of the Songpan–Garze fold belt. Inset shows location of study area. NC=North China block; YC=Yangtze block; SC=South China fold belt; KL=Kunlan Mountains; QLS=Qilian Mountains; QL=Qinling Mountains; DB=Dabieshan; JS=Jinshajian suture; A-MS=A'nimaque–Mainlue suture.

granitoids, with U–Pb zircon SHRIMP ages of 221 ± 4 Ma and 216 ± 6 Ma, respectively, have been identified to be adakitic (Zhang et al., 2006). These adakitic granitoids are characterized by high Sr, low Y and HREE. However, they display high K contents and evolved Sr–Nd isotopic compositions (e.g., $\epsilon_{\text{Nd}}(t) < 0$), showing that they are distinct from typical adakites generated from partial melting of a subducted MORB slab (Condie, 2005, and references therein), but similar to adakitic rocks resulted from partial melting of thickened continental crust (Chung et al., 2003; Hou et al., 2004; Wang et al., 2005). In southeastern part (Markan–Wolong area) of the belt, granitoids can be divided into two groups (Roger et al., 2004): Group 1 (197 ± 6 Ma, U–Pb zircon TIMS) formed by partial melting of the Yangtze basement below the Songpan–Garze décollement level; Group 2 (188 ± 2 Ma and

153 ± 3 Ma, U–Pb zircon TIMS) formed by partial melting of the Middle Triassic sediments. However, whether these two groups of granitoids are adakitic is unclear because there is a lack of major and trace element data. In the southeastern corner (Jiulong area) of the belt, adakitic granitoids (219 ± 3 Ma, U–Pb zircon LA-ICPMS) are also identified, which are coeval or slightly younger than I-type granitoids (225–229 Ma, U–Pb zircon LA-ICPMS) (Xiao et al., 2007). It was proposed that the adakitic and I-type granitoids formed via lithospheric delamination after crustal thickening (Xiao et al., 2007). Present data show that the adakitic granitoids in the Songpan–Garze belt are Triassic in age (216–221 Ma).

A-type granite in the Songpan–Garze belt has been unknown until this study. We investigate the Nianbaoyeche (NB) granite, with an area of $\sim 820 \text{ km}^2$, and

identify it to be an A-type granite (see below). The NB granite is located in the central part of the Songpan–Garze belt and intrudes the folded Triassic sediments (Fig. 1). The NB granite is orange to red–brown in color and undeformed. From the margin to interior of the intrusion, the granite varies from medium- to coarse-grained in texture, but their mineral compositions are similar. Based on modal mineral composition obtained by point counting and then plotting on QAP diagram (Fig. 2) for rock classification, seven NB granite samples grade from alkali-feldspar granite (six samples) to syenogranite (one sample). The NB granite contains quartz (32–40%), plagioclase (3–10%), alkali-feldspar (50–55%), biotite (1–2%), arfvedsonite (0–1%) and accessory minerals (<1%), including zircon, allanite, monazite and Fe–Ti oxides. For the NB granite, quartz occurs as interstitial grains and quartz-feldspar intergrowths are common. Alkali-feldspar is subhedral perthite, displaying distinct K- and Na-feldspar perthitic texture. Some alkali-feldspar occurs as megacrysts of >1 cm in size. Microcline is rarely seen. Plagioclase occurs as small euhedral laths, but lacks oscillatory zoning. Both biotite and arfvedsonite are anhedral to euhedral crystals. Biotite occurs as independent grains but arfvedsonite occurs as aggregates.

3. Analytical methods

Analyses of major element compositions were undertaken at the State Key Laboratory of Continental

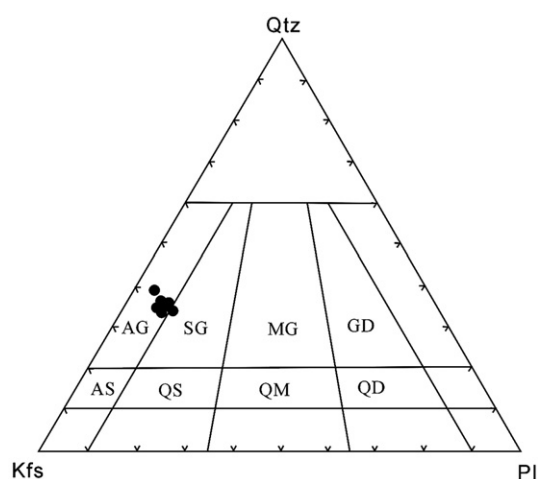


Fig. 2. Modal classification of the granitoids. Dark dot shows NB granite (same as below). AG=alkali-feldspar granite; AS=alkali-feldspar syenite; SG=Syenogranite; QS=quartz syenite; MG=Monzogranite; QM=quartz monzonite; GD=Granodiorite; QD=quartz monzodiorite. Fields and nomenclature after Streckeisen (1967).

Dynamics, Northwest University (Xi'an, China) by XRF. The analytical uncertainty is usually <5%. Trace elements and rare earth elements (REE) were measured using ICP-MS method at China University of Geosciences with analytical uncertainty better than 5–10%. For analytical methods see Zhang et al. (2002).

Whole-rock Sr–Nd isotopic data were obtained using an Nu Plasma ICP-MS at the State Key Laboratory of Continental Dynamics, Northwest University. Sr and Nd isotopic fractionations were corrected to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$, respectively. During the period of analysis, NBS987 standard yielded an average value of $^{87}\text{Sr}/^{86}\text{Sr}=0.710244\pm 14$ (2σ) and the Johnson-Matthey internal standard and BCR-2 standard gave average values of $^{143}\text{Nd}/^{144}\text{Nd}=0.511825\pm 6$ (2σ) and $^{143}\text{Nd}/^{144}\text{Nd}=0.512644\pm 6$ (2σ), respectively. Total procedural Sr and Nd blanks are <4 ng and <1 ng, respectively.

Zircons were separated using conventional techniques at China University of Geosciences. We used both TIMS and LA-ICPMS methods for U–Pb zircon dating. TIMS measurements were made at NERC Isotope Geosciences Laboratory, British Geological Survey. Zircons were analyzed on single or small numbers of grains using a ^{205}Pb – ^{233}U – ^{235}U tracer and a Finnigan Triton mass spectrometer using single Re filaments and arrays of both faraday and ion counting detectors. Chemical and mass spectrometric methods were similar to Parrish et al. (1987), and Noble et al. (1993). The solution made from the zircon standard 91500 was measured together with several U and Pb blanks which averaged <0.4 pg and <5 pg, respectively. LA-ICPMS analyses were conducted on an Elan 6100 DRC ICPMS equipped with 193-nm excimer laser, which is housed at the State Key Laboratory of Continental Dynamics, Northwest University. Zircon 91500 was used as a standard and NIST 610 was used to optimize the machine. The spot diameter was 30 μm . The detailed analytical technique was described in Yuan et al. (2004). Common Pb correction is made by using the measured ^{204}Pb and this was possible because of the very low Hg content in the Ar carrier gas. Data for TIMS and LA-ICPMS measurements were processed using Isoplot (Ludwig, 1997).

4. Results

4.1. U–Pb zircon chronology

U–Pb zircon LA-ICPMS and TIMS data are together listed in Table 1, and their U–Pb concordia plots and representative zircon CL images are shown in Fig. 3.

Table 1

LA-ICPMS and TIMS U–Pb zircon analytical data

Analysis	$^{204}\text{Pb}^{\text{c}}$ (%)	U (ppm)	Th (ppm)	Th/ U	$^{206}\text{Pb}^{\text{a,b}}$ (ppm)	Age (Ma) ^c $^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	Age (Ma) ^c $^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	Age (Ma) ^c $^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{206}\text{Pb}^*/^{238}\text{U}^{\text{c}}$	$\pm\%$	$^{207}\text{Pb}^*/^{235}\text{U}^{\text{c}}$	$\pm\%$
<i>LA-ICPMS</i>															
1.01	0.02	451	220	0.49	62.96	210	1	215	5	278	41	0.03306	0.73	0.23613	2.38
1.02	0.03	329	152	0.46	46.72	213	2	212	5	212	45	0.03354	0.75	0.23273	2.55
1.03	0.01	512	202	0.39	72.35	211	1	213	5	238	43	0.03325	0.72	0.23344	2.44
1.04	0.02	585	239	0.41	83.91	211	1	211	5	217	42	0.03328	0.72	0.23157	2.40
1.06	0.04	196	89	0.45	28.3	211	2	213	5	228	46	0.03335	0.75	0.23323	2.61
1.07	0.02	329	144	0.44	48.14	212	2	211	6	193	52	0.03347	0.81	0.23057	2.89
1.09	0.03	283	175	0.62	42.04	210	3	211	10	223	97	0.03316	1.33	0.23146	5.26
1.11	0.03	260	171	0.66	37.79	209	2	220	7	344	63	0.03298	0.97	0.24245	3.58
1.12	0.02	433	234	0.54	62.88	209	1	207	4	191	35	0.03293	0.61	0.22644	1.98
1.13	0.02	434	223	0.51	63.77	210	2	221	7	343	82	0.03311	0.79	0.24351	3.45
1.14	0.02	489	244	0.50	71.99	211	1	221	5	324	43	0.03331	0.72	0.24278	2.48
1.16	0.03	260	172	0.66	38.69	213	2	235	6	464	53	0.03352	0.87	0.26004	3.09
1.17	0.02	538	204	0.38	80.95	214	1	213	4	209	52	0.03371	0.56	0.23379	2.11
1.18	0.02	469	202	0.43	69.61	211	1	210	4	205	58	0.03322	0.60	0.22997	2.36
1.19	0.03	326	179	0.55	48.82	212	2	207	5	148	47	0.03343	0.75	0.22587	2.62
<i>TIMS</i>															
Z1(1)	0.03	529	212	0.40	17.86	211.6	0.7	213.4	1.1	233.6	9.4	0.03337	0.17	0.23391	0.27
Z2(5)	0.11	216	102	0.47	7.475	212.1	0.7	214.0	1.3	235.3	13.1	0.03344	0.17	0.23461	0.35
Z3(3)	0.10	345	138	0.40	11.65	211.4	0.8	211.6	1.5	213.9	15.8	0.03334	0.18	0.23173	0.4
Z4(3)	0.03	404	194	0.48	13.88	210.4	0.8	210.8	1.2	215.5	11.1	0.03318	0.19	0.23076	0.31

^aCommon portion; ^bradiogenic portion; ^cCorrected using measured ^{204}Pb . Digit in parentheses is number of zircon grain.

Zircons from the NB granite (sample WQ-354, latitude N32°19'26" and longitude E101°10'51") are dominated by light pink to colorless euhedral crystals.

The zircon CL images exhibit clear oscillatory zoning. Inherited zircons are very rare in this sample. Fifteen zircon crystals with good magma oscillatory zoning

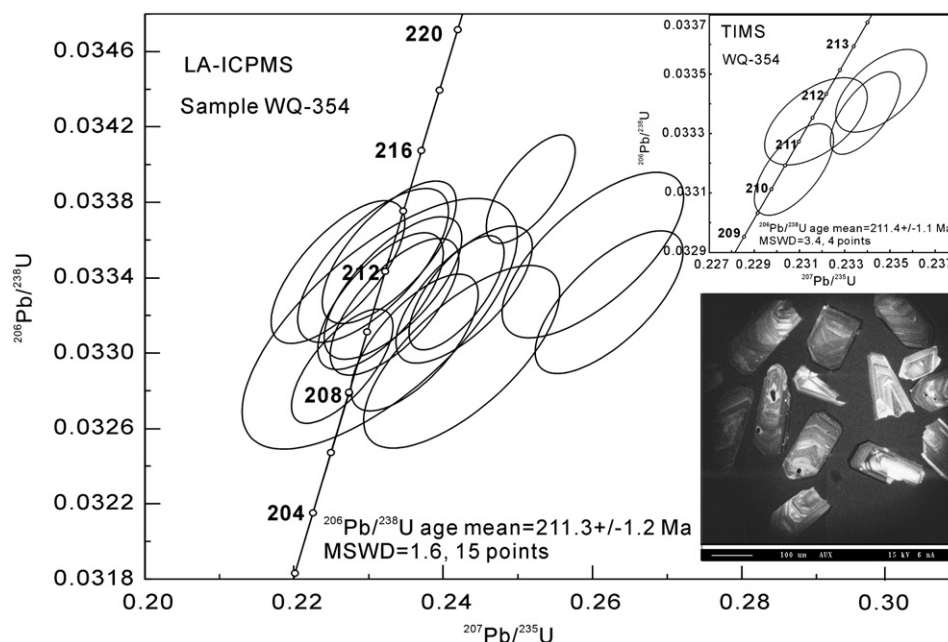


Fig. 3. U–Pb concordia diagram for sample WQ-354. Upper right inset shows TIMS result of this sample and down-right inset shows representative zircon CL images of this sample.

were successfully dated by LA-ICPMS. Th/U ratios range from 0.39 to 0.66. Eleven analyses are concordant within error, whereas four analyses are slightly away from concordia line (Fig. 3), possibly due to an undercorrection for common Pb and/or relatively poor measurement of ^{207}Pb . All fifteen analyses show $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 209 to 214 Ma, with a weighted mean age of 211.3 ± 1.2 Ma (MSWD=0.66). Single- and multi-grain strongly abraded zircons from this sample were used for TIMS measurements. Four analyses yield Th/U ratios of 0.40–0.48, with data being concordant or slightly discordant (Fig. 3). Their $^{206}\text{Pb}/^{238}\text{U}$ ages range from 211 to 214 Ma, with a weighted mean age of 211.4 ± 1.1 Ma (MSWD=3.4), which is identical to the LA-ICPMS result. Both the LA-ICPMS and TIMS results are consistent with the magma crystallization age of the NB granite being 211 ± 1 Ma.

4.2. Major and trace elements

Data on major and trace elements of the NB granite are listed in Table 2. In contrast to the adakitic and/or I-type granitoids in the Songpan–Garze belt (Zhang et al., 2006; Xiao et al., 2007), the NB granite is enriched in silica (SiO_2 ranging from 74.00% to 78.16%) and alkalis ($\text{K}_2\text{O}=4.87\text{--}6.28\%$, $\text{Na}_2\text{O}=3.00\text{--}3.47\%$ and $\text{K}_2\text{O}+\text{Na}_2\text{O}=8.2\text{--}10.2\%$). The NB granite displays low CaO (0.39–1.24%), Al_2O_3 (11.38–12.85%), FeO^{tot} (1.33–2.80%) and MgO (0.07–0.27%) but high $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}}+\text{MgO})$ (0.90–0.95). The NB granite is metaluminous (Fig. 4a). According to a new geochemical classification scheme for granitoids, proposed by Frost et al. (2001), the NB granite belongs to ferroan granite (Fig. 4b), which is consistent with worldwide A-type granites (Fig. 4b). Overall, the major element compositions of the NB granite are similar to those of A-type granite, as defined by Collins et al. (1982), Whalen et al. (1987).

Trace elemental compositions of the NB granite are also distinct from those of the adakitic and I-type granitoids in the Songpan–Garze belt (Zhang et al., 2006; Xiao et al., 2007). The NB granite is enriched in Rb (218–346 ppm), Y (34.8–76.2 ppm) and high field strength elements (HFSE) (Nb: 19.0–29.2 ppm; Ta: 1.67–3.05 ppm; Zr: 148–297 ppm; Hf: 5.41–10.2 ppm) and depleted in Sr (15.6–60.4 ppm) and Ba (65.1–281 ppm), which are also similar to typical A-type granite (Collins et al., 1982; Whalen et al., 1987). The NB granite is characterized by high 10,000 Ga/Al ratios ranging from 2.96 to 4.30, with an average of 3.75, which is equal to the global average of 3.75 for A-type granites (Whalen et al., 1987). In A-type granite

Table 2

Major element (%) and trace element (ppm) data

Sample	WQ-354	WQ-355	WQ-356	WQ-357	WQ-358	WQ-359	WQ-360
SiO_2	74.95	76.80	74.00	77.40	74.86	74.51	78.16
TiO_2	0.22	0.18	0.30	0.13	0.22	0.12	0.13
Al_2O_3	12.28	11.38	12.30	11.49	12.18	12.85	11.31
TFeO	2.48	1.77	2.80	1.34	2.52	1.33	1.14
MnO	0.04	0.03	0.04	0.01	0.04	0.03	0.02
MgO	0.17	0.19	0.27	0.07	0.14	0.10	0.11
CaO	0.83	0.70	1.24	0.56	0.80	0.57	0.39
Na_2O	3.19	3.07	3.25	3.47	3.35	3.47	3.00
K_2O	5.17	4.87	5.01	4.91	5.31	6.28	5.29
P_2O_5	0.04	0.04	0.07	0.02	0.04	0.02	0.01
LOST	0.48	0.85	0.55	0.50	0.40	0.52	0.42
Total	99.85	99.88	99.83	99.90	99.86	99.80	99.98
$\text{K}_2\text{O}/\text{Na}_2\text{O}$	1.62	1.59	1.54	1.41	1.59	1.81	1.76
A/CNK	0.99	0.98	0.94	0.95	0.96	0.95	0.99
Be	6.30	9.01	5.55	9.19	5.76	3.80	5.03
Sc	4.54	3.53	5.76	2.43	4.57	0.58	0.39
V	4.18	4.68	7.93	1.34	5.09	1.57	1.20
Cr	4.12	5.77	4.74	4.22	2.95	3.49	2.84
Co	1.16	1.32	2.40	0.48	1.20	0.57	0.49
Ni	1.22	2.51	27.55	1.37	0.68	2.20	2.18
Cu	5.00	9.59	20.00	19.79	13.65	5.64	8.13
Zn	94.7	51.5	100	52.2	100	61.4	42.6
Ga	26.59	25.90	23.28	25.18	25.56	20.18	19.43
Rb	289	347	218	297	245	314	251
Sr	44.21	37.78	60.42	15.57	39.40	40.80	24.47
Y	58.61	58.69	51.85	76.19	57.19	34.83	50.84
Zr	252	216	281	200	297	148	191
Nb	24.92	22.85	21.53	29.24	23.90	18.97	22.93
Cs	26.56	10.51	18.08	14.21	21.64	13.25	14.63
Ba	249	156	282	106	269	281	65
La	66.80	56.00	60.20	34.12	59.36	38.48	32.77
Ce	126.6	98.6	124.8	78.7	124.0	72.6	80.7
Pr	16.36	13.51	14.74	10.40	14.40	8.91	9.09
Nd	64.30	51.30	57.74	43.89	56.96	33.79	36.15
Sm	11.92	10.04	11.83	11.92	12.35	7.06	8.54
Eu	0.73	0.46	0.78	0.35	0.80	0.76	0.25
Gd	10.03	8.39	9.77	10.56	10.33	6.40	7.94
Tb	1.94	1.63	1.61	1.98	1.66	1.10	1.50
Dy	10.77	8.74	10.48	13.78	10.55	6.51	9.53
Ho	2.17	1.90	1.97	2.92	2.17	1.30	2.00
Er	5.76	5.13	5.85	8.63	6.53	3.77	5.95
Tm	0.84	0.71	0.82	1.21	0.92	0.58	0.95
Yb	5.97	5.11	5.73	8.62	6.33	3.81	6.06
Lu	0.74	0.71	0.91	1.37	1.00	0.57	0.87
Hf	8.83	8.01	9.79	10.18	10.41	5.41	7.54
Ta	2.14	2.65	2.07	3.05	1.87	1.67	2.15
Pb	36.46	33.95	44.12	46.35	45.35	39.55	35.67
Th	28.40	37.87	25.81	55.46	26.35	19.05	26.81
U	4.99	6.03	3.24	6.45	3.39	2.91	4.57
$(\text{La}/\text{Yb})_{\text{N}}$	7.54	7.39	7.08	2.67	6.32	6.81	3.65
Eu/Eu*	0.20	0.15	0.21	0.09	0.21	0.34	0.09

discrimination diagrams (Fig. 5), all samples of the NB granite fall in the field of A-type granite. The NB granite is also enriched in rare earth elements (REE)

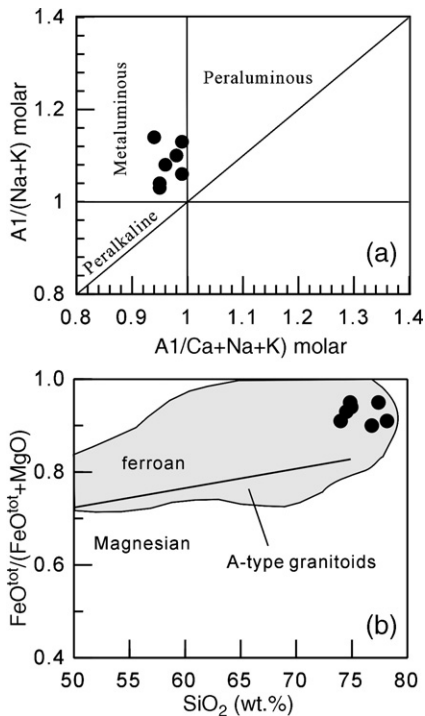


Fig. 4. (a) Molar $Al/(K+Na)$ vs. $Al/(Ca+Na+K)$ diagram; (b) $FeO^{tot}/(FeO^{tot}+MgO)$ vs. SiO_2 (after Frost et al., 2001). A-type granite field compiled by Frost et al. (2001).

with total REE concentration of 202–324 ppm. Chondrite-normalized REE patterns show slight enrichment of light rare earth elements (LREE) relative to heavy

rare earth elements (HREE) with $(La/Yb)_N$ ratios of 2.67–7.54 and strongly negative Eu anomalies ($Eu^*/Eu=0.09–0.34$) (Fig. 6a). In the element spider diagram (Fig. 6b), the NB granite shows negative anomalies of Ba, Nb, Ta, Sr, P, Eu and Ti, which agrees with element compositional patterns of A-type granites (Wu et al., 2002).

The above geochemical characteristics, combined with the presence of alkali-rich minerals such as arfvedsonite, show clearly that the NB granite is an A-type granite.

4.3. Sr and Nd isotopes

Whole-rock Sr and Nd isotopic data for the NB granite are given in Table 3. $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ data of five samples yield an isochron age of 208 ± 26 Ma (MSWD=2), with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7108 ± 0.0070 (Fig. 7), indicating that the Rb–Sr isotopic system was not reset by late tectono-thermal events. For the five samples, initial $^{87}Sr/^{86}Sr$ (I_{Sr}) and $\epsilon_{Nd}(t)$ values are back-calculated at the magma crystallization age of 211 Ma (U–Pb zircon age). The calculated I_{Sr} values range from 0.70897 to 0.71230, which can be comparable with the I_{Sr} value obtained by Rb–Sr isochron (Fig. 7) within errors, and the ϵ_{Nd} (211 Ma) values range from -2.72 to -4.26 , with mantle-depletion Nd model ages (T_{DM}) ranging from 1.15 to 1.51 Ga. These results indicate that the magma of the NB granite could be derived from a crustal source,

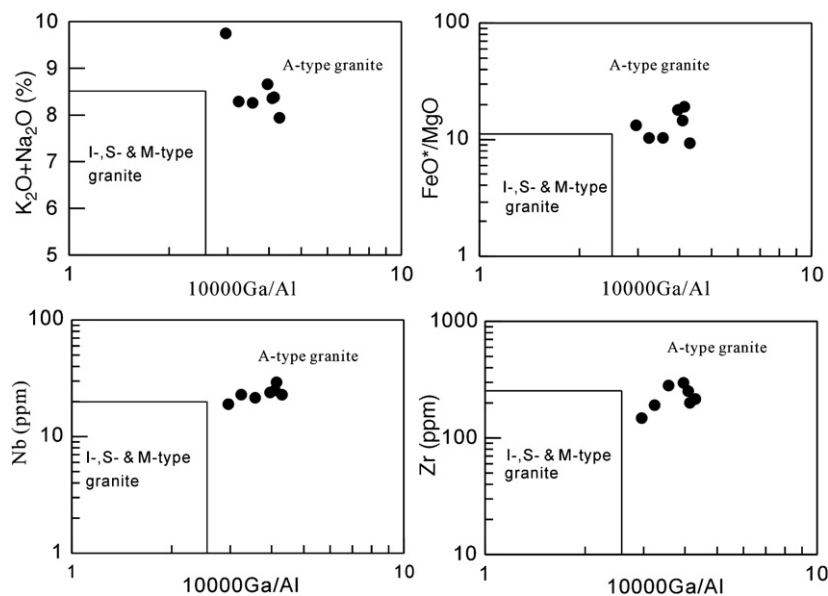


Fig. 5. A-type granite discrimination diagram (after Whalen et al., 1987).

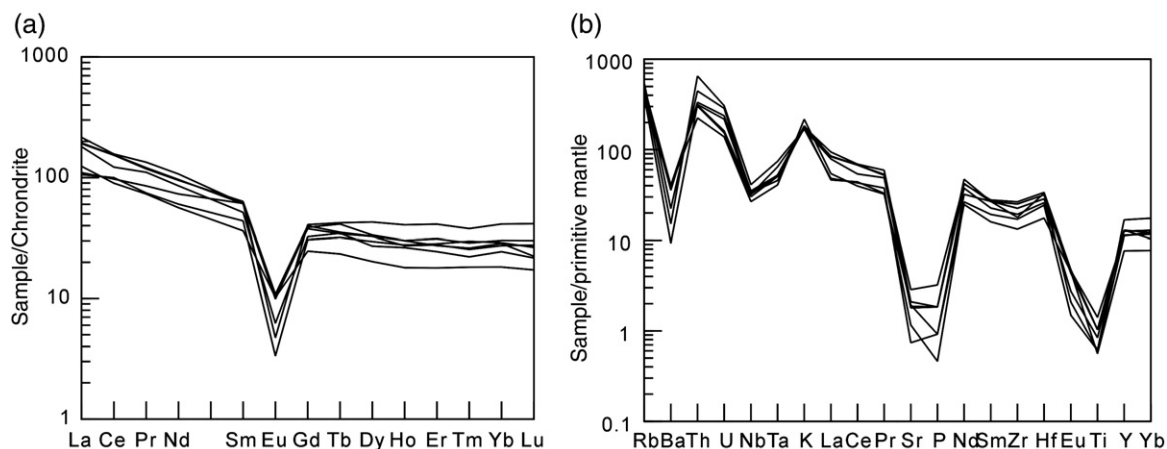


Fig. 6. (a) Chondrite-normalized REE patterns. Normalizing values from Taylor and McLennan (1985); (b) primitive mantle-normalized element spider diagram. Normalizing values from Sun and McDonough (1989).

but a mantle or enrichment mantle source contribution is not ruled out because of the moderate $\varepsilon_{\text{Nd}}(t)$ values.

5. Discussion

5.1. Tectonic setting: anorogenic or post-orogenic A-type granite?

It is commonly accepted that A-type granite formed in a crustal extensional environment and occurred in both post-orogenic and/or anorogenic settings (Collins et al., 1982; Whalen et al., 1987; Sylvester, 1989; Bonin, 1990; Rogers and Greenberg, 1990; Eby, 1992; Nedelec et al., 1995; Whalen et al., 1996; Pitcher, 1997; Barbarin, 1999). However, it is not easy to use such granite to distinguish between the two origins because of the lack of contrast in petrological, mineralogical or geochemical features (Sylvester, 1989; Bonin, 1990; Turner et al., 1992).

Eby (1992) subdivided A-type granites into A₁ and A₂ groups. The two types have very different sources and tectonic settings. The A₁ group occurs in anorogenic settings such as continental rifts or intraplate environments. Their magmas are derived from sources like those of

oceanic–island basalts. The A₂ group forms in a much broader range of environments, including post-collisional granites and those emplaced at the end of a long period of apparently high heat flow and granitic magmatism. The A₂ group magmas were derived from continental crust or underplated crust that has experienced a cycle of continent–continent collision or island–arc magmatism. The A₁ and A₂ groups can be discriminated using the Rb/Nb–Y/Nb and Y–Nd–Ce diagrams (Fig. 8a and b), given by Eby (1992). As shown in Fig. 8a and b, the NB A-type granite falls into the A₂ group, suggesting a post-collisional environment for the NB A-type granite. This is consistent with the magma crystallization age (211 Ma) that postdates the Early Triassic closure of the Paleo-Tethys ocean (Xu et al., 1992; Mattauer et al., 1992; Sengör and Natalin, 1996), as represented by the A’nimaque–Mianlue ophiolite in the north (Xu et al., 2002b; Elena et al., 2003; Bian et al., 2004) and the Jinshajian ophiolite in the south (Sengör, 1985; Wang et al., 2000). It also postdates the early Indosinian continental collision (Li et al., 1996; Reid et al., 2005), early crustal thickening deformation (Harrowfield and Wilson, 2005) and the magma emplacement (216–230 Ma) of adakitic granitoids (Zhang et al., 2006; Xiao

Table 3
Whole-rock Sr and Nd isotope data

Sample	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	I_{Sr}	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	$\varepsilon_{\text{Nd}}(t)$	T_{DM} (Ga)
WQ-354	18.98	0.76884	2	0.71230	0.112	0.512382	5	−2.72	1.15
WQ-356	10.45	0.74172	2	0.71058	0.124	0.512405	6	−2.58	1.26
WQ-358	18.05	0.76277	1	0.70900	0.131	0.512329	4	−4.26	1.51
WQ-359	22.32	0.77531	1	0.70879	0.126	0.512425	5	−2.27	1.27
WQ-360	29.76	0.79902	1	0.71036	0.143	0.512439	4	−2.43	1.53

I_{Sr} and $\varepsilon_{\text{Nd}}(t)$ values are calculated at $t=211$ Ma based on present-day $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}}=0.1967$ and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}=0.512638$.

TDM values are calculated based on present-day $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{DM}}=0.2137$ and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{DM}}=0.51315$.

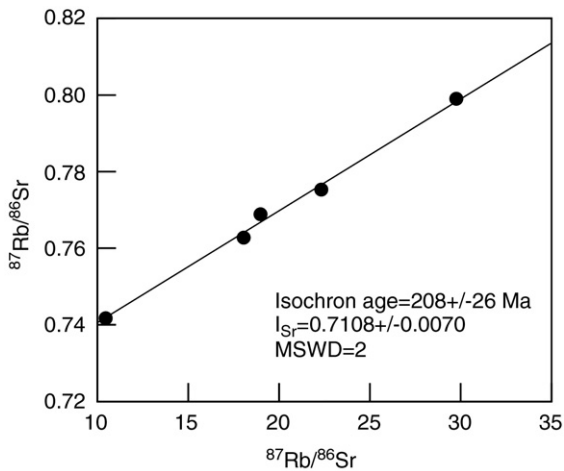


Fig. 7. Rb–Sr isochron for NB granite.

et al., 2007). Therefore, the occurrence of the NB A-type granite in the Songpan–Garze belt marks a tectonic transfer from compression to extension.

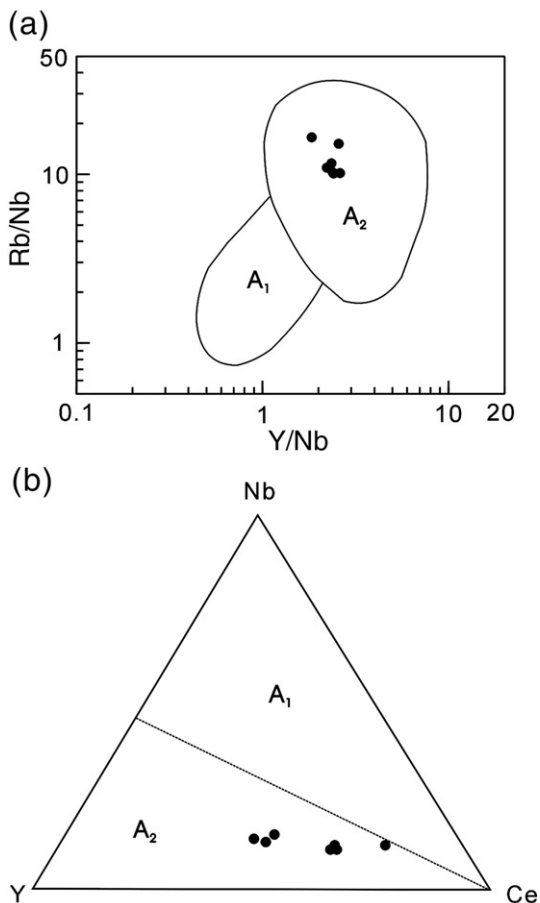


Fig. 8. A₁ and A₂ subgroup discrimination of A-type granites (after Eby, 1992).

5.2. Magma source

A number of petrogenetic schemes have been proposed for magma sources of A-type granites. These essentially fall into two categories, involving crustal and mantle sources (Kemp and Hawkesworth, 2003; and references therein). In some cases, magmas of A-type granites result from mixing between crust and mantle sources (Foland and Allen, 1991; Kerr and Fryer, 1993; Poitrasson et al., 1995; Schmitt et al., 2000). The A₂ group affinities of the NB A-type granite (Fig. 8a and b) imply that the magma source of the NB A-type granites was from continental crust or underplated basaltic protolith (Eby, 1992). However, the Sr and Nd isotopic results ($I_{\text{Sr}} = 0.70897\text{--}0.71230$, $\varepsilon_{\text{Nd}}(211 \text{ Ma}) = -2.72$ to -4.26) of the NB A-type granite cannot rule out contributions from mantle or enrichment mantle materials. Therefore, we consider various crustal sources in the Songpan–Garze belt and its adjacent area to see if they are plausible contributors to the magma source of the NB A-type granite or require a contribution from other source.

The source of the NB A-type granite is distinct from that of the Triassic adakitic granitoids or of the Triassic I-type granitoids in the Songpan–Garze belt, as revealed by their coupled Sr and Nd isotopic data (Fig. 9). In contrast to the NB A-type granite, the Triassic adakitic granitoids in the northeast of the Songpan–Garze belt have less radiogenic I_{Sr} values (0.7068–0.7078) and more unradiogenic $\varepsilon_{\text{Nd}}(t)$ values (-6.0 to -7.4) (Zhang et al., 2006), and the Triassic adakitic granitoids in the southeast Songpan–Garze belt (Xiao et al., 2007) display less

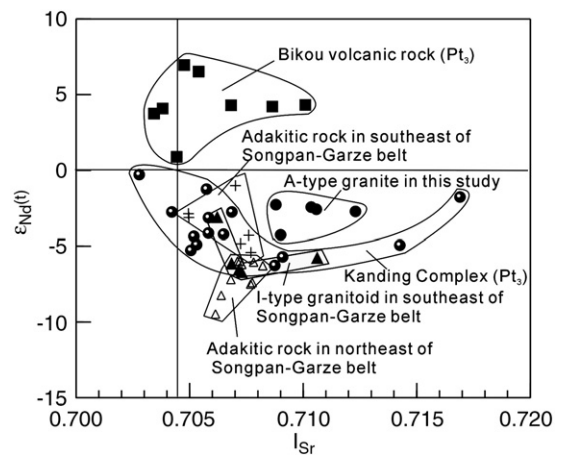


Fig. 9. $\varepsilon_{\text{Nd}}(t)$ vs. I_{Sr} diagram. Data sources: the Bikou Group volcanic rocks from Yan et al. (2004); the Kanding Complex from Ling et al. (1998), Chen et al. (2000); adakitic granitoids in northeast of the Songpan–Garze belt from Zhang et al. (2006); adakitic and I-type granitoids in southeast of the Songpan–Garze belt from Xiao et al. (2007); A-type granite from this study.

radiogenic I_{Sr} values (0.7079–0.7077) but their $\varepsilon_{\text{Nd}}(t)$ values (–1.01 to –5.41) overlap with those of the NB A-type granite. The field of coupled Sr and Nd isotopic data of the Triassic I-type granites in the southeast of the Songpan–Garze belt is also distinct from that of the NB A-type granite (Fig. 9).

Within the Songpan–Garze Triassic flysch basin, no Proterozoic basement is exposed. However, such basement is exposed along the western margin of the Yangtze block (Fig. 1). In these areas of Proterozoic rocks, the Kanding complex (796–797 Ma, U–Pb zircon SHRIMP, Zhou et al., 2002), composed of granitic gneiss and amphibolite, is located southeast of the Songpan–Garze belt (western margin of the Yangtze block). The Bikou Group (776–840 Ma, U–Pb zircon SHRIMP, Yan et al., 2003), composed of meta-basic volcanic rocks, is located in the northeast of the Songpan–Garze belt (northwestern margin of the Yangtze Block).

According to published Nd–Sr isotopic data from these blocks (Yan et al., 2004; Ling et al., 1998; Chen et al., 2000), the I_{Sr} and $\varepsilon_{\text{Nd}}(t)$ values have been calculated at $t=211$ Ma and shown in Fig. 8. The Bikou Group meta-volcanic rocks have $\varepsilon_{\text{Nd}}(211 \text{ Ma})$ values of >0 , indicating that the Bikou Group volcanic rocks are unlikely to be the magma source for the NB A-type granite. The Kanding complex alone is also unlikely to be the magma source, since the field of coupled I_{Sr} and $\varepsilon_{\text{Nd}}(t)$ data of the Kanding complex is distinct from that of the NB A-type granite (Fig. 8).

Lack of inherited zircons in igneous rocks may indicate that magma was derived from high temperatures of >900 °C (e.g., Clemens et al., 1986). It is possible that the high-temperature magma assimilated sedimentary cover that may have consisted of the metamorphosed Triassic sediments exposed within the Songpan–Garze belt or of Cambrian–Permian sediments exposed along the western margin of the Yangtze block. Their initial $\varepsilon_{\text{Nd}}(211 \text{ Ma})$ values range from –8 to –18 (Chen and Yang, 2000; Chen et al., 2006), which are distinct from the $\varepsilon_{\text{Nd}}(211 \text{ Ma})$ values (–2.72 to –4.26) of the NB A-type granite. This implies that the NB A-type granitic magma assimilation with those sediments may have been rather limited.

Present Sr–Nd isotopic data show that the crustal components of the Songpan–Garze belt and its adjacent area cannot solely serve as the magma source of the NB A-type granite. Thus, it is possible that there is a mantle or enrichment mantle source contribution to the NB granitic magma. Because of poor exposure of Triassic mantle-derived rocks, mantle nature of the Songpan–Garze belt is unclear, leading to that mantle end-member proportions of the NB granitic magma cannot be well

constrained. We suggest that a mantle source is required to account for the Sr and Nd isotopic compositions of the NB granite.

5.3. Geodynamic implications

In the Songpan–Garze belt, the magma crystallization age (211 ± 1 Ma) of the NB A-type granite is slightly younger than the upper limit (216 ± 6 Ma) of the Triassic adakitic granitoids (Zhang et al., 2006), both of which formed in post-collisional environment. Therefore, both granitic suites may have had the same geodynamic setting. For adakitic rocks in continental settings, there are several possible origins by partial melting of (1) thickened lower crust (Chung et al., 2003; Hou et al., 2004; Wang et al., 2005); (2) underplated basaltic protolith (Atherton and Petford, 1993; Petford and Atherton, 1996) and (3) delaminated lower crust (Xu et al., 2002a; Gao et al., 2004; Wang et al., 2006). The post-collisional A-type granites occurred in lithospheric extensional regimes due to upwelling of asthenosphere, which was probably related to lithospheric delamination (Jung et al., 1998; Wu et al., 2002; Ilbeyli et al., 2004). Recent geochemical and Sr–Nd isotopic data of the adakitic rocks in the Songpan–Garze belt suggested that the adakitic magma was derived from partial melting of thickened lower crust (Zhang et al., 2006; Xiao et al., 2007). Whether the adakitic magma generation resulted from lithospheric delamination is unclear, because the adakitic rocks lack geochemical signatures of interaction between delaminated lower crust and convecting mantle. The finding of the post-collisional NB A-type granite provides line of evidence that lithospheric delamination that may have occurred in the Songpan–Garze belt.

A Triassic lithospheric delamination model in the Songpan–Garze belt is summarized in Fig. 10.

- (1) In the Early Triassic, the Songpan–Garze belt crust was strongly thickened due to continental collision between the Yangtze, the North China and the North Tibet (Qiangdan) continental blocks (Fig. 10a). The thickened lower crust experienced granulite- and/or eclogite-facies metamorphism, resulting in an increase in the lower crustal density.
- (2) Lithospheric delamination occurred in the Middle Triassic because thickened lower crustal density increasing led to gravity instability of the lower crust. Asthenospheric material upwelled and filled into the space of previously occupied by the delaminated lithosphere. The asthenospheric upwelling heated the base of the lower crust and

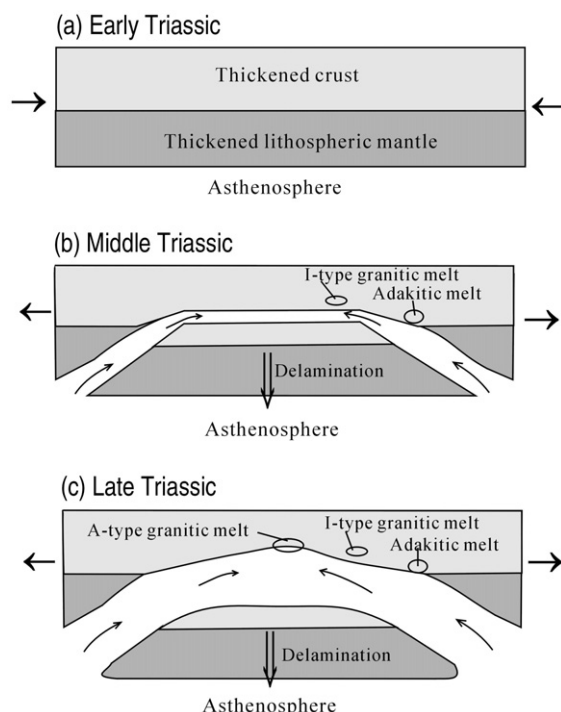


Fig. 10. Cartons showing the Triassic lithospheric delamination model of the Songpan–Garze belt. (a) Lithospheric thickening of the Songpan–Garze belt due to convergence of the Yangtze, the North China and the Qindan continental blocks during the Early Triassic; (b) the Songpan–Garze belt taken place lithosphere delamination and adakitic and I-type granitoids formed during the Middle Triassic; (c) the delaminated lithosphere was sunk to lower level and asthenospheric upwelling resulted in strongly thinning of overlaid lithosphere and tectonic decompression and then A-type granite melt generation in the lithospheric thinning centre.

promoted partial melting of the lower crust to generate the adakitic magma (lower crustal level) and/or I-type granitic magma (relatively upper crustal level) (Fig. 10b). During this period, the tectonic regime had transferred from compression to extension. This is made by large voluminous granitic melt generation, resulting from asthenospheric upwelling and lithospheric decompression.

- (3) In the Late Triassic, sinking delaminated lithosphere caused asthenospheric upwelling, which led in turn to the thinning of overlying lithosphere, inducing partial melting to form the A-type granites due to the heat from the asthenosphere and tectonic decompression. Partial melting resulted in the formation of A-type granite such as the NB granite. Considering that the magma source of the NB granite was probably from a mixture of crust and mantle sources, we suggest that the melting region was near the crust–mantle transition zone (Fig. 10c).

6. Conclusions

The NB granite from the central part of the Songpan–Garze belt is an A-type granite with an age of 211 ± 1 Ma, slightly younger than the adakitic rocks (216 ± 6 Ma) in this belt. The NB A-type granite formed in a post-collisional tectonic setting. It is suggested that the magma was sourced dominantly from the crust, but contribution from the mantle source cannot be ruled out. The Triassic lithospheric delamination model in the Songpan–Garze belt can account for the magma generation of both the Triassic adakitic rocks and the Triassic A-type granite. The Triassic lithospheric delamination resulted from the crustal thickening of the Songpan–Garze belt in the Early Triassic due to convergence between the Yangtze, North China and North Tibetan continental blocks. Our results show that the adakitic and A-granite magma association in post-collisional environment could be a useful indicator of lithospheric delamination.

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