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# Growth and evolution of Precambrian continental crust in the southwestern Tarim terrane: New evidence from the ca. 1.4 Ga A-type granites and Paleoproterozoic intrusive complex

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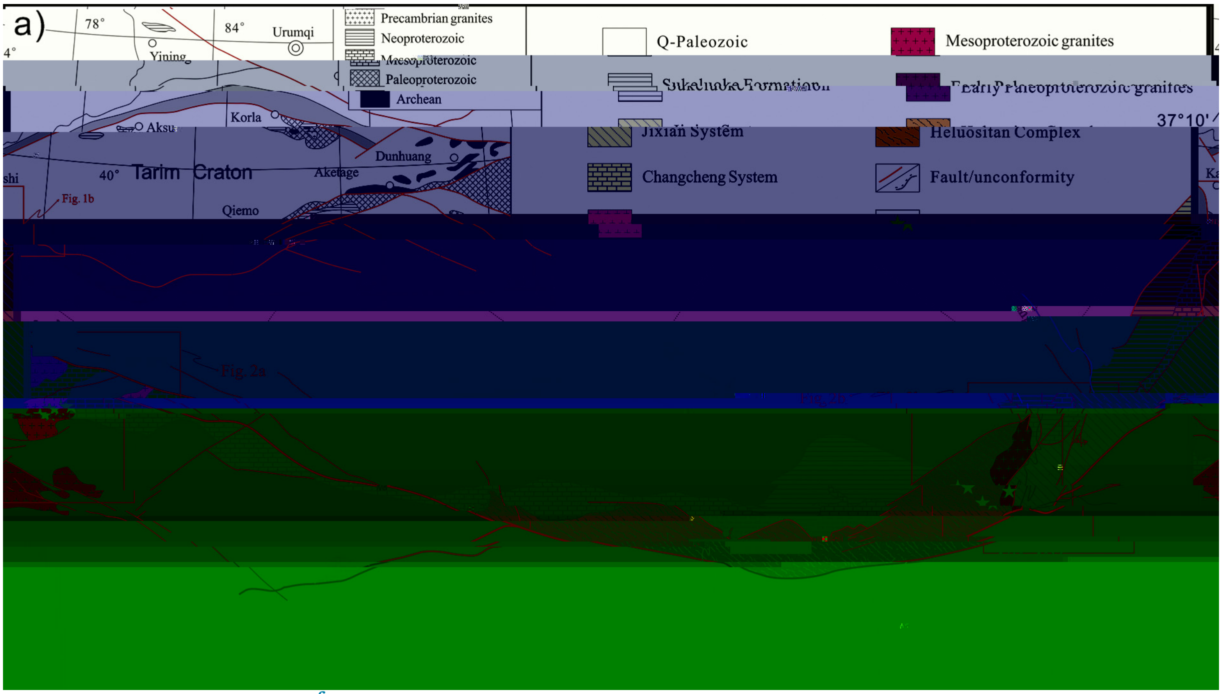


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**Fig. 1.** (a) Tectonic framework of the Tarim Craton and its marginal area showing the Precambrian terranes along its margin. (b) Precambrian geology in the southwestern section of the Tarim Craton (modified after HNGS, 2004a,b).

corresponding to the assembly and breakup of the supercontinent Rodinia (Zhang et al., 2006a,b, 2010). However, despite the availability of some geochronological and geochemical data have been reported (Wang et al., 2014; Zhang et al., 2007a), continental growth processes and tectonic evolution are poorly understood.

In this contribution, we present detailed field observations, petrography, zircon U–Pb ages and Hf–O isotopes, whole-rock major and trace element geochemistry, and Sr–Nd isotopes of the Azibailedi A-type granites (ferroan granites) in the southwestern margin of Tarim Craton. We also report zircon U–Pb ages and Hf isotopes of the early Paleoproterozoic Heluositan intrusive complex, zircoeswhich findings, in combination with those from previous investigations provide new insights into: (1) the petrogenesis of the 1.4 Ga Azibailedi A-type granites, and their implications on the history of breakup of the Columbia supercontinent; (2) the Precambrian tectonic evolution and continental crustal growth and (3) the architecture of the early Precambrian basement of the Tarim Craton.

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## 2. Regional geology

The Tarim Craton is bound by the Tianshan, Western Kunlun and Central-Southern Altyn-Tagh mountain belts to the north, south and southeast, respectively (Fig. 1a) (Lu et al., 2008; Zhang et al., 2013a). The craton shows typical double-layered structure consisting of a Precambrian basement (pre-Neoproterozoic) and late Neoproterozoic to Cambrian cover series (Xinjiang BGMR, 1993; Feng et al., 1995). The Precambrian rocks in the Tarim Craton are mostly exposed along the northern, eastern and southwestern margins.

The Precambrian basement rocks of the Quruqtagh-Dunhuang area are composed of orthogneisses (tonalite-trondhjemite-granodiorite; TTG), amphibolite and metasedimentary rocks. Previous studies indicated that the TTG rocks were mainly emplaced at ca. 2.7–2.5 Ga. Metamorphism main at ca. 1.85–1.80 Ga has been identified in both Archean and the Paleoproterozoic paragneisses (Ge et al., 2014; Zhang et al., 2013b) and the Paleoproterozoic metamorphism has been correlated to the assembly of the Columbia supercontinent (Ge et al., 2013a; Zhang et al., 2012a, 2013b; Lei et al., 2012). A recent study on 1470 Ma metadiabase from this region correlates with the breakup of the Columbia supercontinent (Wu et al., 2014). In the Aketage area, Paleoproterozoic metamorphic events are recorded by the Archean Milan Group, mostly composed of TTG rocks, hypersthene granulite, and mafic granulite, metamorphosed at ∼2.0 Ga (Zhang et al., 2014a), followed by 1.85 Ga post-orogenic extension represented by OIB-like mafic dykes and massive potassic granites (Lu et al., 2008; Zhang et al., 2014a). Detrital zircon U–Pb dating and field mapping indicate the absence of Archean basement in the Akesu area (Fig. 1a) (Xinjiang BGMR, 1993; Zhang et from

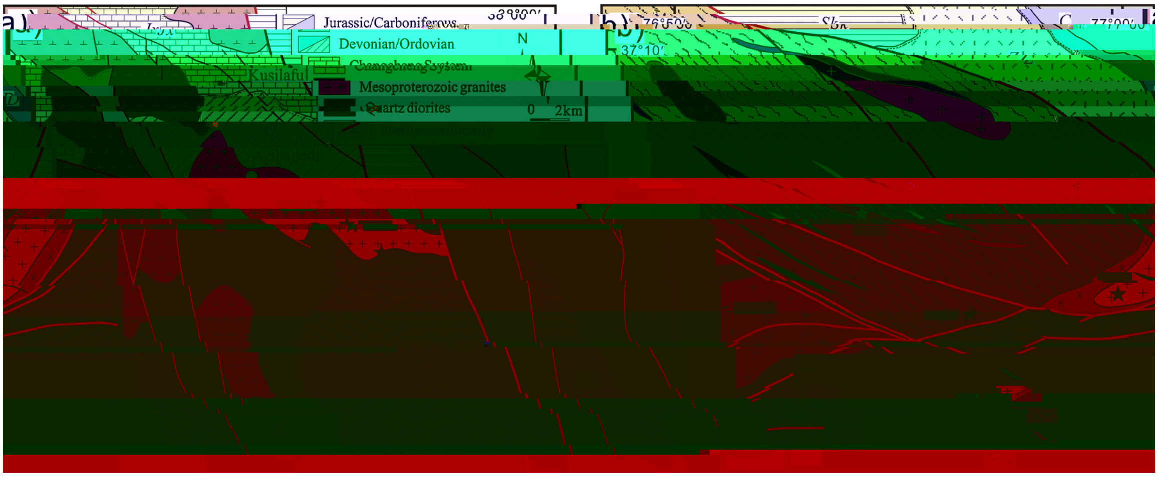


**Fig. 2.** (a) Geological map of the Azibailedi pluton. (b) Geological map of the Akazi pluton and amphibolites from the Heluositan Complex. The number and the star symbol show the sample number and the sampling locality.

of the Aketao County (Fig. 2a). These rocks were first reported in the STT by Huang et al. (2012). However, their petrogenesis and tectonics need further discussion.

## 3. Petrography

### 3.1. Azibailedi A-type granites

The Azibailedi pluton is located in the north-western section of the STT (Fig. 1b) with an outcrop area covering 12 $km^2$. The pluton intruded Mesoproterozoic carbonate rocks of the Changcheng system. The Changcheng system was unconformably covered by Ordovician-Carboniferous sandstone and conglomerate (Fig. 2a). Migmatite developed along the margin of the Azibailedi pluton. The Changcheng System carbonate rocks were extensively invaded by high temperature granitic melts, and therefore the zircon growth in the migmatite and granite occurred coevally. The migmatite shows banded structure and is mainly comprised quartz and feldspar phenocrysts set within a felsic matrix with minor carbonate minerals (Fig. 3a and g). The Azibailedi pluton is relatively homogeneous with the main rock type being biotite monzogranite. The rock shows grayish color and of gneissic structure (Fig. 3b and c), with medium to coarse granitic texture. The mineralogy is defined by K-feldspar (30–45%), plagioclase (25–35%), quartz (25–30%), biotite (5–7%), hornblende (less than 2%) with accessory minerals such as zircon, titanite and monazite (Fig. 3h). Recrystallized quartz and biotite suggest metamorphism and/or deformation after emplacement (Fig. 3i).

### 3.2. The granitic rocks and amphibolites from Heluositan Complex

The petrography of Akazi pluton has been described in detail by Zhang et al. (2007a) and Wang et al. (2014). The main rock types are pinkish granodiorite and quartz monzonite (Fig. 2b) showing medium to coarse texture and gneissic structure. The presence of remelting textures indicates that the rocks witnessed post-emplacement metamorphism, as is also evident from the core-rim structure of the zircons grains from this pluton (Zhang et al., 2007a).

The gneissic granites are quartz monzonite (Fig. 2b) which display medium to coarse-grained texture and strong gneissic structure (Fig. 3d–f). The dominant minerals are plagioclase (30–40%), K-feldspar (25–35%), Quartz (25–30%), biotite (5–7%), hornblende (2–5%) together with accessory minerals such as apatite and zircon.

An amphibolite dyke of about 3 km in length and 200–300 m width intrudes the Heluositan granitic gneiss (Fig. 2b). The rock is medium to coarse grained, dark in color and shows gneissic structure. It is dominantly composed of hornblende (50–60%), plagioclase (30–40%), biotite (2–5%) and minor pyroxene (1–2%) (Fig. 3j–l). Apatite and Ti–Fe oxide occur as accessory minerals. The mineral assemblage suggests mafic protolith.

## 4. Analytical methods

Zircon separation was carried out using conventional heavy liquid and magnetic techniques. Zircon grains and zircon standards were then hand-picked under a binocular microscope and representative grains and zircon standards were mounted in an epoxy resin disk, and then polished to about half their thickness. Zircons were photographed under transmitted and reflected light and their cathodoluminescence

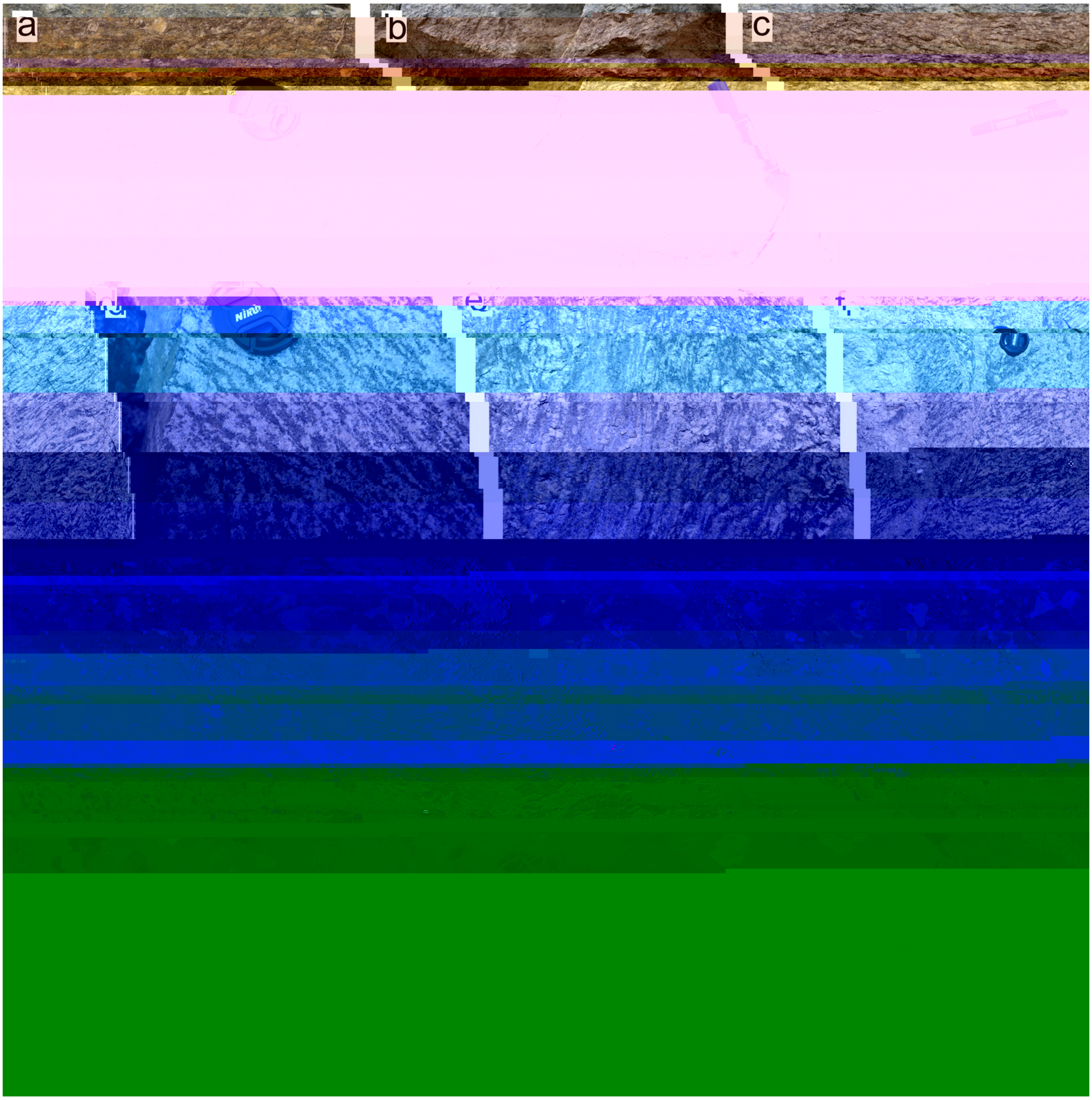


**Fig. 3.** Representative field photographs and photomicrographs of migmatite and granites from the Azibailedi pluton. (a) The banded migmatite is composed of quartz and feldspar phenocrysts. (b, c) The biotite monzogranites show gneissic textures. (d–f) The granites show medium to coarse granitic and strong gneissic structures. (g) The mineral assemblage of the migmatite (parallel nicols). (h–i) The recrystallization of quartz and biotite possibly represent metamorphic effect (crossed nicols). (j) The mineral assemblage of the amphibolites from the Heluositan Complex (crossed nicols). (k, l) Relict clinopyroxene in amphibolites (crossed nicols). *Abbreviations*: Cal, carbonate; Kfs, K-feldspar; Pl, plagioclase; Bi, biotite; Q, quartz; Hb, hornblende; Cpx, clinopyroxene.

within errors with the reported value of 5.4 ± 0.2‰ (Li et al., 2013). Zircon oxygen isotopic data are listed in Supplementary Table 3.

Major elements were measured by Rigaku ZSX100e X-ray fluorescence spectrometer (XRF) at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (CAS). Whole rock samples were crushed and powdered to less than 200 mesh in an agate mill, and

**Table 1**
Geochemical compositions of the Azibailedi granite pluton.

| Sample | 13TR02H1 | 13TR02H2 | 13TR02H3 | 13TR02H4 | 13TR02H5 | 13TR02H6 | 13TR02H7 | 13TR03H1 | 13TR03H2 | 13TR03H3 | 13TR03H5 | 13TR03H6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Major elements (%)* | | | | | | | | | | | | |
| $SiO_2$ | 74.0 | 75.1 | 72.8 | 73.2 | 73.3 | 73.6 | 74.4 | 73.1 | 73.7 | 75.1 | 73.5 | 74.2 |
| $TiO_2$ | 0.34 | 0.27 | 0.35 | 0.30 | 0.39 | 0.27 | 0.32 | 0.31 | 0.32 | 0.30 | 0.27 | 0.31 |
| $Al_2O_3$ | 15.9 | 12.0 | 12.4 | 12.0 | 12.4 | 11.1 | 12.3 | 12.0 | 12.4 | 12.2 | 12.3 | 11.8 |
| $Fe_2O_3^T$ | 2.41 | 2.42 | 2.97 | 2.32 | 2.89 | 2.90 | 2.78 | 2.46 | 2.67 | 2.09 | 2.31 | 2.73 |
| MnO | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 | 0.04 | 0.05 | 0.03 | 0.04 | 0.04 |
| MgO | 0.39 | 0.45 | 0.44 | 0.68 | 0.87 | 0.76 | 0.55 | 0.42 | 0.30 | 0.52 | 0.29 | 0.40 |
| CaO | 1.55 | 0.50 | 0.82 | 0.43 | 0.20 | 0.53 | 0.31 | 0.60 | 0.87 | 0.42 | 0.91 | 0.82 |
| $Na_2O$ | 2.11 | 2.47 | 2.00 | 3.74 | 2.67 | 2.44 | 2.17 | 4.08 | 2.72 | 2.82 | 3.01 | 2.14 |
| $K_2O$ | 5.65 | 5.45 | 6.22 | 5.92 | 5.92 | 6.56 | 6.02 | 5.68 | 5.52 | 5.40 | 5.67 | 5.98 |
| $P_2O_5$ | 0.05 | 0.04 | 0.05 | 0.05 | 0.07 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| LOI | 1.00 | 0.96 | 1.51 | 1.04 | 0.80 | 1.41 | 0.79 | 0.97 | 1.07 | 0.68 | 1.25 | 1.22 |
| Total | 103.4 | 99.7 | 99.7 | 99.7 | 99.6 | 99.7 | 99.7 | 99.7 | 99.7 | 99.7 | 99.7 | 99.7 |
| A/CNK | 1.28 | 1.10 | 1.08 | 0.90 | 1.11 | 0.92 | 1.15 | 0.86 | 1.03 | 1.09 | 0.97 | 1.03 |
| *Trace elements (ppm)* | | | | | | | | | | | | |
| Sc | 11.8 | 10.8 | 13.2 | 9.81 | 11.3 | 10.4 | 12.5 | 12.7 | 12.1 | 11.7 | 10.7 | 11.8 |
| V | 11.3 | 8.48 | 10.1 | 10.5 | 12.6 | 9.37 | 9.05 | 9.43 | 9.07 | 7.26 | 8.37 | 8.75 |
| Cr | 4.91 | 4.24 | 4.45 | 3.88 | 5.59 | 3.95 | 4.98 | 3.57 | 4.13 | 3.43 | 3.60 | 5.46 |
| Co | 1.94 | 1.57 | 1.68 | 1.66 | 1.75 | 1.34 | 1.52 | 1.63 | 1.64 | 0.988 | 1.55 | 1.34 |
| Ni | 3.99 | 3.17 | 1.72 | 1.28 | 2.37 | 1.20 | 1.64 | 1.38 | 1.41 | 1.42 | 1.31 | 1.62 |
| Cu | 3.20 | 3.95 | 10.27 | 3.99 | 3.58 | 2.74 | 4.89 | 12.66 | 6.55 | 3.53 | 8.14 | 3.05 |
| Zn | 50.1 | 52 | 83.4 | 40.7 | 60.1 | 77.2 | 70.2 | 58.6 | 64.2 | 63.5 | 59.5 | 57.8 |
| Ga | 17.4 | 18.3 | 19.5 | 18.0 | 18.8 | 19.8 | 19.5 | 18.0 | 19.6 | 18.0 | 19.2 | 16.7 |
| Rb | 210 | 207 | 240 | 219 | 282 | 316 | 288 | 248 | 226 | 228 | 209 | 257 |
| Sr | 53.1 | 42.4 | 46.1 | 40.8 | 31.4 | 23 | 35.7 | 43.9 | 60.3 | 32.9 | 53.6 | 35.4 |
| Y | 46.4 | 49.1 | 54.1 | 53.1 | 58.7 | 57.4 | 61.5 | 50.8 | 56.9 | 57.8 | 49.1 | 68.4 |
| Zr | 264 | 258 | 301 | 253 | 287 | 225 | 278 | 311 | 265 | 272 | 230 | 292 |
| Nb | 23.9 | 22.7 | 27.9 | 20.6 | 25.6 | 21.5 | 29.0 | 25.1 | 27.2 | 26.8 | 21.1 | 26.1 |
| Cs | 6.25 | 2.22 | 4.48 | 3.01 | 8.11 | 6.24 | 6.65 | 8.60 | 7.36 | 4.64 | 2.81 | 4.26 |
| Ba | 836 | 716 | 887 | 697 | 784 | 866 | 743 | 697 | 799 | 743 | 858 | 907 |
| La | 59.3 | 66.4 | 64.4 | 76.0 | 77.0 | 92.0 | 90.3 | 57.1 | 68.4 | 79.6 | 78.1 | 106 |
| Ce | 120 | 133 | 129 | 156 | 154 | 184 | 182 | 115 | 137 | 162 | 160 | 218 |
| Pr | 13.2 | 14.4 | 14.3 | 16.7 | 16.7 | 19.5 | 19.5 | 12.8 | 14.9 | 17.2 | 17.3 | 22.8 |
| Nd | 49.1 | 52.3 | 53.1 | 60.2 | 60.4 | 69.1 | 69.7 | 48.0 | 54.8 | 62.4 | 62.6 | 83.6 |
| Sm | 8.82 | 9.40 | 9.77 | 11.3 | 10.9 | 11.9 | 12.5 | 9.15 | 9.90 | 11.2 | 11.1 | 14.9 |
| Eu | 0.812 | 0.645 | 0.991 | 0.722 | 0.741 | 1.02 | 0.997 | 0.845 | 0.949 | 0.887 | 0.846 | 1.38 |
| Gd | 8.45 | 8.85 | 9.40 | 10.2 | 10.4 | 10.7 | 10.9 | 8.99 | 9.65 | 10.4 | 9.53 | 13.3 |
| Tb | 1.37 | 1.45 | 1.54 | 1.72 | 1.74 | 1.72 | 1.84 | 1.43 | 1.62 | 1.76 | 1.64 | 2.18 |
| Dy | 7.93 | 8.19 | 8.91 | 9.76 | 10.00 | 9.63 | 10.40 | 8.51 | 9.58 | 10.20 | 9.25 | 12.7 |
| Ho | 1.64 | 1.68 | 1.91 | 1.96 | 2.02 | 1.92 | 2.10 | 1.75 | 2.00 | 2.09 | 1.87 | 2.59 |
| Er | 4.80 | 4.97 | 5.61 | 5.54 | 5.85 | 5.78 | 6.23 | 5.20 | 6.02 | 6.23 | 5.67 | 7.71 |
| Tm | 0.702 | 0.712 | 0.797 | 0.743 | 0.808 | 0.844 | 0.894 | 0.762 | 0.871 | 0.893 | 0.800 | 1.10 |
| Yb | 4.33 | 4.62 | 5.42 | 4.48 | 5.09 | 5.29 | 5.67 | 4.72 | 5.70 | 5.72 | 5.08 | 7.06 |
| Lu | 0.639 | 0.670 | 0.780 | 0.627 | 0.711 | 0.755 | 0.840 | 0.696 | 0.838 | 0.826 | 0.733 | 1.02 |
| Hf | 7.38 | 7.23 | 8.25 | 6.71 | 7.51 | 6.28 | 7.55 | 8.29 | 7.17 | 7.82 | 7.18 | 8.88 |
| Ta | 1.58 | 2.01 | 1.84 | 1.08 | 2.01 | 1.52 | 1.88 | 1.74 | 1.89 | 1.86 | 1.57 | 1.91 |
| Pb | 21.7 | 31.5 | 34.9 | 22.9 | 13.8 | 17.0 | 22.4 | 25.5 | 27.9 | 23.1 | 29.5 | 26.3 |
| Th | 22.8 | 26.0 | 21.6 | 28.4 | 27.3 | 26.0 | 29.1 | 20.4 | 27.3 | 26.6 | 25.7 | 30.7 |
| U | 3.60 | 3.53 | 3.80 | 3.13 | 3.22 | 3.53 | 3.73 | 4.38 | 4.09 | 5.27 | 6.54 | 3.48 |
| $T_{Zr}$ (°C) | 853 | 837 | 847 | 809 | 846 | 802 | 848 | 822 | 830 | 841 | 810 | 840 |

ratios for LRIG and BCR-2 were $^{143}Nd/^{144}Nd = 0.512196 \pm 3\ (2\sigma)$ and $0.512634 \pm 4\ (2\sigma)$, respectively. The analytical results and calculated parameters are listed in Table 2.

## 5. Results

### 5.1. U–Pb zircon geochronology

#### 5.1.1. The Azibailedi pluton (migmatite sample 13TR01: N 37°54.70′, E 76°16.78′; gneissic granite samples 13TR02: N 37°55.31′, E 76°16.15′ and 13TR03: N 37°55.64′, E 76°16.17′)

Zircons from the three samples are prismatic and colorless, with lengths of 100–150 μm and length to width ratios between 1 and 2. In CL images, internal growth zoning is clear in most zircon crystals and no core-rim structure has been observed (Fig. 4). Total 30 analyses from 13TR01 show large range of U and Th concentrations (U = 135–1095 ppm, Th = 57–361 ppm) with Th/U ratios ranging from 0.23 to 0.62 (Supplementary Table 1). The measured $^{206}Pb/^{238}U$ ages are in good agreement within analytical errors, and yield a weighted mean age of 1414 ± 3 Ma (MSWD = 1.7; Fig. 5a). The data from sample 13TR02 yield variable concentrations of U (189–3629 ppm) and Th (86–1923 ppm), with Th/U ratios of 0.26–0.83 (Supplementary Table 1). The data yield a well-defined discordia with upper intercept age of 1405 ± 9 Ma, which is consistent with the weighted mean $^{207}Pb/^{206}Pb$ age of 1405 ± 6 Ma (MSWD = 0.76; Fig. 5b). The features and U, Th contents of sample 13TR03 are similar to those of the sample 13TR02. Due to variable radiogenic Pb loss, most analyses yield discordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages. However, all the analyses define a discordia with an upper intercept age of 1412 ± 12 Ma (MSWD = 3.5; Fig. 5c). Their consistent $^{207}Pb/^{206}Pb$ ages yield a weight mean age of 1401 ± 5 Ma (MSWD = 0.77; Fig. 5c). The ca. 1.4 Ga age obtained from these samples is regarded as the best estimate of the crystallization age of the Azibailedi pluton.

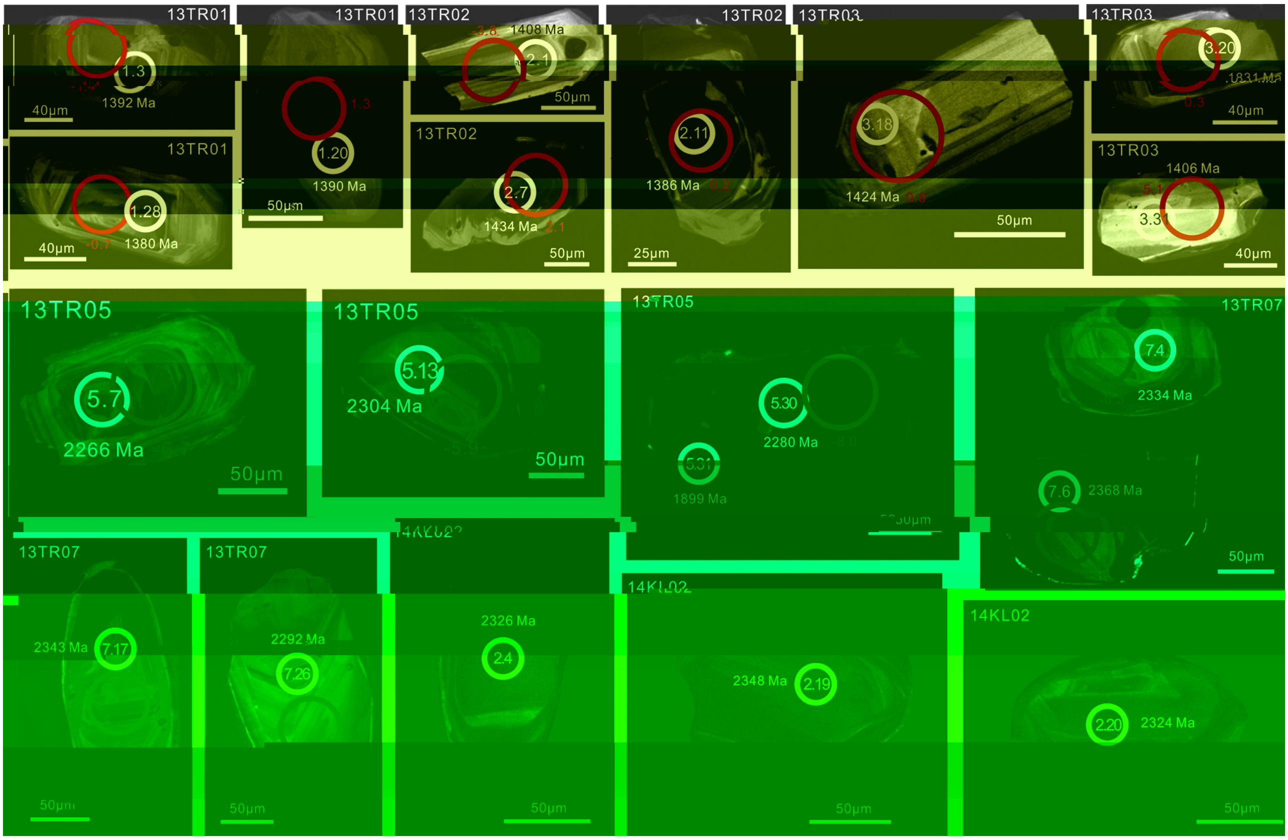


**Fig. 4.** Representative CL images of

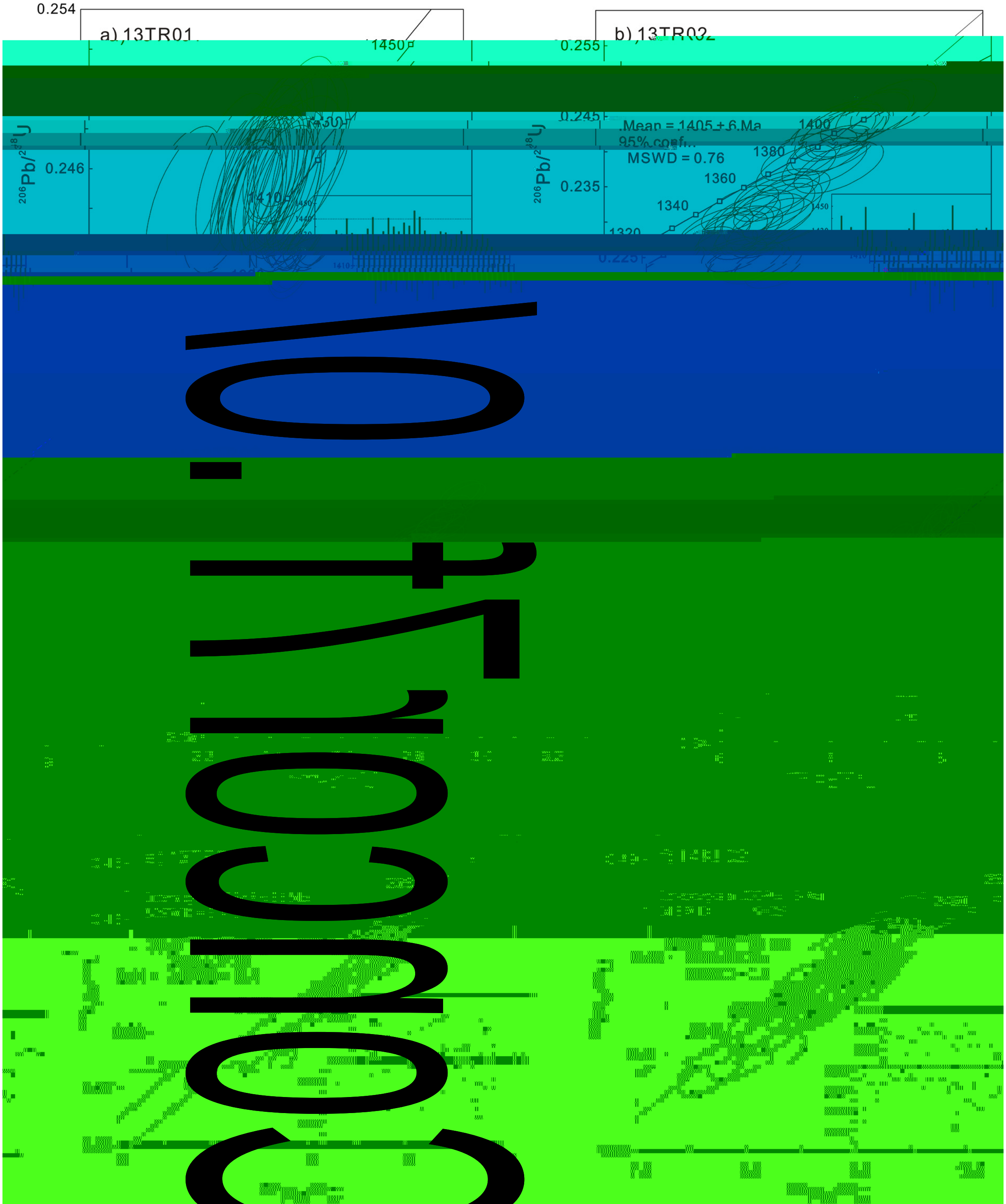


**Fig. 5.** Concordia(/)TjET/GS1gsBT/F21Tf.000200-.00052f.000200-.0002188.3888214.1217Tm()TjET3761006.3761191.776214.1217Tm(Concordia(/)TjET/G

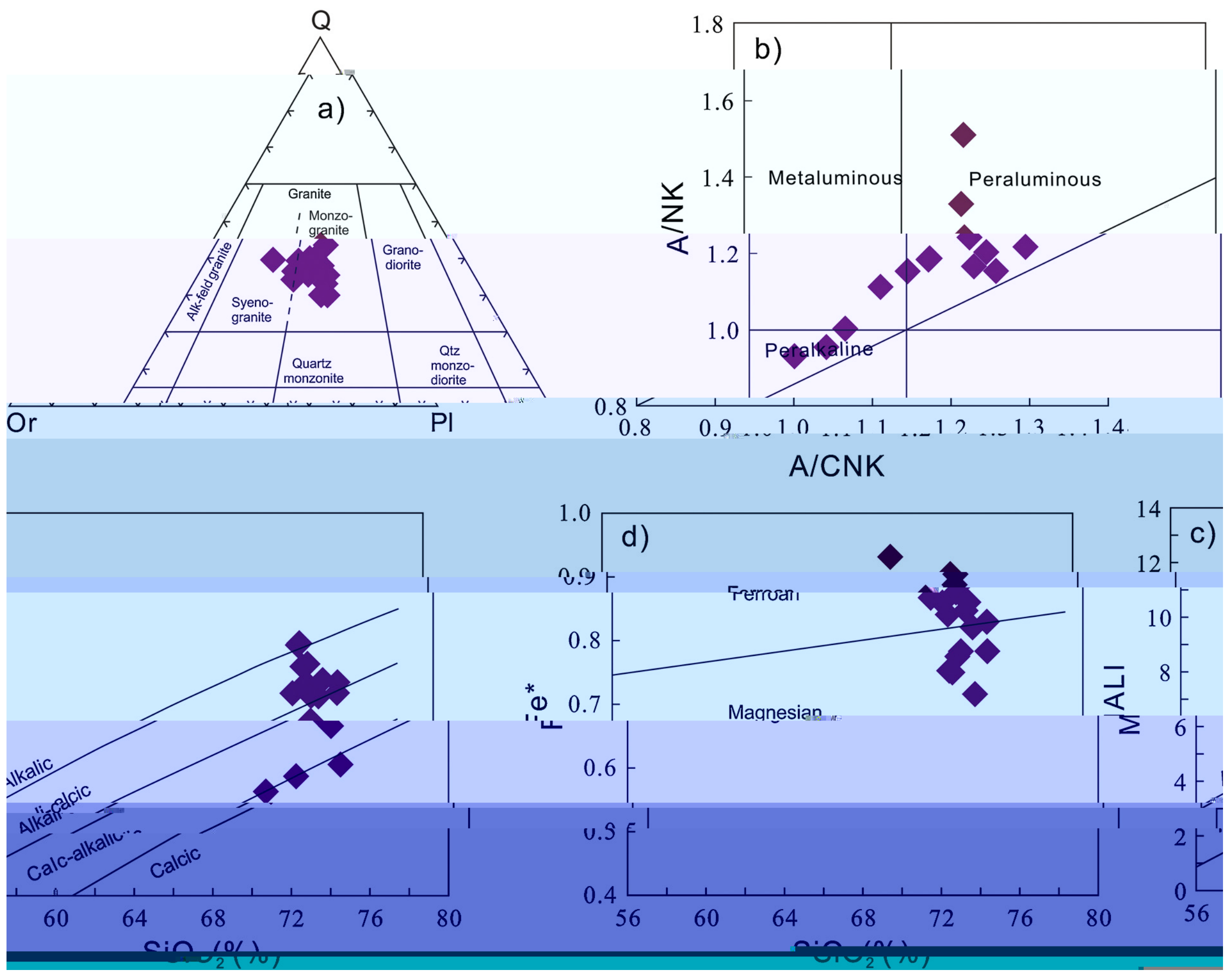


**Fig. 6.** (a) Normalized Q-A-P classification diagram showing the granites from the Azibailedier pluton is monzogranite. (b) A/NK vs. A/CNK plot (Maniar and Piccoli, 1989). (c) MALI vs. $SiO_2$ (%) and (d) Fe* vs. $SiO_2$ (%) plot (Frost et al., 2001; Frost and Frost, 2008). A = $Al_2O_3$, N = $Na_2O$, K = $K_2O$, C = CaO (all in molar proportion); MALI = $Na_2O + K_2O - CaO$ (%); Fe* = $FeO^t/(MgO + FeO^t)$ (%).

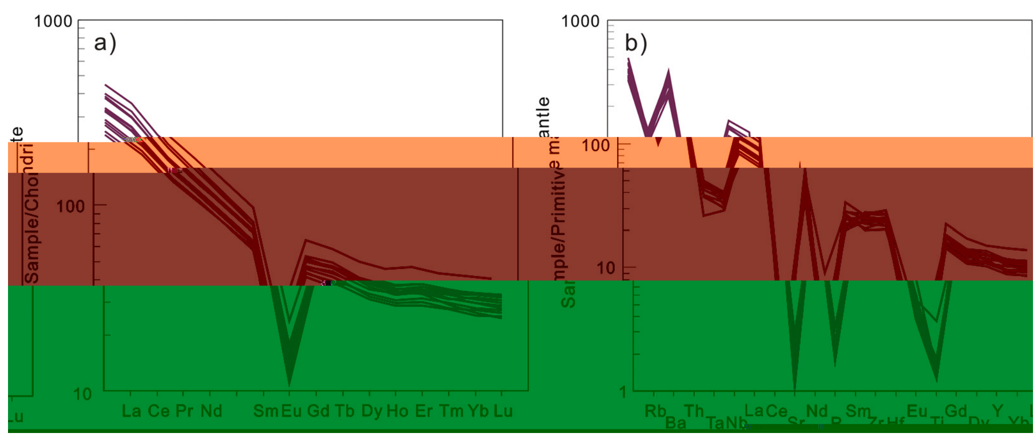


**Fig. 7.** (a) Chondrite-normalized rare earth element (REE) patterns and (b) primitive mantle-normalized trace element spider diagram for Azibailedi A-type granites.

(0.1072–0.1112) and $^{143}Nd/^{144}Nd$ (0.511640–0.511717), corresponding to relatively homogeneous initial $^{143}Nd/^{144}Nd$ ratios (0.510663–0.510719) and $\varepsilon_{Nd}(t)$ values (−3.5 to −2.2) (Fig. 8) and with a restricted range of $T_{DM}{}^{C}$ from 2.26 Ga to 2.38 Ga. Their Rb–Sr isotopic compositions are quite variable with initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.54422 to 0.70303. They show abnormally low $(^{87}Sr/^{86}Sr)_i$ ratios due to their high $^{87}Sr/^{86}Sr$ ratios (up to 11). Thus, the ratios cannot be considered as true initial Sr isotopic compositions (Jahn, 2004; Wu et al., 2002).

### 5.4. Zircon Hf–O isotopes

Almost all the dated zircon grains were also measured for their Lu–Hf isotope compositions and the results are listed in Supplementary Table 2 (the calculation formula and the relevant constant used in calculations are presented in the footnote of this table).

Zircons from the Azibailedi granites have a range of initial $^{176}Hf/^{177}Hf$ ratios (0.281782–0.282187) (Fig. 9a), yielding a large range of $\varepsilon_{Hf}(t)$ values from −4.1 to +6.1 (Fig. 9b) with weight mean

**Table 2**
Sr–Nd isotopic compositions of the granites.

| Sample | Rock type | Rb (ppm) | Sr (ppm) | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ ($2\sigma$) | $(^{87}Sr/^{86}Sr)_i$ | Sm (ppm) | Nd (ppm) | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ ($2\sigma$) | $(^{143}Nd/^{144}Nd)_i$ | $\varepsilon_{Nd}(t)$ | $T_{2DM}$ (Ga) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13TR02H1 | Granite | 210 | 53.1 | 11.69 | 0.926771 (8) | 0.69209 | 8.82 | 49.1 | 0.1086 | 0.511717 (8) | 0.510719 | −2.2 | 2.26 |
| 13TR02H3 | Granite | 240 | 46.1 | 15.40 | 0.936298 (12) | 0.62708 | 9.77 | 53.1 | 0.1112 | 0.511714 (6) | 0.510691 | −2.7 | 2.27 |
| 13TR02H5 | Granite | 282 | 31.4 | 26.72 | 0.997400 (14) | 0.46086 | 10.9 | 60.4 | 0.1091 | 0.511666 (4) | 0.510663 | −3.3 | 2.34 |
| 13TR02H7 | Granite | 288 | 35.7 | 24.10 | 1.039874 (12) | 0.55598 | 12.5 | 69.7 | 0.1084 | 0.511660 (8) | 0.510663 | −3.2 | 2.35 |
| 13TR03H5 | Granite | 209 | 53.6 | 11.53 | 0.934587 (18) | 0.70303 | 11.1 | 62.6 | 0.1072 | 0.511652 (4) | 0.510666 | −3.2 | 2.36 |
| 13TR03H6 | Granite | 257 | 35.4 | 21.56 | 0.977102 (12) | 0.54422 | 14.9 | 83.6 | 0.1077 | 0.511640 (10) | 0.510649 | −3.5 | 2.38 |
| BCR-2 ($n = 2$) | | | | | 0.704966 (6) | | | | | 0.512634 (8) | | | |
| LRIG ($n = 2$) | | | | | | | | | | 0.512196 (6) | | | |
| NBS987 ($n = 3$) | | | | | 0.710219 (10) | | | | | | | | |

Chondrite uniform reservoir (CHUR) values ($^{87}Rb/^{86}Sr = 0.0847$, $^{87}Sr/^{86}Sr = 0.7045$; $^{147}Sm/^{144}Nd = 0.1967$, $^{143}Nd/^{144}Nd = 0.512638$) are used for the calculation. $\lambda_{Sm} = 6.54 \times 10^{-12}$ year$^{-1}$ (Lugmair and Harti, 1978). The $(^{87}Sr/^{86}Sr)_i$, $(^{143}Nd/^{144}Nd)_i$, $\varepsilon_{Nd}(t)$ of the Azibailedi granites were calculated using age of 1400 Ma. The two-stage model age ($T_{2DM}$) calculations are given by Jahn et al. (1999).

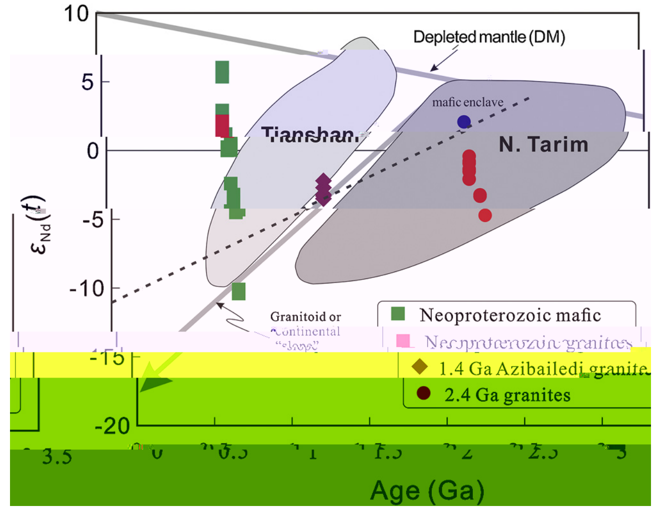


**Fig. 8.** Whole rock $\varepsilon_{Nd}(t)$ vs. crystallization age of the igneous rocks from the south-western margin of the Tarim Craton.
Data are from Hu et al. (2000), Zhang et al. (2003, 2004, 2006a,b, 2007a,b, 2010).

$\varepsilon_{Hf}(t)$ of 1.26 (Fig. 10a). The two-stage Hf model ages ($T_{DM}{}^{C}$) range from 1.93 Ga to 2.82 Ga (mostly 2.16 Ga to 2.66 Ga) with weighted mean value of 2.37 Ga (Fig. 10b) which is identical with two-stage Nd model ages.

The measured $^{176}Hf/^{177}Hf$ ratios of granite samples from the Heluositan complex range from 0.281016 to 0.281302, corresponding to initial $^{176}Hf/^{177}Hf$ ratios of 0.280987 to 0.281273 (Fig. 9a) and $\varepsilon_{Hf}(t)$ values of −11.0 to −3.1 (Fig. 9b). The weighted mean $\varepsilon_{Hf}(t)$ value is −7.8 and two-stage Hf model ages ($T_{DM}{}^{C}$) range from 3.29 Ga to 3.98 Ga (Fig. 10c, d).

The O isotope values of the fifty-one zircons of the Azibailedi granites are fairly homogeneous. The measured zircon $\delta^{18}O$ values range from 7.1‰ to 8.7‰ (with the exception of one analysis which is up to 10.1‰ due to unknown reason). The data define a Gaussian distribution (Fig. 11a) with a peak at 7.9 ± 0.1‰ (2SD) (Fig. 11a), which is higher than the normal mantle zircon values of 5.3 ± 0.6‰ (2SD) (Valley et al., 1998, 2005) (Fig. 11b).

## 6. Discussion

### 6.1. Classification of the Azibailedi pluton

Granitoids are generally divided into I-, S-, A- and M-types according to the nature of protolith and pressure-temperature conditions of melting (Bonin, 2007). Several attempts have been made to distinguish A-type granites from other types (Eby, 1990; Loiselle and Wones, 1979; Whalen et al., 1987). Among these, the characteristics of high $Na_2O + K_2O$, Fe/Mg (in molar) and Ga/Al ratios, low CaO content, enrichment in HFSEs and depletion in Sr, Eu have been considered a significant role to discriminate A-type granites (Bonin, 2007; Collins et al., 1982; King et al.,

2007;

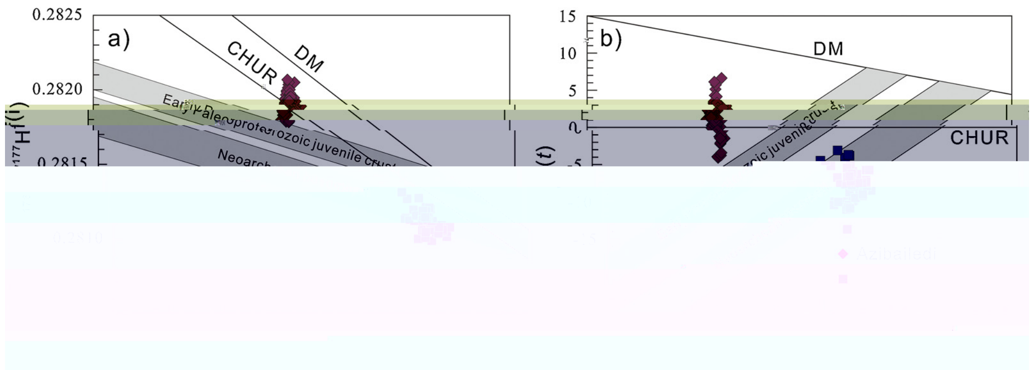


**Fig. 9.** (a) Zircon initial $^{176}Hf/^{177}Hf(i)$ and (b) $\varepsilon_{Hf}(t)$ vs. crystallization age of the Azibailedi and Akazi pluton.

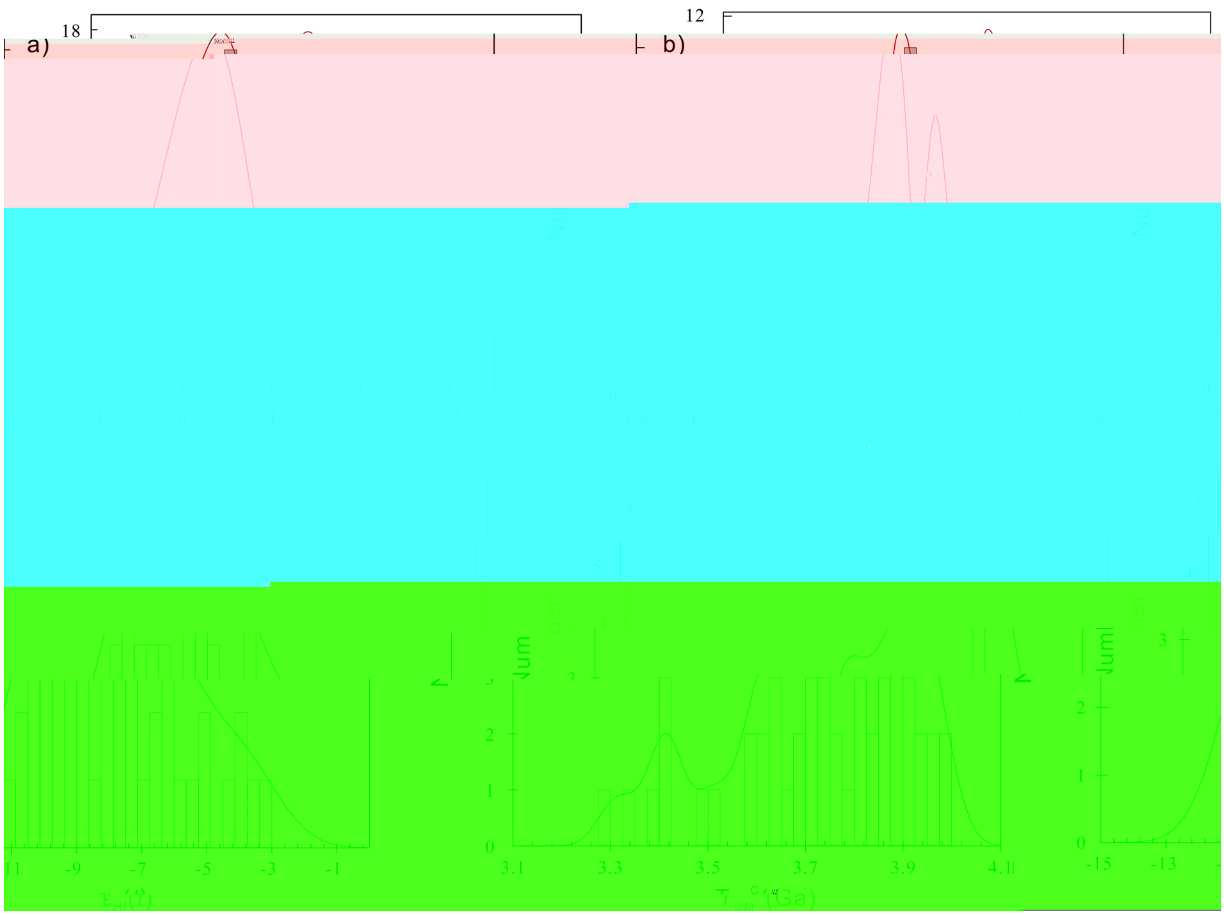


**Fig. 10.** Histograms of zircon $\varepsilon_{Hf}(t)$ and $T_{DM}{}^{C}$ for the rocks of the Azibailedi pluton and granitic gneisses from Heluositan Complex.

Zircon saturation thermometry provides a minimum estimation of magma temperature (Jung et al., 2000; Miller et al., 2003; Watson and Harrison, 1983). The calculated zircon saturation temperatures ($T_{Zr}$)

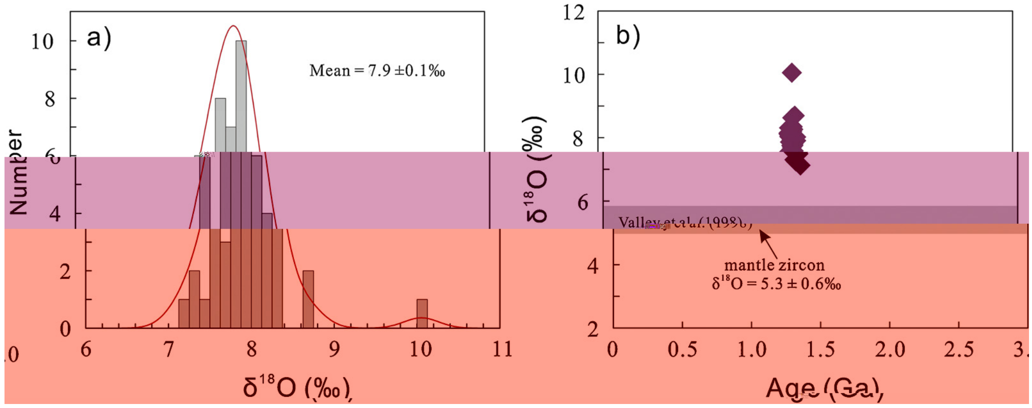


**Fig. 11.** (a) Histogram of single zircon $\delta^{18}O$ values for the Azibailedi granites. (b) single zircon $\delta^{18}O$ data vs. $^{207}Pb/^{206}Pb$ ages for the Azibailedi granites. Field of mantle zircon

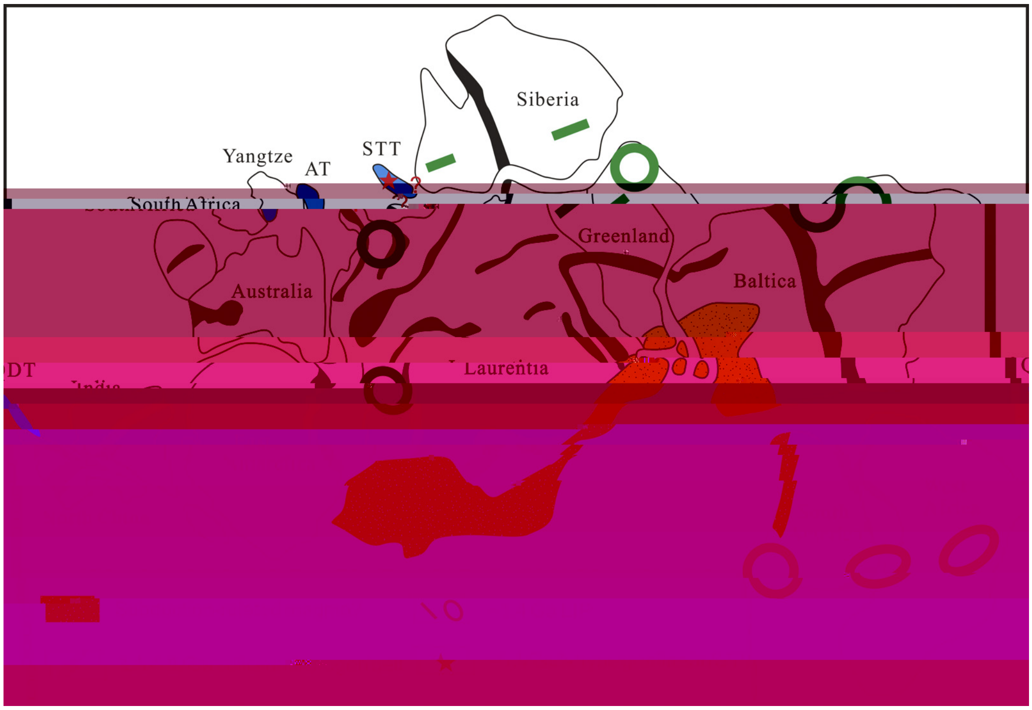


**Fig. 13.** Possible position of the STT in the Columbia supercontinent (modified after Zhao et al., 2002, 2004; Chen et al., 2013; Ernst et al., 2013; Zhang et al., 2014a).

the ~2.4 Ga granite yielded initial $\varepsilon_{Nd}(t)$ value of +2.15 at ~2.4 Ga (Zhang et al., 2007a) (Fig. 8), corresponding to $\varepsilon_{Nd}(t)$ value of −3.1 at ~1.4 Ga. The recalculated Nd isotopic composition falls within the range of $\varepsilon_{Nd}(t)$ values (−3.5 to −2.2) of the Azibailedi granites. Thus, the Nd isotope compositions suggest that the Azibailedi granitic pluton originated mainly from partial melting of the early Paleoproterozoic mafic lower crust.

However, the initial $\varepsilon_{Hf}(t)$ values of the Azibailedi granites vary between −4.1 and +6.1, suggesting the mixing of felsic magmas with variable amounts of basaltic magmas derived from depleted mantle sources. However, the granites have high zircon $\delta^{18}O$ values (7.1–8.7‰), which are obviously higher than those of zircons crystallized from the mantle-derived mafic magma. Thus, the possibility of incorporation of basaltic magmas could be excluded. The $\delta^{18}O$ values (7.1–8.7‰) are beyond the range of $\delta^{18}O$ values of 6.5–7.5‰ recognized for Archean TTG rocks (Valley et al., 2005), suggesting involvement of supracrustal components. On the other hand, zircons from the granites show few high positive initial $\varepsilon_{Hf}(t)$ values (+4.1 to +6.1), corresponding to relatively juvenile two-stage Hf model ages (1.93–2.11 Ga), arguing for the contribution of Paleoproterozoic juvenile crust.

Collectively, we propose that the magmas parental to the Azibailedi granites are alkaline felsic melts, which were most probably generated by partial melting of the pre-existing early Paleoproterozoic mafic lower crust with involvement of variable amount of Paleoproterozoic juvenile crust. The primitive magmas might have further experienced extensive differentiation, as inferred from the observed geochemical features of the Azibailedi granites.

### 6.3. Tectonic implications of the Azibailedi pluton

It is generally accepted that A-type granites are genetically related to extensional or non-compressional regimes and formed in both post-orogenic and/or anorogenic settings (Barbarin, 1999; Collins et al., 1982; Eby, 1992; Whalen et al., 1987, 1996).

Based on regional geology (see Section 2), there is no evidence for any Mesoproterozoic subduction-collision events in STT. Moreover, juvenile arc-related materials might have been involved in the genesis of the A-type granites which are genetically related to post-orogenic settings (e.g. Goodge and Vervoort, 2006). However, the high zircon $\delta^{18}O$ and weak positive $\varepsilon_{Hf}(t)$ values are in contrast with the involvement of juvenile materials. Accordingly, we conclude that the Azibailedi granites were formed in anorogenic setting rather than post-orogenic regime.

On the global-scale, ca. 1.4 Ga magmatic activities have been identified in many continental fragments, such as the 1410 Ma mafic dykes in both Fennoscandian Shield and Baltica Craton (Ernst and Buchan, 2001), the ~1.38 Ga mafic sills and their related volcanics in western Laurentia (western Canada and north-western America) (Abbott, 1997; Ernst and Buchan, 2001), the 1382 Ma Zig-Zag Dal basalts in northern Greenland (Upton et al., 2005), the 1384 mafic dyke swarms in northern Siberia (Ernst and Buchan, 2001), the ca. 1380 Ma Mashak igneous event in eastern Baltica (Puchkov et al., 2013), the 1380 Ma doleritic dykes in the West African Craton (El Bahat et al., 2013), the 1380–1370 Ma mafic-ultramafic complex and A-type granites in the southern margin of the Congo Craton (Ernst et al., 2013; Mayer et al., 2004) (Fig. 13).

We suggest that the formation of the Azibailedi A-type granite formed part of the global ca.1.4 Ga anorogenic igneous activity, most possibly related to the breakup of the Columbia supercontinent (Evans and Mitchell, 2011; Hou et al., 2008; Rogers and Santosh, 2002, 2009; Santosh, 2010; Santosh et al., 2006, 2009; Zhao et al., 2002, 2003, 2004, 2009, 2011; Zhang et al., 2009, 2012b; Meert, 2014).

### 6.4. Continental crust growth process of the STT

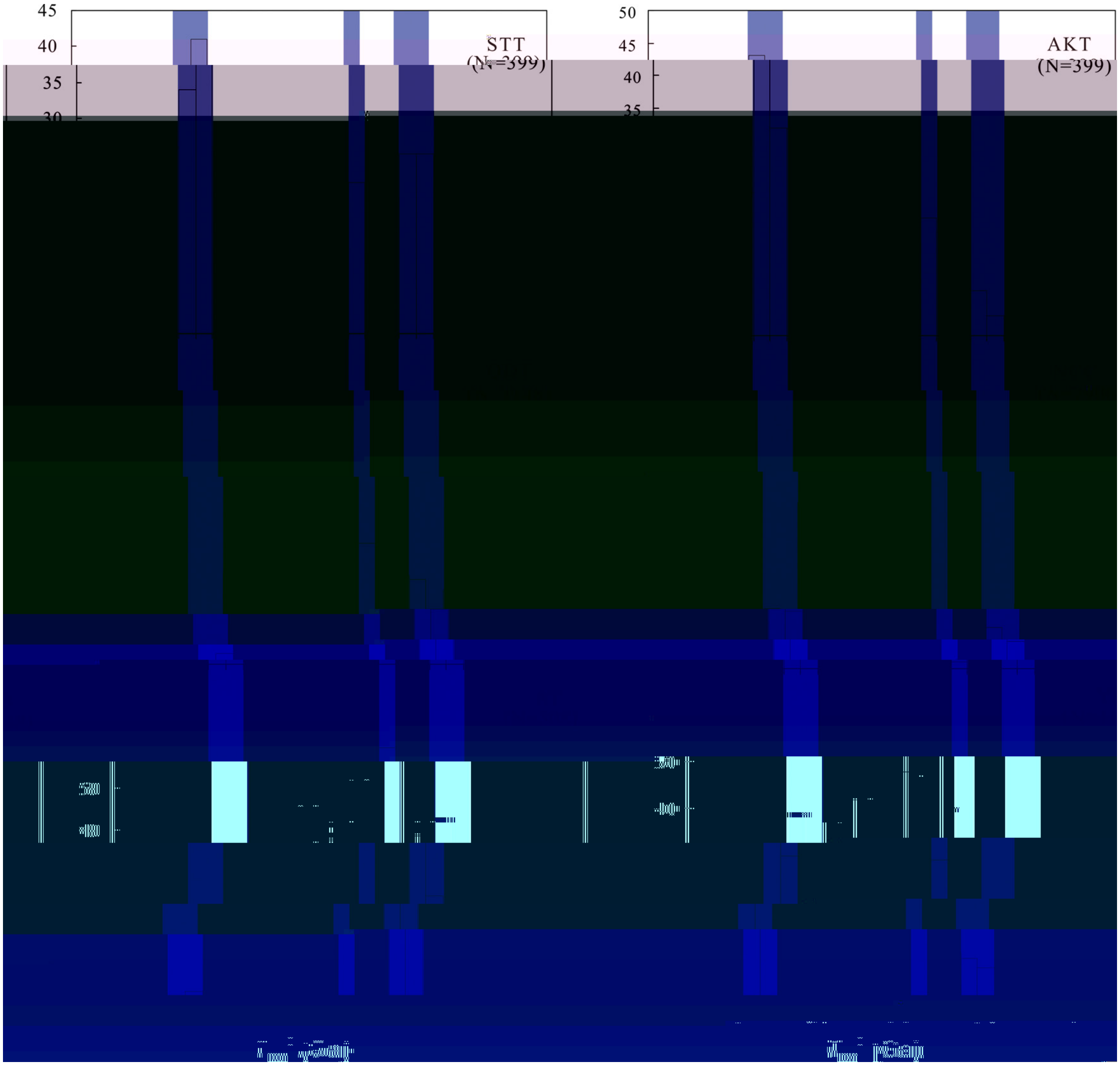


**Fig. 14.** Histograms of zircon Hf-crust model ages of early Precambrian rocks from STT, QDT, AT, AKT, NNC and YB. The data of the STT are from this study and our unpublished data; the data of the QDT are from Ge et al. (2013b, 2014), He et al. (2013), Long et al. (2010), and Zhang et al. (2013b); the data of the AT are from Long et al. (2014) and Zhang et al. (2014a); the data of NNC are from Geng et al. (2012) and Wan et al. (2015); the data of the YB are from Zhang et al. (2006a, b), Zhang and Zheng (2013), and Zhao et al. (2010). STT, Southwestern Tarim terrane; QDT, Quruqtagh-Dunhuang terrane; AT, Aketage terrane; AKT, Akesu terrane; NNC, North China Craton; YB, Yangtze Block.

former is the most important for the upper continental crust growth and the latter for the lower continental crust (Condie, 1997).

Compared with Sm–Nd isotope system, the Lu–Hf system is a better proxy to trace the evolution of continental crust (Hawkesworth and Kemp, 2006; Spencer et al., 2014; Lancaster et al., 2015). Moreover, zircon is a refractory mineral that forms a highly robust phase in most geological environments and thus is ideal for radiometric dating and geochemical tracing (e.g., Zheng et al., 2007). Thus, the zircon Hf isotope plays a pivotal role in unraveling the record of crustal evolution. In the STT, the distribution of Hf-crust model ages reveals that the early Precambrian continental crustal growth occurred mainly during 2.2–4.0 Ga, with major peaks at 2.3–2.5 Ga, 3.3 Ga and 3.6–3.8 Ga (Fig. 14).

In the Quruqtagh-Dunhuang terrane (QDT), crustal growth took place mainly during 2.5–3.9 Ga with major peaks at ca. 2.6–2.7 Ga and 3.0–3.2 Ga (Ge et al., 2013b, 2014; He et al., 2013; Long et al., 2010; Zhang et al., 2013b), which is similar to that of the North China Craton (NCC) (Geng et al., 2012 and references therein) (Fig. 14). In the Aketage terrane, zircon Hf isotope studies revealed that the growth of early Precambrian continental crust took place mainly during 2.7–3.8 Ga with peaks at 2.8 Ga, 3.3 Ga, 3.5–3.7 Ga (Long et al., 2014; Zhang et al., 2014a) which show significant affinity with that of Yangtze Block (YB) (Zhang et al., 2006a,b; Zhang and Zheng, 2013; Zhao et al., 2010) (Fig. 14). As for the Akesu terrane, the peaks of Hf-crustal model ages appear at 2.3–2.6 Ga and 3.0–3.2 Ga (Zhang et al., 2014b) (Fig. 14). The continental growth process of the individual terranes at different times from the Tarim Craton argue that the Precambrian basement of the Tarim was likely composed by discrete terranes detached from different Precambrian nuclei (Zhang et al., 2014a,b).

### 6.5. *Possible affinity of the STT*

Recently, Xu et al. (2013) classified the >900 Ma rocks in the Tarim Precambrian basement into three main tectonic units: the North Tarim terrane, the South Tarim terrane and the Neoproterozoic central suture zone. Nevertheless, according to the significant differences in timings of the late Paleoproterozoic collision events and the late Paleo-Mesoproterozoic breakup events among the different terranes of the Tarim Craton, Zhang et al. (2014a,b) proposed that the Precambrian basement of the Tarim Craton is composed of discrete terranes including Quruqtagh-Dunhuang terrane, Aketage terrane, Akesu terrane, southwest Tarim terrane and even some unknown terranes in central Tarim. Zhang et al. (2014a,b) argued

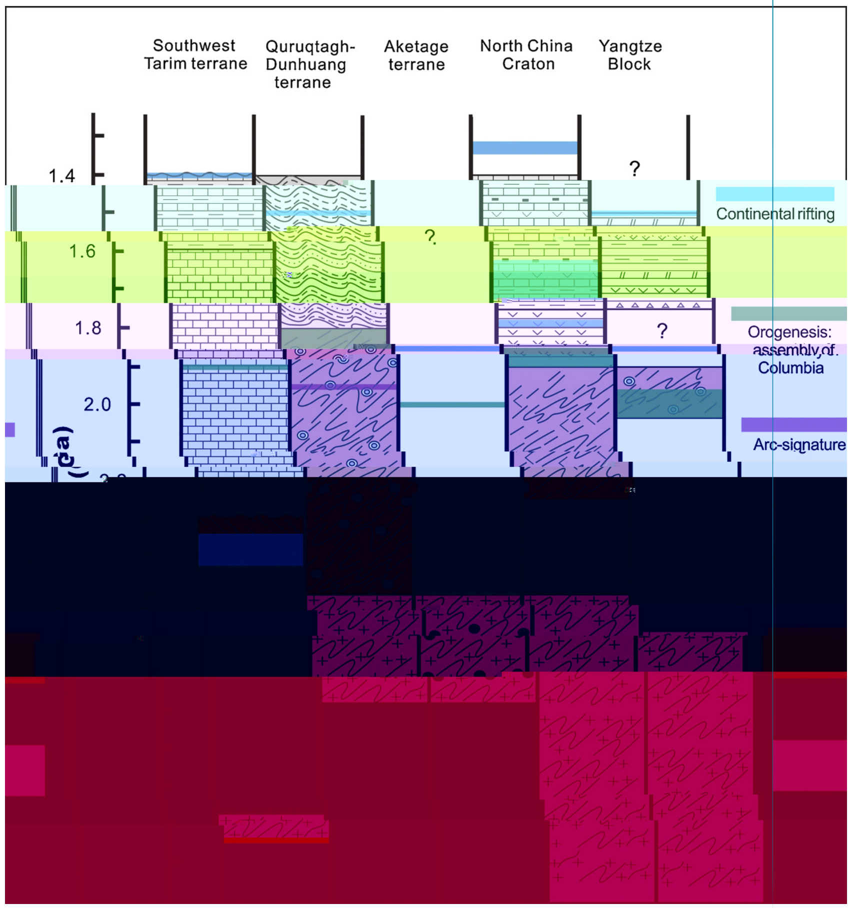


**Fig. 15.** Archean to Mesoproterozoic tectonothermal events of the STT, QDT, AT, YB and NNC. The data of the QDT are from Ge et al. (2013b), Lei et al. (2012), Wu et al. (2014), and Zhang et al. (2012a, 2013b); the data of the AT are from Long et al. (2014) and Zhang et al. (2014a); the data of the NNC are from Zhao and Zhai (2013) and Zhai et al. (2015); the data of the YB are from Chen et al. (2013) and references therein. The Precambrian rock series for the discrete terranes are from Zhai (2015). STT, Southwestern Tarim terrane; QDT, Quruqtagh-Dunhuang terrane; AT, Aketage terrane; NNC, North China Craton; YB, Yangtze Block.

that these terranes might have been derived from various continental nuclei.

Global-scale 2.1–1.8 Ga collision events have been well documented in a number of large continental cratons, and are linked with the assembly of the Columbia supercontinent (Rogers and Santosh, 2002, 2009; Santosh et al., 2006, 2009; Zhao et al., 2002, 2003, 2009, 2011; Meert, 2014). It is represented by the 2.1–2.0 Ga Transamazonian and Eburnean orogens in South America and West Africa; ~2.0 Ga Limpopo belt in south Africa and Capricorn Belt in Western Australia; 1.95–1.85 Ga Trans-Hudson Orogen or its equivalents in Laurentia (North America and Greenland); ~1.9 Ga Kola-Karelia, Volhyn-Central Russian, and Pachelma orogens in Baltica; and ~1.85 Ga Trans-North China Orogen in North China (Zhao et al., 2002, 2011; Yang and Santosh, 2015a,b).

The ~1.9 Ga metamorphism in the STT was believed to be related to the assembley of the Columbia supercontinent (Zhang et al., 2007a). Although no magmatic rocks of ~1.9 Ga have been reported in this terrane, the ~1.9 Ga detrital zircons of magmatic origin found in most of the volcano-sedimentary successions (Wang et al., 2015 and our unpublish data) are also indicative of this event.

In comparison with the timing of the Columbia supercontinent assembly, the STT is close to Laurentia, Siberia and Baltica (Fig. 13). Though at present it is difficult to correlate the STT with any of the three cratons above, it is obvious that the STT does not

affinities with the Quruqtagh-Dunhuang or Aketage terrane, Akesu (see Section 2). Furthermore, Zhang et al. (2014a,b) pointed out that the Quruqtagh-Dunhuang terrane shows clear affinity with that of the North China and the southern India Cratons (Figs. 13 and 15), whereas the Akesu terranes was possibly detached from

(3) Significant temporal discrepancy of Paleo- to Mesoproterozoic orogenic and extensional events and distinct timings in continental crustal growth processes for the different terranes in the Tarim Craton suggest that the basement of this craton was composed of discrete terranes during early Precambrian.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2015.12.017.

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