Journal of Geosciences, 59 (2014), 275–291
DOI: 10.3190/jgeosci.172

Original paper

Petrology and zircon U–Pb dating combined with Hf isotope study of granitic rocks from the Kuluketage Block (Tarim Craton, NW China)

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We report the petrology, whole-rock geochemistry, zircon LA-ICP-MS U–Pb chronology and zircon Hf isotopic data of Daxigou granitoids (western part of the Kuluketage Block, NW China) to evaluate their likely petrogenesis and tectonic setting. Zircons from syenogranite can be divided into two groups: 1) those that display oscillatory zoning and high Th/U ratios (average = 1.38), implying their magmatic origin and 2) those that exhibit weak zoning and extremely high U and Pb contents but low Th/U ratios (average = 0.35), resembling zircons that experienced hydrothermal alteration. The zircon LA-ICP-MS U–Pb dating of the two groups of zircons yielded weighted mean ages of 1830 ± 12 Ma (MSWD = 0.78) and 1798 ± 21 Ma (MSWD = 1.6) respectively.

The Daxigou granitoids belong mostly to normal-K and sodium-rich metaluminous calc-alkaline type, systematically enriched in LREE and large ion lithophile elements (LILE, e.g., K, Ba and Rb), but significantly depleted in high field strength elements (HFSE, e.g., Ti, P, Nb, Ta and U). Their εHf(t) values and two-stage Hf model ages range from –7.16 to –5.03 and 2.69 to 2.76 Ga, respectively. Taken together, it is suggested that Daxigou granitoids are of I-type affinity and that they were derived by partial melting of a Neoarchaean TTG (e.g., Tuoge Complex) rocks in a continental-arc environment. These new data, combined with previous regional geological studies, demonstrate that a series of Palaeoproterozoic (*c.* 2.0–1.8 Ga) tectono-magmatic events occurred in Kuluketage Block during the assembly of Columbia.

Keywords: Kuluketage Block, syenogranite, LA-ICP-MS zircon dating, Hf isotopes, Paleoproterozoic
Received: 7 June 2013; accepted: 16 June 2014; handling editor: M. Kohút

1. Introduction

The formation and reworking of early Precambrian continental crust are of great importance in understanding the early evolution of the Earth (Condie 1989, 1994; Rudnick 1995; Hawkesworth and Kemp 2006; Long et al. 2010). The Tarim, as well as the North and South China cratons, constitute three major continental blocks in China and represent an important part of the early crustal evolutionary history of northwest China and adjacent areas (Hu AQ et al. 1997; Lu et al. 2008; Demoux et al. 2009; Xiao and Kusky 2009; Lei et al. 2012). The Tarim Craton has a poorly dated Archaean–Paleoproterozoic basement which sporadically crops out along the margins of the Mesozoic–Cenozoic Tarim Basin (Lu et al. 2002). By contrast, the Kuluketage Block (also spelled as Kuruqtagh or Quruqtagh) on the northeastern margin of the Tarim Craton (Fig. 1a–b) is predominantly composed of the Precambrian basement (Lu et al. 2002, 2008; Wang et al. 2013) and provides a good opportunity to study the Precambrian evolutionary history of the Tarim Craton.

Several tectono-thermal events from Neoarchaean to the latest Neoproterozoic have been determined in this area. However, most of the previous studies have mainly focused on Neoproterozoic magmatism and tectonic evolution related to the break-up of Rodinia (Xu et al. 2005; Luo et al. 2007; Sun and Huang 2007; Lu et al. 2008; Zhu et al. 2008; Zhang et al. 2009; Shu et al. 2010; Cao et al. 2011), e.g., *c.* 800–820 Ma Qiganbulake mafic–ultramafic–carbonatite complex, 820 ± 10 Ma Xingdi granodiorite, 795 ± 10 Ma Taiyangdao granite (Zhang et al. 2007a), *c.* 755 Ma bimodal volcanic rocks in the Xinger area (Xu et al. 2005) and 630–650 Ma mafic dykes in Korla (Zhu et al. 2008).

By contrast, little is known about pre-Neoproterozoic magmatism (especially for Mesoproterozoic–Paleoproterozoic magmatism) and the tectonic evolution of the Kuluketage Block. A few studies that have reported on the Paleoproterozoic magmatism and tectonic evolution in the area, mainly dealt with Nd model ages (Feng et al. 1995) and ages from zircons, detrital (Guo et al. 2003; Hu and Wei 2006; Long et al. 2010; Shu et al.

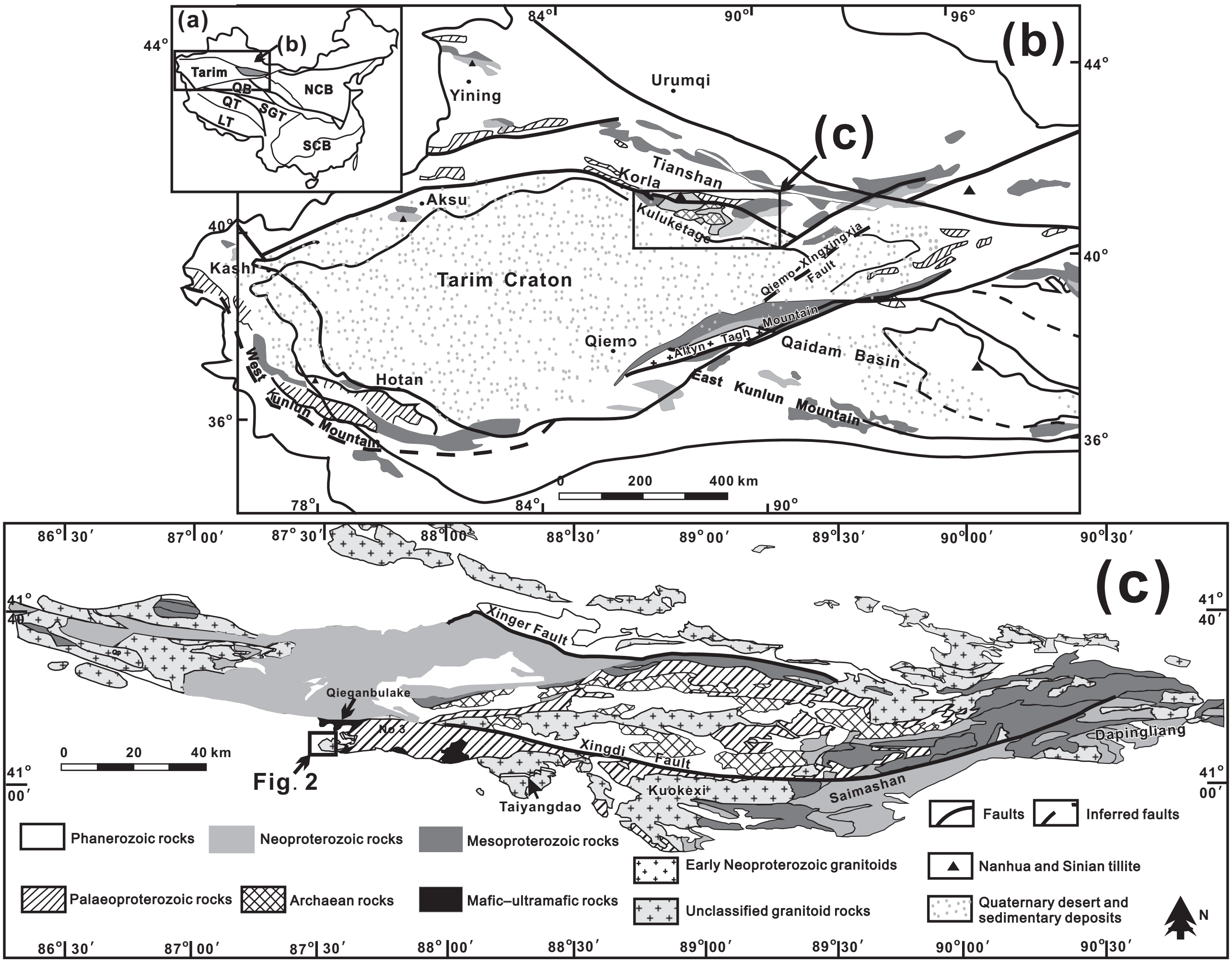


Fig. 1a – Main tectonic domains of China (simplified from Cao et al. 2011). NCB: North China Block, SCB: South China Block, SGT: Songpan–Ganzi Terrane, QB: Qaidam Basin, QT: Qiangtang Terrane, LT: Lhasa Terrane; **b** – Schematic geological map of Tarim Craton and adjacent areas (adopted from Cao et al. 2011); **c** – Schematic geological map of the Kuluketage Block on the northeast margin of the Tarim Craton (Wang et al. 2007).

2010) or metamorphic (Lei et al. 2012). However, no Paleoproterozoic ages of magmatic zircons have been reported yet. Moreover, detailed field observations, precise isotopic ages and high-quality geochemical data are very sparse for late Paleoproterozoic rocks, and this hinders a good understanding of the tectonic evolution of the Tarim Craton, especially the tectonic setting of the Paleoproterozoic magmatism and its relationship to the Palaeo–Mesoproterozoic Columbia Supercontinent (Lei et al. 2012).

Based on detailed field and petrological studies, we report comprehensive geochronological, geochemical and zircon Hf isotope analyses of the Daxigou Complex (syenogranite and granodiorite) in the Kuluketage Block with the aim of characterising its petrogenesis and tectonic setting. Together with regional geology and geochronological data, the Palaeo–Mesoproterozoic assembly of Columbia is being investigated.

2. Geological setting

The Kuluketage Block is composed of two units: the basement which includes Archaean, Paleoproterozoic, Mesoproterozoic and early Neoproterozoic lithologies and the middle Neoproterozoic to Phanerozoic sedimentary cover (Gao et al. 1993; Cheng 1994; Feng et al. 1995; Lu et al. 2008) (Fig. 1b). The Xinger and Xingdi faults are the main regional E–W-oriented structures (Fig. 1c).

Archaean rocks sporadically crop out in the Kuluketage area, known as the Tuoge Complex. It is mainly composed of granitic gneisses with minor amphibolite xenoliths (derived from gabbroic protoliths) (Hu AQ et al. 1999, 2000); it yielded a SHRIMP U–Pb zircon age of 2601 ± 21 Ma (Zhang et al. 2012a) and LA–ICP–MS U–Pb upper intercept zircon age of 2659 ± 15 Ma (Long et al. 2011a). Mostly metasedimentary

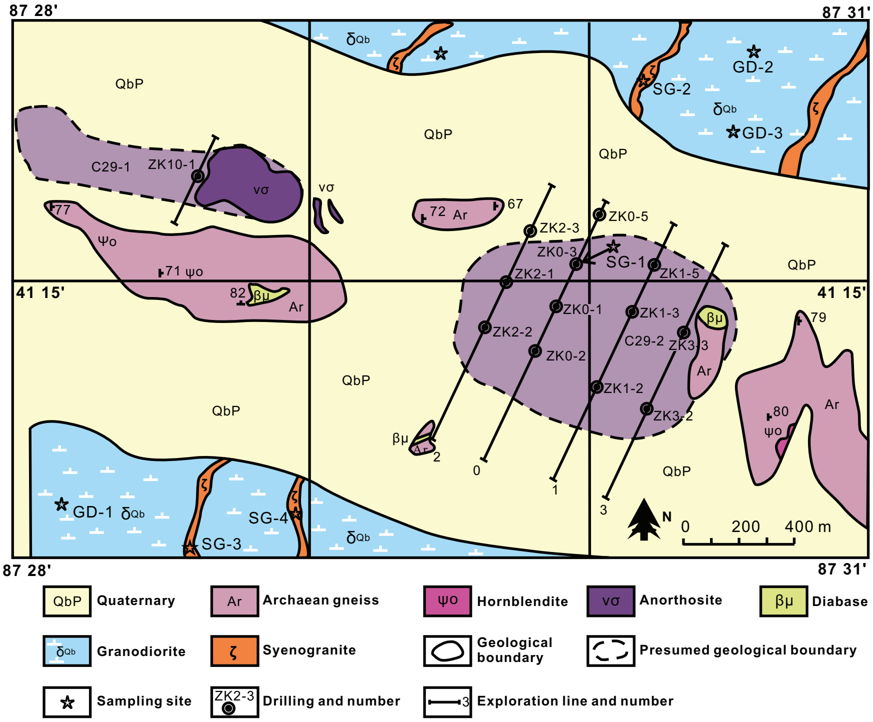


Fig. 2 Geological map of the Daxigou iron–phosphorite deposit in the western Kuluketage (Xia et al. 2010) showing the locations of geochronological and geochemical samples (SG-1 to SG-4: syenogranite; GD-1 to GD-3: granodiorite).

Paleoproterozoic rocks (Xingditage Complex) occur in the western part of the Kuluketage Block. Despite the limited precise geochronology, at the end of the Paleoproterozoic, an important metamorphic event was postulated to have affected Archaean TTG suites and the overlying Paleoproterozoic sedimentary rocks (e.g., Feng et al. 1995; Lu et al. 2002; Zhang et al. 2007b). Mesoproterozoic to early Neoproterozoic low-grade metamorphic rocks, including metamorphosed carbonate and clastic metasedimentary rocks, as well as granitoids, are widespread in the area (Feng et al. 1995; Lu et al. 2008). Middle Neoproterozoic to Phanerozoic rocks consist of mafic dyke swarms, bimodal volcanics as well as fine sandstones, siltstones, shales, dark limestones and chert nodule-bearing dolomites. The mafic dykes with bimodal volcanics were formed at 820–744 Ma and 650–630 Ma (Zhang et al. 2007a; Zhu et al. 2008; Xu et al. 2009). Late Neoproterozoic glacial deposits are also well exposed (Xu et al. 2009).

The Daxigou Complex is the first low-grade, large iron–phosphate deposit discovered at the northern margin of the Tarim Craton (Xia et al. 2010). Several similar complexes with Fe–P mineralization are located along the Xingdi Fault (Xia et al. 2010) and form a strong linear aeromagnetic anomaly (Yuan et al. 2013). From west to east, the petrology of these igneous bodies is as follows: Duosike pyroxenite Complex, Kawuliuketage pyroxenite–hornblendite–syenite Complex, Ao'ertang gabbro–pyroxenite Complex, Daxigou granodiorite–syenogranite Complex and Qieganbulake biotite pyroxenite–carbonate Complex (Xia et al. 2010).

3. Field geology and petrography

The Daxigou Complex is located south of the Xingdi Fault in Kuluketage Block (Fig. 1c) and is controlled by its subsidiary fault. The coordinates of the working area are 87°27'00"–87°31'00"E and 41°12'30"–41°15'30"N. Rocks of this complex are distributed NW–SE over an area of 2.1 × 0.9 km (Fig. 2). They intruded into the Archaean Tuoge Complex which is mainly composed of amphibole-bearing tonalitic gneiss (Xia et al. 2010).

The Daxigou Complex is built mainly by greyish white granodiorite (GD) that exhibits coarse-grained granitic texture and blocky structure. The main mineral components are plagioclase (45–50 vol. %), quartz (25–30 vol. %), K-feldspar (14–17 vol. %), hornblende (8 vol. %), magnetite (1–2 vol. %) and apatite (1 vol. %). Accessory minerals include zircon and ilmenite.

Syenogranites (SG) occur mainly as dykes accompanying the granodiorite, and account for 30 % of the complex. Typically they are pinkish and show massive, medium- to coarse-grained granitic textures. Modal compositions include plagioclase (An_{35-50} 30–50 vol. %), quartz (25–35 vol. %), K-feldspar (18–22 vol. %), biotite (2–5 vol. %), hornblende (1–2 vol. %), and accessory minerals such as apatite, zircon and ilmenite.

Rocks of the Tuoge Complex are composed of plagioclase (40–48 vol. %), quartz (25–30 vol. %), alkali feldspar (25–30 vol. %) and biotite (5–10 vol. %) with some accessory minerals, e.g., titanite, apatite and zircon. Generally, the Tuoge Complex exhibits considerable weathering in the Daxigou area, rendering it not suitable for chemical analyses.

4. Analytical methods

4.1. Zircon U–Pb dating

Zircon grains were separated using conventional crushing, grinding and wet shaking table methods, followed by heavy liquid (tetrabromomethane) and magnetic separation. Hand-picked zircon grains were mounted in epoxy blocks and polished prior to LA-ICP-MS analysis, the surfaces of grain mounts were washed in dilute HNO_3 and pure alcohol to remove any potential lead contamination. The selection of zircon grains for isotopic analyses was based upon cathodoluminescence (CL) images (Fig. 3). Zircon U–Th–Pb measurements were done at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan (GPMR-CUGW), using a GeoLas 2005 System. An Agilent 7700a ICP-MS instrument was employed, with a 193 nm ArF-excimer laser (32 µm beam diameter). Details on instrumentation and analytical accuracy were given by Liu et al. (2008, 2010). Time-dependent drifts of U–Th–Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of external zircon standard 91500 (i.e., 2× 91500 – 5 samples – 2× 91500) (Liu et al. 2010). The ages were calculated by in-house software ICPMSDataCal (ver 9.0) (Liu et al. 2008), and Concordia diagrams were plotted by Isoplot/Ex ver. 3.0 (Ludwig 2003).

4.2. Whole-rock geochemistry

Rock samples for the major- and trace-element analyses were carefully selected to be representative of geographical distribution of the two different rock types (Fig. 2): four syenogranites and three granodiorites. Whole-rock samples were crushed to 0.5 cm chips in a steel-faced jaw crusher and powdered with an agate mill.

Major elements were analysed with a PAN analytical Axios X-ray fluorescence spectrometer (XRF) at ALS Chemex (Guangzhou) Ltd. A calcined or ignited sample (0.9 g) was added to 9.0 g of lithium borate flux (1 : 1 $Li_2B_4O_7$–$LiBO_2$), mixed well and fused in an auto fluxer between 1050–1100 °C. A flat molten glass disc was prepared and analysed by XRF with a precision better than 5 %.

Trace-element concentrations were determined with an Elan 9000 ICP-MS at the same lab. To the sample powder (0.2 g) was added lithium metaborate flux (0.9 g), mixed well and fused in a furnace at 1000 °C. The resulting melt was then cooled and dissolved in 100 ml of 4 % HNO_3/2 % HCl solution and analyzed by ICP-MS with a precision better than 10 % for all elements.

4.3. In situ zircon Hf isotope analysis

In situ zircon Hf isotopic analyses were conducted using a Neptune Plus MC-ICP-MS, in combination with a Geolas 2005 excimer ArF laser-ablation system, at the GPMR-CUGW. During the analysis, a laser repetition rate of 20 Hz at 200 mJ was used with the spot diameter of 44 µm. Details of the analytical technique were described in (Hu ZC et al. 2012). During the analysis, the $^{176}Hf/^{177}Hf$ ratios of the standard zircon (GJ-1) were 0.282013 ± 0.000022 (2σ, n = 276), agreeing with the recommended values (Woodhead and Hergt 2005; Wu FY et al. 2006; Sláma et al. 2008; Li et al. 2010) within 2σ error. Off-line selection and integration of analytical signals, and isobaric interference and mass fractionation correction of Lu–Hf isotopic ratios were also performed by the ICPMS-DataCal.

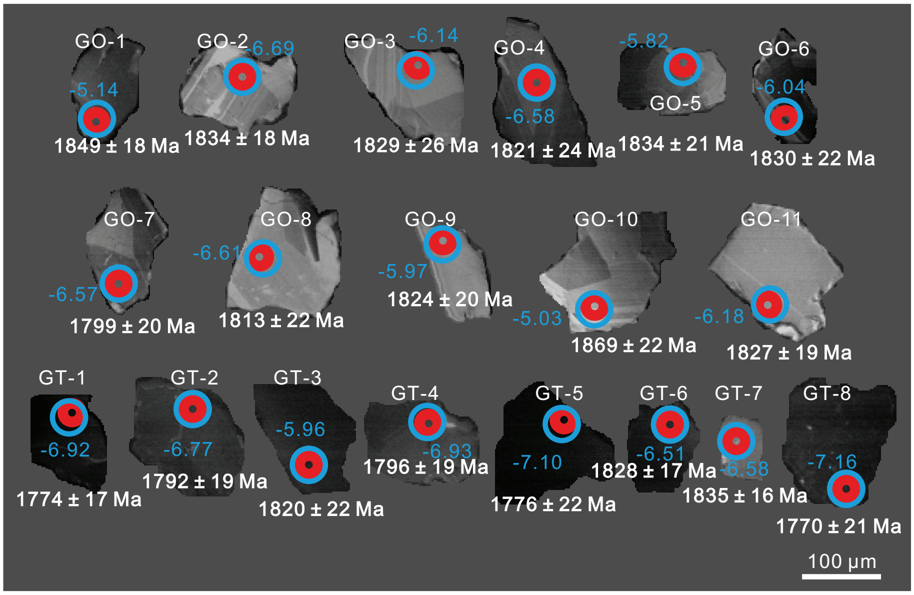


Fig. 3 Cathodoluminescence (CL) images of zircons from the syenogranite SG-2. LA-ICP-MS U–Pb (red circles) and *in situ* Hf determination spots (bigger circles) with $^{207}Pb/^{235}U$ ages and εHf(t) values are indicated.

5. Analytical results

5.1. Zircon U–Pb geochronology

Zircons are relatively abundant in the dated syenogranite sample SG-2 (Fig. 2). According to the shape, colour and length/width ratios, they can be categorised into two groups, distinguished below. The measured Pb isotopic ratios and calculated ages for 19 analyses on 19 zircon crystals are given in Tab. 1.

5.1.1. Group one (igneous) zircons

Group one (GO) zircons are sub-euhedral, short to long prismatic, and transparent, and their length/width ratios are *c.* 2.7. In CL images (Fig. 3; upper two rows), they exhibit oscillatory zoning, a feature typical of magmatic zircon (Corfu et al. 2003), but a few grains show clear core–rim textures (GO-6).

The analyses display variable abundances of U (99–513 ppm), Th (123–622 ppm) and Pb (49–256 ppm) but consistently high Th/U ratios (1.09–2.11) which are suggestive of an igneous origin (Hanchar and Rudnick 1995; Hoskin and Black 2000). This group of closely clustered concordant analyses yields a weighted mean $^{207}Pb/^{235}U$ age of 1830 ± 12 Ma (MSWD = 0.78) (Fig. 4a), which we adopt as the crystallization age of the syenogranite.

5.1.2. Group two (recrystallized) zircons

By contrast, group two (GT) zircons are irregular in shape

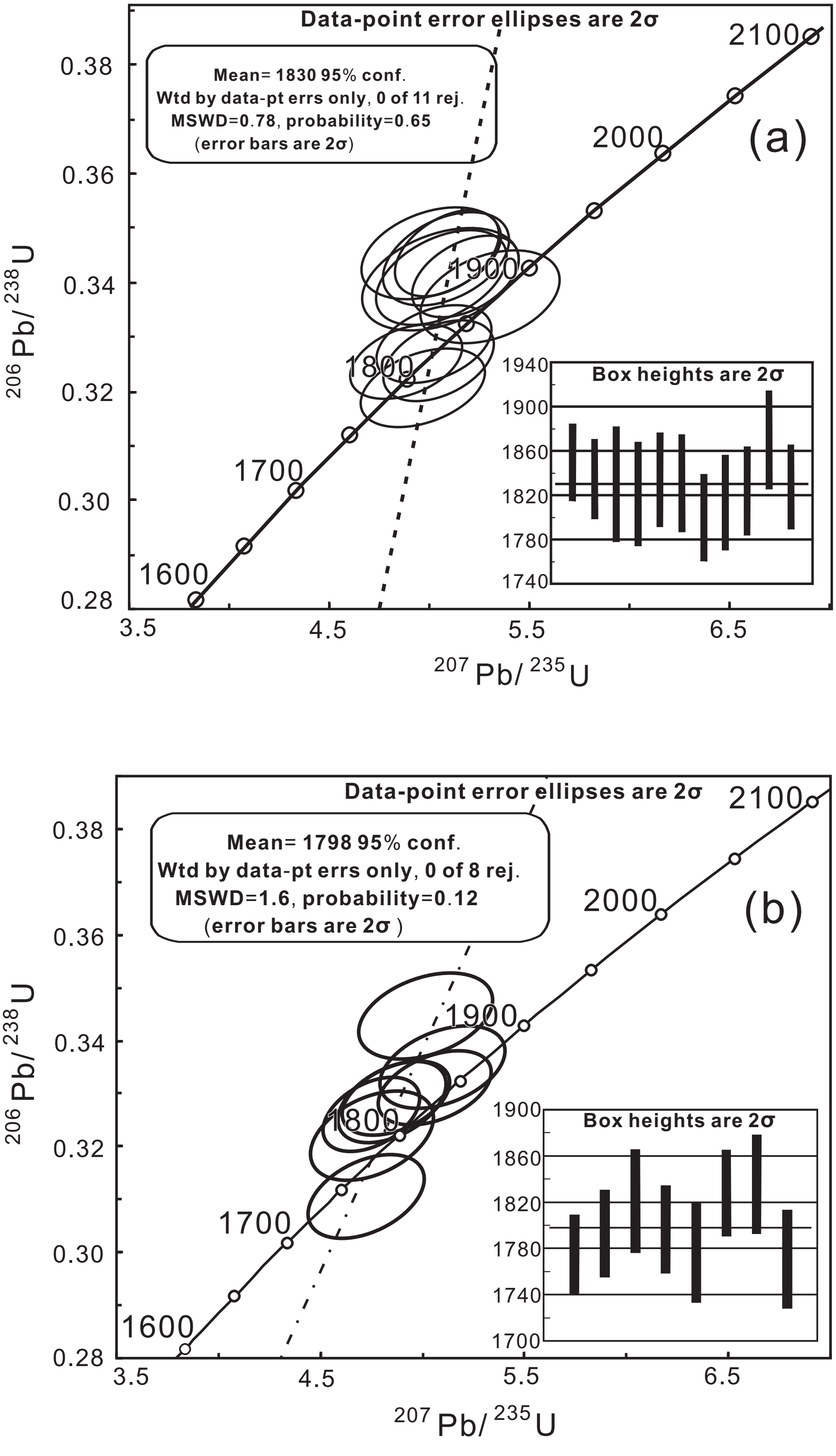
Tab. 1 Laser-ablation ICP-MS U–Pb isotopic data for zircon from the dated syenogranite

Sample	Concentrations (ppm)				U–Th–Pb isotopic ratios						Ages (Ma)					
spot	Pb	Th	U	Th/U	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
GO-1	152.0	553	262	2.11	0.1088	0.0022	5.1793	0.1067	0.3411	0.0030	1789	36	1849	18	1892	14
GO-2	145.4	363	282	1.29	0.1056	0.0022	5.0890	0.1078	0.3452	0.0031	1726	39	1834	18	1912	15
GO-3	49.7	130	99	1.31	0.1068	0.0034	5.0600	0.1560	0.3404	0.0039	1746	57	1829	26	1889	19
GO-4	256.0	622	513	1.21	0.1036	0.0029	5.0081	0.1391	0.3454	0.0034	1700	52	1821	24	1912	16
GO-5	169.1	457	325	1.41	0.1057	0.0027	5.0851	0.1275	0.3442	0.0035	1728	46	1834	21	1907	17
GO-6	66.9	181	129	1.40	0.1063	0.0027	5.0659	0.1318	0.3407	0.0036	1737	47	1830	22	1890	17
GO-7	151.8	455	286	1.59	0.1071	0.0025	4.8826	0.1138	0.3255	0.0028	1752	44	1799	20	1816	14
GO-8	105.7	246	218	1.13	0.1107	0.0029	4.9628	0.1263	0.3207	0.0031	1811	48	1813	22	1793	15
GO-9	131.8	340	260	1.31	0.1092	0.0026	5.0250	0.1183	0.3287	0.0029	1787	43	1824	20	1832	14
GO-10	55.6	123	113	1.09	0.1129	0.0030	5.3033	0.1385	0.3373	0.0036	1847	48	1869	22	1873	17
GO-11	128.5	333	257	1.30	0.1113	0.0025	5.0454	0.1138	0.3257	0.0030	1820	36	1827	19	1818	15
Average	128.4	345.7	249.5	1.38	□	□	□	□	□	□	□	□	□	□	□	□
GT-1	820.0	293	2248	0.13	0.1041	0.0021	4.7391	0.0965	0.3257	0.0029	1698	69	1774	17	1817	14
GT-2	488.0	598	1216	0.49	0.1056	0.0023	4.8428	0.1084	0.3280	0.0031	1726	41	1792	19	1828	15
GT-3	356.3	392	841	0.47	0.1038	0.0028	5.0067	0.1323	0.3444	0.0034	1692	49	1820	22	1908	16
GT-4	952.0	546	2411	0.23	0.1056	0.0024	4.8638	0.1094	0.3288	0.0030	1724	41	1796	19	1833	14
GT-5	1146.1	493	3024	0.16	0.1052	0.0027	4.7483	0.1224	0.3217	0.0034	1718	47	1776	22	1798	17
GT-6	242.2	302	569	0.53	0.1091	0.0024	5.0494	0.1114	0.3308	0.0030	1785	40	1828	19	1842	15
GT-7	203.8	290	466	0.62	0.1087	0.0027	5.0934	0.1284	0.3349	0.0034	1789	51	1835	21	1862	16
GT-8	936.0	471	2354	0.20	0.1089	0.0028	4.7151	0.1199	0.3100	0.0033	1781	14	1770	21	1741	16
Average	643.1	423.1	1641.1	0.35	□	□	□	□	□	□	□	□	□	□	□	□

GO = group one; GT = group two

and orange in colour under the optical microscope; their length/width ratios are *c.* 1.2. In CL images (Fig. 3, the bottom row), they are much darker than magmatic rims and exhibit no zoning. This suggests that they may have undergone hydrothermal alteration, similar to the zircons in alkali syenites (Corfu et al. 2003).

The group two zircons show much higher U (466–3024 ppm), Pb (204–1146 ppm) and total REE contents, but lower Th/U ratios (0.13–0.62) than those of group one (Tab. 1). However, they show ^{176}Lu/^{177}Hf and ^{176}Hf/^{177}Hf(t) ratios identical to the GO zircons (see Tab. 3). These characteristics are similar to those of zircons formed by alteration with an aqueous fluid or a hydrous melt (e.g., Gerdes and Zeh 2009). Eight analyses of eight irregular grains with bad oscillatory zoning yielded a weighted mean ^{207}Pb/^{235}U age of 1798 ± 21 Ma (MSWD = 1.6, 2σ) (Fig. 4b), i.e. postdating by nearly 30 Ma the intrusion (GO). Thus we interpreted this datum as the age of post-magmatic alteration.



5.2. Major elements

The representative whole-rock major- and trace-element compositions are given in Tab. 2, including those for the Tuoge Complex. In addition, these samples may have undergone some degree of alteration, such as chloritization, even though their LOI values are moderate (2.09–3.63 wt. %), except the sample SG-3 (6.58 wt. %).

The syenogranites are characterised by variable SiO_2 (60.44–73.28 wt. %), K_2O (1.05–6.23 wt. %), high Na_2O (3.17–5.62 wt. %), and low P_2O_5 (0.014–0.113 wt. %), TiO_2 (0.03–0.43 wt. %) with MgO (0.24–1.66 wt. %). After rejection of the K-rich sample (SG-1), the Na_2O/K_2O ratios range from 1.19 to 5.35, i.e. are characteristic of I-type granites

Fig. 4 U–Pb Concordia plots and recalculated weighted mean ^{207}Pb/^{235}U ages of group one zircons (**a**) and group two zircons (**b**) are given in the text box.

Tab. 2 Major- (wt. %) and trace-element data (ppm, including REE) from the Daxigou granitoids (this work) and Tuoge Complex (Long et al. (2010)

Sample No.	SG-1	SG-2	SG-3	SG-4	GD-1	GD-2	GD-3	TC-1	TC-2	TC-3	TC-4
Lithology	Syenogranite				Granodiorite			Tuoge Complex			
SiO_2	69.83	73.28	60.44	68.86	69.25	72.05	61.85	69.30	68.90	71.00	66.30
Al_2O_3	14.22	12.23	14.46	12.75	12.61	12.43	14.98	13.50	13.60	13.10	14.40
$Fe_2O_{3(T)}$	0.52	3.38	4.38	1.60	5.08	2.70	6.90	4.06	4.50	3.69	4.94
CaO	2.17	0.96	4.58	4.23	1.46	2.07	3.59	2.57	2.50	0.98	2.74
MgO	0.24	1.40	1.66	0.39	1.79	0.91	2.30	0.97	1.36	1.26	1.71
Na_2O	3.17	3.87	5.62	4.05	4.45	5.16	4.21	3.72	3.63	4.54	3.30
K_2O	6.23	2.59	1.05	3.40	1.49	1.43	1.02	3.00	2.68	3.34	3.43
TiO_2	0.03	0.08	0.43	0.03	0.22	0.26	0.94	0.81	0.86	0.56	0.89
MnO	<0.01	0.05	0.07	0.02	0.07	0.04	0.06	0.08	0.08	0.09	0.07
P_2O_5	0.01	0.03	0.11	0.02	0.09	0.09	0.35	0.25	0.25	0.19	0.31
SrO	0.02	0.02	0.04	0.03	0.02	0.03	0.07	–	–	–	–
BaO	0.13	0.07	0.08	0.09	0.10	0.05	0.10	–	–	–	–
LOI	2.46	2.09	6.58	3.63	2.57	2.44	2.80	1.23	1.10	0.83	1.32
∑	99.02	100.05	99.50	99.10	99.19	99.65	99.17	99.50	99.50	99.60	99.40
Na_2O/K_2O	0.51	1.49	5.35	1.19	2.99	3.61	4.13	1.24	1.35	1.36	0.96
Na_2O+K_2O	9.40	6.46	6.67	7.45	5.94	6.59	5.23	6.72	6.31	7.88	6.73
A/NK	1.19	1.33	1.39	1.23	1.41	1.24	1.87	1.44	1.53	1.18	1.58
A/CNK	0.89	1.12	0.77	0.71	1.09	0.90	1.03	0.96	1.01	1.02	1.02
δ	3.29	1.38	2.55	2.15	1.34	1.49	1.45	1.72	1.54	2.22	1.94
Co	82.50	78.20	33.70	64.40	22.60	46.70	41.90	4.38	6.58	6.34	6.67
Ni	10.00	9.00	17.00	8.00	10.00	10.00	26.00	5.67	3.82	6.65	7.39
Rb	126.5	52.9	23.2	67.8	30.5	30.2	13.4	48.6	61.7	39.9	69.5
Ba	1205	699	739	828	957	554	887	2206	2044	1974	2586
Th	0.58	4.14	4.77	3.42	8.4	4.62	0.47	7.81	7.80	11.07	14.96
U	0.25	0.59	0.69	1.01	0.51	0.47	0.44	0.52	0.52	0.44	0.50
K	51715.9	21499.9	8716.2	28223.7	12368.6	11870.6	8467.1	24911.3	22254.1	27734.6	28481.9
La	3.6	9.2	38.8	6.8	28.0	21.8	35.3	108.0	116.0	110.0	153.0
Ce	6.6	15.5	70.7	13.1	53.8	41.7	78.1	236.0	250.0	232.0	304.0
Pb	18.00	10.00	6.00	13.00	5.00	9.00	25.00	17.58	10.97	9.93	13.23
Pr	0.65	1.62	7.33	1.52	5.80	4.36	9.77	28.00	29.70	28.00	32.30
Sr	223	206	370	283	207	241	682	346	265	140	436
P	61.50	140.57	496.40	96.64	421.72	395.36	1550.69	1091.34	1091.34	829.42	1353.26
Nd	2.30	6.00	26.60	5.90	20.70	16.20	41.00	102.00	106.00	98.70	109.00
Ta	0.40	0.30	0.50	0.50	0.30	0.30	0.30	1.14	0.77	0.53	0.65
Zr	41	45	209	46	145	143	281	408	253	300	310
Hf	1.70	1.30	5.40	1.70	4.20	4.60	6.60	10.25	6.23	7.57	7.70
Sm	0.45	1.04	4.26	1.42	3.81	3.27	7.34	17.20	16.40	15.00	13.20
Eu	0.50	0.51	1.16	0.75	1.09	0.81	2.06	3.53	3.37	2.63	2.70
Ti	143.65	383.06	2058.96	143.65	1053.42	1244.95	4500.98	4856.25	5156.01	3357.40	5335.88
Gd	0.36	1.05	3.64	1.60	3.15	4.01	6.09	14.10	13.00	10.50	10.00
Tb	0.05	0.18	0.46	0.26	0.48	0.64	0.72	2.14	1.79	1.49	1.05
Dy	0.25	1.03	2.54	1.56	3.06	3.66	3.56	12.00	9.65	7.92	4.98
Y	1.6	5.9	14.2	10.6	16.8	19.5	16.2	59.5	46.9	38.1	22.7
Nb	1.0	1.4	9.8	4.3	4.1	5.9	5.4	18.5	18.1	11.6	10.1
Ho	0.05	0.21	0.47	0.33	0.60	0.69	0.60	2.38	1.81	1.47	0.89
Er	0.14	0.64	1.34	1.07	1.65	2.03	1.62	6.42	4.63	3.68	2.21
Tm	0.03	0.09	0.20	0.16	0.28	0.29	0.20	0.92	0.62	0.47	0.30
Yb	0.15	0.69	1.32	1.13	1.60	1.93	1.16	5.88	3.80	2.71	1.77
Lu	0.03	0.10	0.20	0.19	0.24	0.28	0.16	0.86	0.53	0.35	0.26
ΣREE	15.16	37.86	159.02	35.79	124.26	101.67	187.68	539.43	557.30	514.92	635.66
LREE	14.10	33.87	148.85	29.49	113.20	88.14	173.57	494.73	521.47	486.33	614.20
HREE	1.06	3.99	10.17	6.30	11.06	13.53	14.11	44.70	35.83	28.59	21.46
LREE/HREE	13.30	8.49	14.64	4.68	10.24	6.51	12.30	11.07	14.55	17.01	28.62
La_N/Yb_N	17.22	9.56	21.08	4.32	12.55	8.10	21.83	13.17	21.90	29.12	62.00
δEu	3.80	1.49	0.90	1.52	0.96	0.68	0.94	0.69	0.71	0.64	0.72

Note: data of Tuoge Complex are from Long et al (2010).
A/NK = molar ratio of $Al_2O_3/(Na_2O + K_2O)$; A/CNK = molar ratio of $Al_2O_3/(CaO + Na_2O + K_2O)$ (Shand 1943);
$\delta = [w(K_2O + Na_2O)^2]/[w(SiO_2 - 43)]$ (Rittmann 1953); $\delta Eu = Eu/Eu^* = Eu_N/\sqrt{Sm_N + Gd_N}$

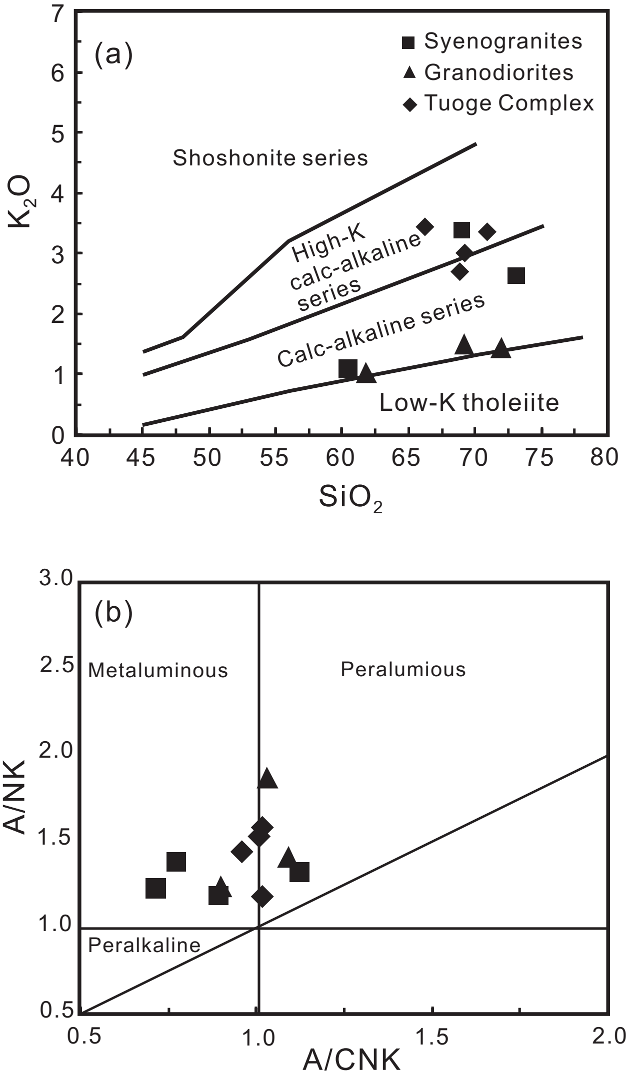


Fig. 5a – Diagram of K_2O–SiO_2 for granitoids of the Daxigou and Tuoge complexes (Peccerillo et al. 1976). **b** – Diagram of A/NK–A/CNK for the same rocks (Shand 1943).

(Chappell and White 1974). Silica alkalic indexes (δ) [wt. % $(K_2O + Na_2O)^2$] / [wt. % $(SiO_2 – 43)$] (Rittmann 1953) range from 1.37 to 3.29, which suggests calc-alkaline characteristics. In addition, most of the data fall in the medium-K, calc-alkaline field on the SiO_2 versus K_2O diagram of Peccerillo and Taylor (1976) (Fig. 5a). The rocks are metaluminous, with the A/CNK [molar Al_2O_3 /(CaO + K_2O + Na_2O)] varying from 0.71 to 0.93, except sample SG-2 (A/CNK = 1.12) (Fig. 5b, Shand 1943).

The Daxigou granodiorites contain 61.85–72.05 wt. % SiO_2, 12.61–14.98 wt. % Al_2O_3, 1.46 %–3.59 wt. % CaO, 0.91–2.3 wt. % MgO and 1.02–1.49 wt. % K_2O, with Na_2O/K_2O ratios of 2.99–4.13 and low silica alkalic indexes (δ = 1.34–1.49). All granodiorites belong to the calc-alkaline series (Fig. 5a) and are subaluminous (A/CNK = 0.90–1.09) (Fig. 5b).

The Tab. 2 and Harker plots (Fig. 6) show that the average compositions of syenogranite and granodiorite are similar, with small differences in $Fe_2O_{3(t)}$ content. Moreover, compared with the Tuoge Complex, the Daxigou granitoids contain rocks with a slightly higher Na_2O and a lower FeOt contents; SiO_2, Al_2O_3, CaO and MgO contents are comparable. In the Harker diagrams, the three rock types show consistent negative correlations between SiO_2 and Al_2O_3, Fe_2O_3t, CaO, MgO and P_2O_5. Laboratory studies have shown the different behaviour of apatite in I-type (Wolf and London 1994) and S-type granites, and this has been successfully used to distinguish granite types (Chappell 1999). Most of our data show that Daxigou granitoids are metaluminous, and the content of P_2O_5 is low and negatively correlated with SiO_2 (Fig. 6), which corresponds to the evolutionary trend of I-type granites (Chappell and White 1992). Therefore, we suggest that Daxigou granitoids are of I-type affinity and may have a genetic relationship with the Tuoge Complex.

5.3. Trace elements

The trace-element concentrations of the Daxigou granitoids are highly variable. However, most show mutually comparable patterns in primitive mantle-normalized spider diagram (Fig. 7a). Most of the trace-element contents of granodiorites are higher than those of syenogranites but lower than those of the Tuoge Complex. Generally, all the samples are enriched in large ion lithophile elements (LILE, e.g., K, Ba and Rb) but depleted in high field strength elements (HFSE, e.g., Ti, P, Nb, Ta and U) (Fig. 7a), and thus show distribution patterns resembling volcanic-arc rocks. We suggest that Ba was elevated by either K-feldspar or biotite accumulation or, along with Rb and K, during hydrothermal alteration.

The chondrite-normalised REE patterns (Fig. 7b) for the granodiorites and the Tuoge Complex have weak to moderate negative Eu anomalies (Eu/Eu* = 0.64–0.96, calculation method in Tab. 2), whereas the syenogranites show weak negative to moderately positive Eu anomalies (Eu/Eu* = 0.90–3.80). Nevertheless, most samples share similar chondrite-normalised REE patterns enriched in LREE over HREE (Fig. 7b).

5.4. In situ zircon Hf isotopic compositions

The zircons of both groups were analysed for their Lu–Hf isotopic compositions on the dated domains (Fig. 3), and the data are presented in Tab. 3 and graphically illustrated in Fig. 8. Table 3 shows that the $^{176}Lu/^{177}Hf$ ratios of all zircons are less than 0.002, which indicates that they accumulated little radiogenic Hf since they formed.

Eleven analyses obtained from the GO zircons yielded rather variable εHf(t) values of –6.69 to –5.03 (Tab. 3),

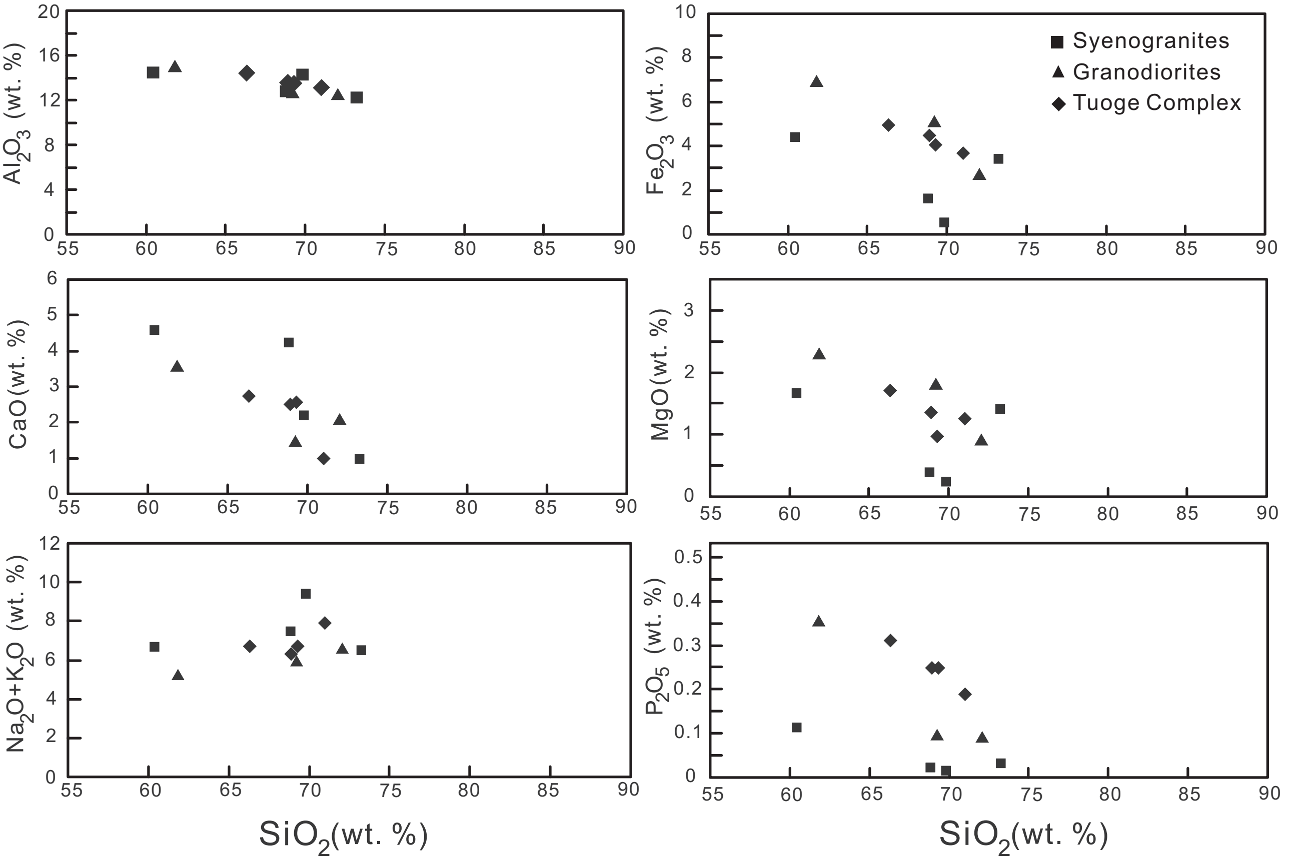


Fig. 6 Harker diagrams for granitoids of the Daxigou and Tuoge complexes.

Tab. 3 Zircon Lu–Hf isotopic compositions for the syenogranite from Daxigou granitoids

Spot	Age (Ma)	$^{176}Hf/^{177}Hf$	1σ	$^{176}Lu/^{177}Hf$	1σ	$^{176}Yb/^{177}Hf$	1σ	εHf(0)	$f_{Lu/Hf}$	εHf(t)	T_{DM1}	T_{DM2}
GO-01	1849	0.281492	0.000014	0.000886	0.000011	0.030306	0.000169	–45.25	–0.97	–5.14	2.45	2.69
GO-02	1834	0.281442	0.000011	0.000418	0.000002	0.013939	0.000137	–47.04	–0.99	–6.69	2.49	2.76
GO-03	1829	0.281481	0.000012	0.001018	0.000001	0.032573	0.000105	–45.65	–0.97	–6.14	2.48	2.73
GO-04	1821	0.281455	0.000013	0.000475	0.000002	0.015776	0.000033	–46.58	–0.99	–6.58	2.48	2.75
GO-05	1834	0.281488	0.000012	0.001045	0.000001	0.034317	0.000117	–45.40	–0.97	–5.82	2.47	2.72
GO-06	1830	0.281471	0.000013	0.000655	0.000001	0.022488	0.000080	–46.02	–0.98	–6.04	2.47	2.73
GO-07	1799	0.281465	0.000011	0.000366	0.000004	0.012501	0.000192	–46.21	–0.99	–6.57	2.46	2.73
GO-08	1813	0.281475	0.000010	0.000917	0.000004	0.031709	0.000227	–45.88	–0.97	–6.61	2.48	2.74
GO-09	1824	0.281474	0.000011	0.000571	0.000001	0.019712	0.000086	–45.92	–0.98	–5.97	2.46	2.72
GO-10	1869	0.281478	0.000014	0.000751	0.000003	0.027590	0.000050	–45.76	–0.98	–5.03	2.46	2.70
GO-11	1827	0.281466	0.000012	0.000581	0.000001	0.020215	0.000065	–46.19	–0.98	–6.18	2.47	2.73
GT-01	1774	0.281503	0.000013	0.001312	0.000002	0.041417	0.000174	–44.87	–0.96	–6.92	2.47	2.73
GT-02	1792	0.281486	0.000011	0.001004	0.000004	0.033979	0.000182	–45.48	–0.97	–6.77	2.47	2.74
GT-03	1820	0.281487	0.000013	0.000882	0.000001	0.030499	0.000060	–45.44	–0.97	–5.96	2.46	2.71
GT-04	1796	0.281465	0.000012	0.000601	0.000004	0.020357	0.000114	–46.21	–0.98	–6.93	2.47	2.75
GT-05	1776	0.281509	0.000011	0.001669	0.000002	0.055547	0.000179	–44.66	–0.95	–7.10	2.48	2.74
GT-06	1828	0.281456	0.000010	0.000591	0.000001	0.020237	0.000052	–46.52	–0.98	–6.51	2.48	2.75
GT-07	1835	0.281455	0.000010	0.000739	0.000001	0.025285	0.000078	–46.56	–0.98	–6.58	2.49	2.76
GT-08	1770	0.281514	0.000011	0.001752	0.000003	0.059155	0.000161	–44.50	–0.95	–7.16	2.48	2.74

GO = group one; GT = group two. $\varepsilon_{Hf}(t) = \{[(^{176}Hf/^{177}Hf)_s - (^{176}Lu/^{177}Hf)_s \times (e^{\lambda t} - 1)]/[(^{176}Hf/^{177}Hf)_{CHUR,0} - (^{176}Lu/^{177}Hf)_{CHUR} \times (e^{\lambda t} - 1)] - 1\} \times 10000$; s = sample, $(^{176}Hf/^{177}Hf)_{CHUR,0} = 0.282772$, $(^{176}Lu/^{177}Hf)_{CHUR} = 0.0332$, $(^{176}Hf/^{177}Hf)_{DM} = 0.28325$, $(^{176}Lu/^{177}Hf)_{DM} = 0.0384$ (according to Blichert-Toft and Albarède 1997; Griffin et al. 2000), t = the crystallization age of zircon, $\lambda = 1.867 \times 10^{-11}$ a^{-1} (Söderlund et al. 2004), $(^{176}Lu/^{177}Hf)_C = 0.015$, S and DM are the upper continental crust, the sample and the depleted mantle, respectively.

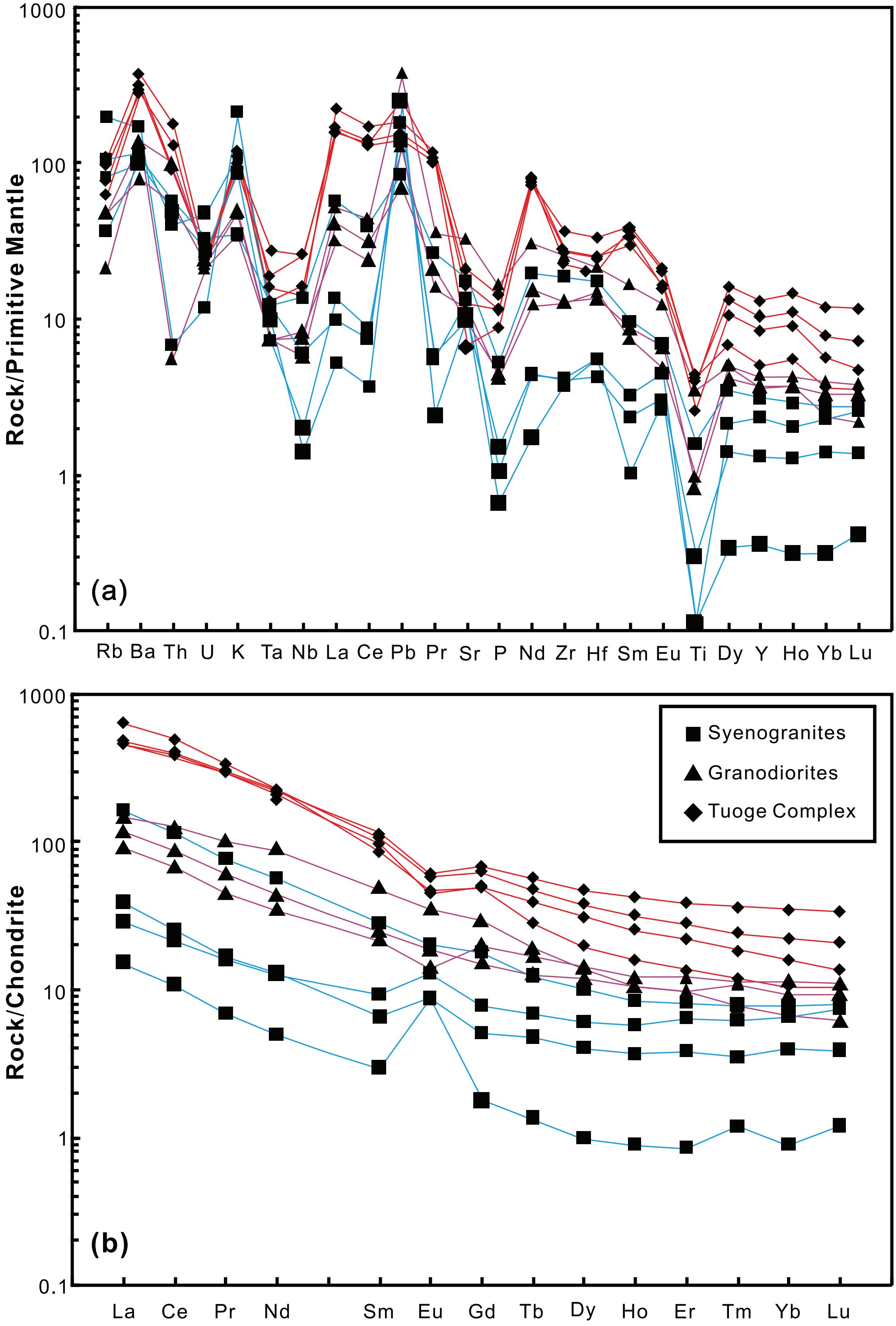


Fig. 7 Primitive mantle-normalized trace-element patterns (**a**) and chondrite-normalized REE patterns (**b**) for the Daxigou granitoids and Tuoge Complex. Normalization data are from Sun and McDonough (1989).

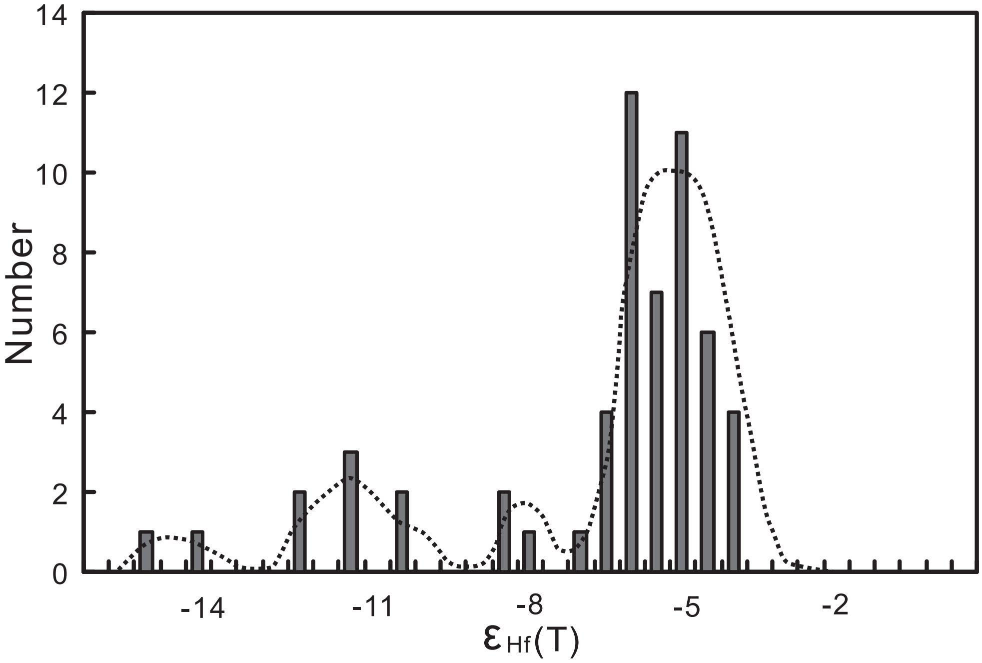


Fig. 8 Frequency histogram of εHf(t) values for zircons of the syenogranite (SG-2).

nearly constant one-stage model ages of 2.45–2.49 Ga and two-stage model ages of 2.69–2.76 Ga. Eight spot analyses for the GT zircons gave εHf(t) values of –7.16 to –5.96, similar one-stage model ages (2.46–2.49 Ga) and two-stage model ages (2.71–2.76 Ga).

Taken together, the studied zircons show a single distribution in εHf(t) values (Fig. 8) with an average of –6.35 (Tab. 3). The Archaean Hf model ages indicate that the studied rocks may have originated from the melting of the Archaean rocks (e.g., TTG) (Fig. 9).

6. Discussion

6.1. Geochemical character, age and likely petrogenesis

As stated above, most samples from the Daxigou granitoids exhibit the mineralogical and geochemical characteristics of I-type granites. Most samples belong to the calc-alkaline series, are fairly rich in SiO_2, Na_2O (Na_2O/K_2O > 1 by weight) and have a metaluminous to subaluminous composition. The MgO (0.24–1.66 wt. %) concentrations are obviously lower than those in the average upper crust (2.48 wt. %; Rudnick and Gao 2003), and this precludes their derivation directly from the mantle. Furthermore, the relatively high alkalis suggest the presence of feldspars and/or biotite in the source (Jiang et al. 2005; Zhao XF et al. 2008). The high LREE/HREE ratios, high Sr contents and Sr/Y ratios, low Yb and Y contents and HFSE (Nb, Ta, P and Ti) depletion indicate that the Daxigou granitoids were likely generated at great depths, with garnet ± apatite, zircon, ilmenite or rutile as the main residual phases. In addition, their low initial εHf(t) values (−7.16 to −5.03, Tab. 3) reveal a continental crustal source. Older Paleoproterozoic rocks (e.g., the Xingditage Complex) can be ruled out as a source on the basis of geochemistry (low SiO_2) and isotopic characteristics (positive εHf(t): Long et al. 2010). A plausible source would represent Archaean rocks, exposed to the west of the Kuluketage Block, e.g., in the Tuoge Complex (2.65–2.75 Ga, Long et al. 2011a). Indeed, the T_{DM2} Hf model ages of the Daxigou granitoids and those for the Tuoge Complex are comparable.

In the Nb–Y diagram (Fig. 10a), all of the Daxigou granitoids fall in the field of the volcanic-arc or syn-collisional granites. However, in the Rb–(Yb + Nb) diagram (Fig. 10b), almost all of the data plot in the volcanic-arc field. As further evidence, all samples are depleted in Nb, which is typical of granitoids with arc affinity (e.g., Pearce et al. 1984) (Fig. 7b). In all, the combination of field investigations, whole-rock geochemical data, U–Pb ages and zircon Hf isotope data imply that the Daxigou granitoids represent the continental-arc I-type granites, which may have originated by remelting of the TTG (Tuoge Complex) materials.

6.2. Tectonic implications

The age and petrogenesis of the host granitoids have been one of main problems since the discovery of the Daxigou iron–phosphate deposit in the Kuluketage Block. We interpret the newly obtained age of 1830 ± 12 Ma in terms of Paleoproterozoic crystallization of the Daxigou

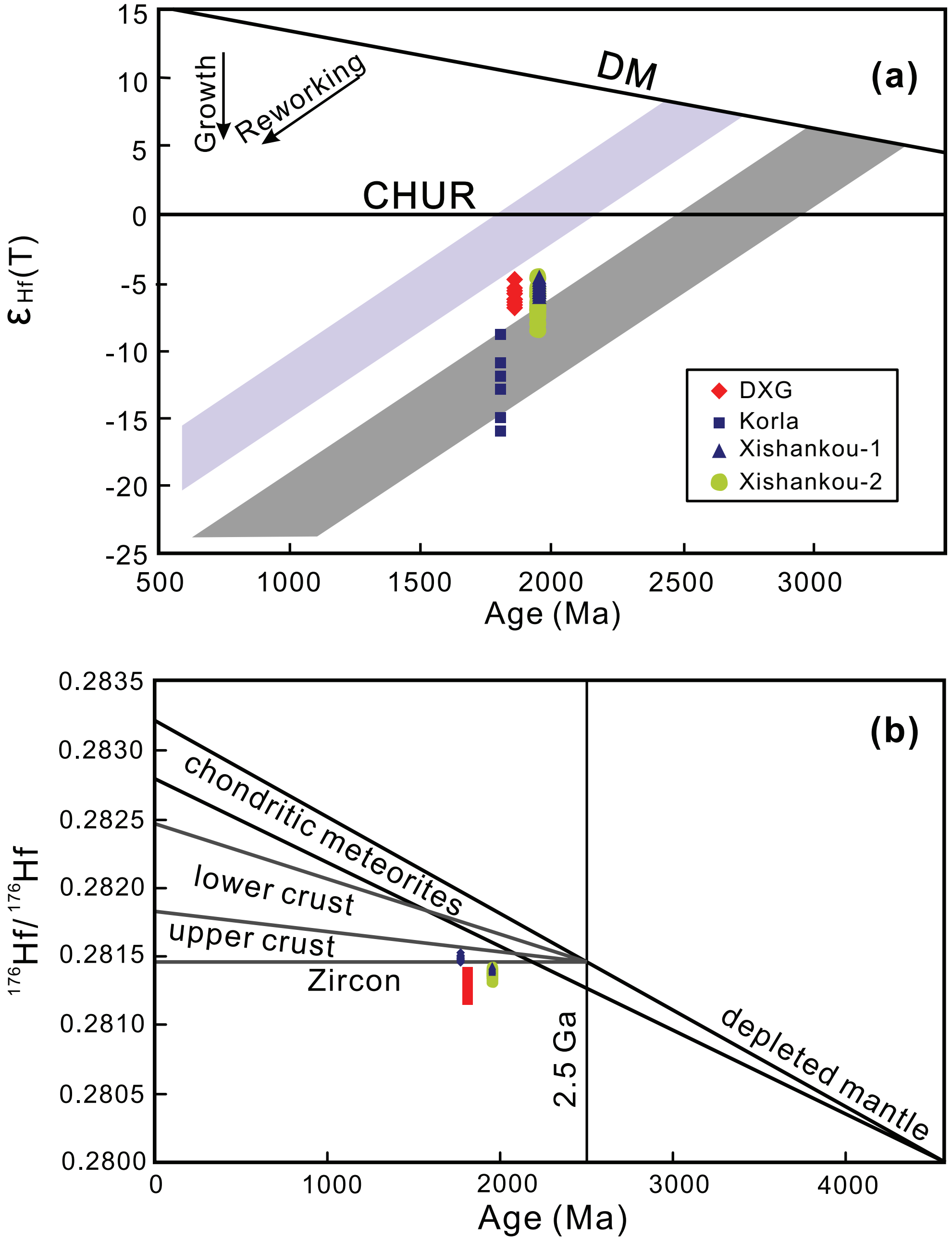


Fig. 9 Diagram of εHf(t)–age (**a**) and (^{176}Hf/^{177}Hf) ratios–age (**b**) for the syenogranite and related occurrences in the northern Tarim Craton. The purple and gray field in Fig. 9a represent the Neoarchaean and Mesoarchaean accretion--transformation, respectively. ^{207}Pb/^{235}U ages and εHf(t) values for the Korla Gneiss are from Long et al. (2010) and for the Xishankou-1 and Xishankou-2 (a Paleoproterozoic granitoid in Kuluketage Block) are from (Lei et al. 2012). DXG = Daxigou syenogranite. The data for the development of the main reservoirs are from Long et al. (2010).

granitoids. The zoning and chemistry of the dated zircons indicate their magmatic origin.

A series of high-precision ages of Tarim Craton basement rocks show that they have mainly experienced two major geological events: about 0.8–1.0 Ga (Zhu et al. 2008; Zhang et al. 2011; Cao et al. 2012) and 2.3–2.8 Ga (Zhang et al. 2012b; Zhang et al. 2013). However, our study indicates that the 1.8–2.0 Ga plutonism may have been important. In addition, the Mesoproterozoic Yangjibulake Group in Kuluketage, which shows effects of greenschist-facies metamorphism, unconformably overlies the Xinditage Group (Zhang et al. 2012a). Therefore, deducing an important tectonic event at the end of the Paleoproterozoic seems reasonable.

Some 1.9–1.8 Ga ages were recently documented at the margins of the Tarim Craton. However, most of these were ascribed to a metamorphic event (Zhang et al. 2012b). For instance, Wu HL et al. (2012) identified the existence of a 1.85 Ga metamorphic age peak from four metasedimentary rocks in Korla; Zhang et al. (2007b) described a *c.* 1.9 Ga metamorphic record from the Archaean gneiss and K-feldspar granite in southwestern Tarim and Zhang et al. documented *c.* 1.85–1.80 Ga metamorphic ages from Archaean TTG rocks and the

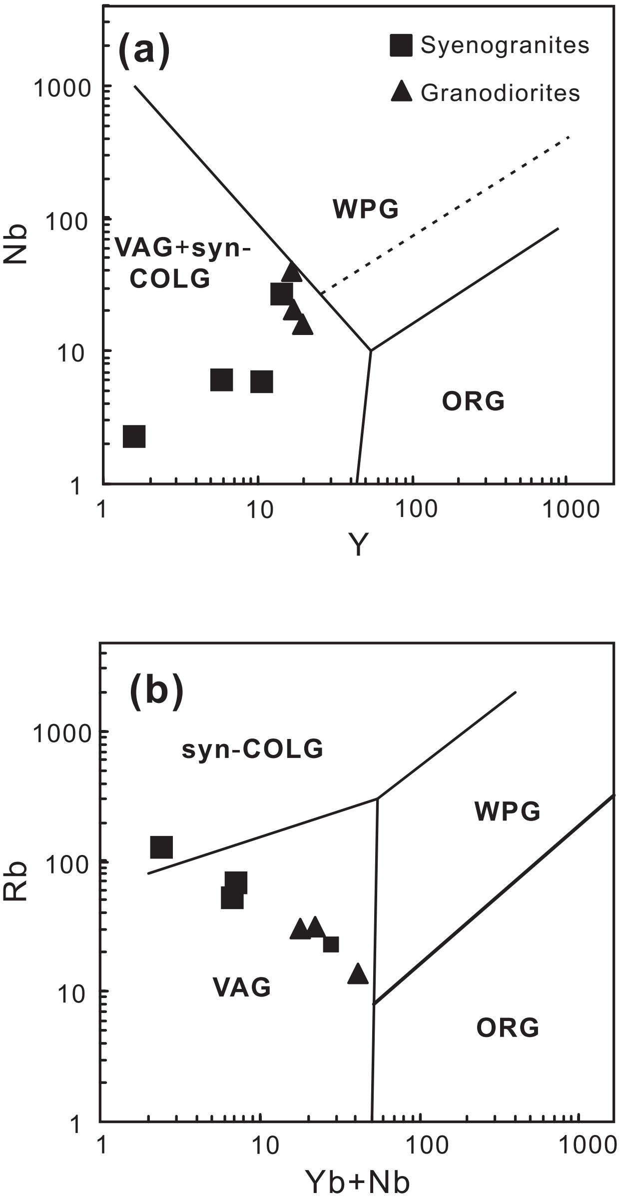


Fig. 10 Granite discrimination diagrams after Pearce et al. (1984): Nb–Y (**a**) and Rb–(Yb + Nb) (**b**). VAG: Volcanic Arc Granite; ORG: Ocean Ridge Granite; WPG: Within-Plate Granite; Syn-COLG: Syn--Collisional Granite; POG: Post-Collisional granite.

Paleoproterozoic metamorphic belt around Kuluketage (Zhang et al. 2012a).

Moreover, we have noticed that some tectono-magmatic events occurred there at 1.9–1.8 Ga, related to the assembly of Columbia Supercontinent. For instance, Zhang et al. (2007a) identified a 1987 ± 20 Ma inherited component in zircon grains from granodiorite north of Xingdi. Deng et al. (2008) obtained an age of 1916 ± 36 Ma by LA-ICP-MS zircon U–Pb dating of several inherited zircons from a gabbro in the Xingdi Valley of Kuluketage and Cao et al. (2010) an age of 1886 ± 61 Ma by LA-ICP-MS zircon U–Pb dating of several inherited zircon grains from Neoproterozoic K-feldspar granite of Dapingliang plutons. Recently, two igneous crystallization ages of 1934 ± 13 and 1944 ± 19 Ma from quartz diorite and granodiorite were obtained west of Kuluketage (Lei et al. 2012). However, the same authors stated that these zircons may have undergone high-temperature metamorphism, considering the nearly identical ages of the cores and metamorphic rims as well as their similar εHf(t) values. We can also see from the above ages that almost all of the zircons are either documented as metamorphic or inherited. In the current study, the 1830 ± 12 Ma age for the Daxigou syenogranite is thus the first reliable crystallization age of the Paleoproterozoic intrusive rocks in the Kuluketage Block.

Based on the above information, we infer an occurrence of an important Paleoproterozoic (*c.* 2.0–1.8 Ga) tectonometamorphic and magmatic event in the Tarim Block. Late Paleoproterozoic collisional orogenic events have been increasingly recognised in Precambrian cratons worldwide and may have ultimately resulted in the formation of the Columbia Supercontinent (e.g., Rogers and Santosh 2002; Zhao GC et al. 2002, 2004; Santosh et al. 2007; Zhao GC et al. 2009; Chen and Xing 2013). Therefore, the Paleoproterozoic (*c.* 1.8–1.9 Ga) tectono-magmatic events documented in this study indicate that the Tarim Craton may have taken part in the assembly of the Columbia Supercontinent as well. Voluminous I-type granitic plutons have been traditionally considered to form at active continental margins related to oceanic crust subduction (Wilson 1989). Because our zircon dating yielded late Paleoproterozoic crystallization ages, a continental arc-type setting is suggested for the northern Tarim at *c.* 1830 Ma. However, obtaining detailed information about the subduction zone, e.g., its polarity and location of the ocean is currently a challenge because of scarce information on the Kuluketage Block. Much more work is required to reconstruct the plate tectonic history in the Tarim Craton.

7. Conclusions

We can draw the following conclusions from our new field, zircon U–Pb ages and geochemical data:

1. LA–ICP-MS U–Pb zircon dating indicates that the emplacement and alteration of the Daxigou syenogranite occurred at 1830 ± 12 Ma and 1798 ± 21 Ma, respectively. This is the first record of a late Paleoproterozoic to early Mesoproterozoic magmatic event in the Kuluketage area.
2. Based on a combination of field investigations and petrographic, geochronological and geochemical evidence, we suggest that Daxigou granitoids belong to Paleoproterozoic continental-arc I-type granites, which may have originated by melting of Neoarchaean TTG (Tuoge Complex) materials.

3. The available data, together with previous studies, demonstrate that a Paleoproterozoic (*c.* 2.0–1.8 Ga) tectono-magmatic event occurred in the Kuluketage Block. We suggest a continental arc-type tectonic setting in the Kuluketage Block at late Paleoproterozoic times (*c.* 1830 Ma). The Tarim Craton may have participated in the assembly of the Columbia Supercontinent.

Acknowledgements. This paper benefited from an insightful and helpful review of Editor-in-chief Vojtěch Janoušek. We also acknowledge Milan Kohút for careful editing and valuable comments to the revised manuscript. Critical and constructive comments by two anonymous reviewers were of great help in improving the manuscript. We are grateful to Zheng Han, Hu Zhao-chu and Tang Wen-xiu of the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, for their assistance in LA-ICP-MS and Hf isotope determinations. All thanks go to Shi Ran for her assistance during the experiments. Geology engineer Xi Guo-qing is acknowledged for leading the field work. This research was founded by the 305 Project of State Science and Technology Support Program (Grant No. 2011BAB06B04-05) as well as the China Postdoctoral Science Foundation projects (Grant No. 2012M521492 and 2013T60758).

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