



Petrogenesis of Paleoproterozoic alkali-feldspar granites associated with alkaline rocks from the Trans-North China Orogen

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ABSTRACT

Granitoids are the dominant component of the continental crust and can be used as probes for crustal formation and evolution. The origin of granites, especially ambiguous granites with alkaline affinities emplaced in orogenic settings, however, remains controversial. Here, we report the petrology, geochronology and geochemistry of Paleoproterozoic alkali-feldspar granites associated with carbonated alkaline rocks from the Trans-North China Orogen in the North China Craton. Corundum-bearing Al-rich gneisses are associated with the granites and occasionally contain granite pockets and veinlets. The rocks have high amounts of K₂O (10–14 wt%) and low CaO (0.3–2.3 wt%) contents and show metaluminous to weakly peraluminous features. Moreover, they have low levels of total REE (18–100 ppm) and show strong LREE enrichment [(La/Yb)_{CN} = 44–128] and positive Eu anomalies ($\delta\text{Eu} = 1.6\text{--}10.2$). The zircons record a U–Pb age of 1809 ± 3 Ma and $\epsilon\text{Hf}(t)$ values ranging from -3.7 to -7.1 , which are consistent with those in the gneisses (1827 ± 14 Ma, $\epsilon\text{Hf}(t) = -3.3$ to -8.4). Inherited zircons occur in both rocks and show similar ages of ~ 2.0 and ~ 2.1 Ga. Considerably high $\delta^{18}\text{O}_{\text{SMOW}}$ ratios (9.9–10.9 ‰) in the zircons and low $\epsilon\text{Nd}(t)$ values (-4.0 to -6.2) of the granites were identified. The granite was generated by partial melting of pelitic rocks instead of differentiation of mantle-derived magmas, whilst the gneiss represents the residuum. The carbonated alkaline magmas arising from the mantle provided sufficient heat for anatexis of the crust. Granitoid rocks showing alkaline affinity in orogenic belts may not be the fractionation products of mantle-derived melts but may have formed from reworked sedimentary materials.

1. Introduction

Granitoids, mainly composed of quartz and two feldspar types, are the most abundant rocks in the upper continental crust, accounting for approximately 86 vol% (Wedepohl, 1991). They characterise the Precambrian shield areas (Kotilainen et al., 2016). The rocks display great diversity because of various origins, evolution processes, and tectonic regimes. The geochemical compositions of granitoid rocks have been used as indicators of distinct geodynamic environments, especially for Precambrian crustal growth (Zhou et al., 2017; Gan et al., 2020). The vast granitoid batholiths and their eruption analogues that dominate the continental landmasses are manifestations of Earth differentiation, which is unique among the known terrestrial planets (Campbell and Taylor, 1983).

During the 1970s, all granites were generally divided into four types, i.e., M, S, I, and A. The alphabet classification has been the most popular division to date. The M-type, abandoned in recent years, is inferred to

have been formed by partial melting of a subducted oceanic crust (White, 1979; Whalen, 1985). The S- and I-types are issued from partial melting of sedimentary and igneous protoliths, respectively (Chappell and White, 1974; Chappell and White, 1992). The petrogenesis of A-type remains controversial, including fractionation of mantle-derived alkali basaltic magmas (e.g., Bonin, 2007; Dostal and Shellnutt, 2015; Frost and Frost, 1997), partial melting of lower crust influenced by mantle heat (e.g., Collins et al., 1982; Whalen et al., 1987; Wang et al., 2018), and magma mixing of mantle and crustal sources (e.g., Kemp et al., 2005; Yang et al., 2006). A-type granites are commonly associated with mafic and intermediate alkaline rocks in tensional tectonic settings (Bonin, 2007; Dall'Agno et al., 2012). Their chemical compositions are dominated by high Na₂O + K₂O, Fe/Mg, Ga/Al, Zr, Nb, Y, Ga, F, and REE (except Eu) and low CaO, Ba, Sr, and Eu contents (Whalen et al., 1987; Eby, 1990; Frost and Frost, 2011). A-type granites were further divided into two chemical groups, i.e., A1 and A2. It is proposed that the two types have different sources and tectonic settings: differentiation of

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magmas derived from oceanic island basalts in continental rifts or intraplates (A1) and from continental or underplated crust in post-orogens (A2) (Eby, 1992). It is noted that mantle-derived melts can provide sufficient heat for partial melting of sedimentary rocks in the crust (Clemens, 2003). The contribution of mantle-derived magmas complicates the granite petrogenesis. Hf–O isotopes recorded in zircon from typical I-type granites support a reworking of sedimentary materials by mantle-like magmas rather than melting of igneous rocks as widely believed (Kemp et al., 2007). Similarly, the origin of A-like granites, yielding alkaline affinities and occurring in orogenic settings, is also controversial because basaltic magma (or its latent heat) commonly interacted with crustal materials (e.g., Huang et al., 2011; Li et al., 2018a; Kamaunji et al., 2020). The ambiguity issue of the genetic alphabet results from flourishing genetic models, mostly based on chemical data, but ignoring petrologic constraints.

In the North China Craton (NCC) from the Trans-North China Orogen (TNCO), Paleoproterozoic alkali-feldspar granites are associated with contemporary carbonatites, pyroxenites, and syenites (Xu et al., 2019; Kuang et al., 2020). In this study, an intrusive association of alkali-feldspar granites and Al-rich gneisses has been observed. The petrology, geochronology, and geochemistry of the granites and gneisses were analysed for determining the petrogenesis of alkali-feldspar granites associated with alkaline rocks in orogenic belts, which indicated that the granites were not differentiation products of mantle-derived magmas.

2. Geological setting and petrology

The NCC is one of the fundamental Precambrian nuclei of the Asian subcontinent and one of the oldest and largest cratonic blocks on Earth. It consists of two major microcontinental blocks, generally referred to as the Western and Eastern blocks, which are stitched together by the TNCO (Fig. 1). The basement of the NCC is dominated by variably exposed Archean to Paleoproterozoic rocks, comprising granite, tonalite–trondhjemite–granodiorite (TTG) gneiss, Al-rich gneiss (khondalite), charnockite, migmatite, amphibolite, pelitic schist, greenschist, banded iron formation (BIF), marble, and calc-silicate rocks (Zhao et al., 2005; Zhao et al., 2012). The Eastern Block is mainly composed of Early to Late Archean TTG gneisses, Late Archean granitoids, and a minor

supracrustal suite of volcanic and sedimentary rocks metamorphosed from greenschist to granulite facies at ~2.5 Ga (Zhao et al., 2001). The Archean rocks underwent multiple phases of deformation and metamorphism between 3.8 and 2.5 Ga (Bai et al., 1992). The Western Block is represented by a Late Archean assemblage, and its metamorphic history and structural style resemble that of the Eastern Block. The Western Block comprises the Yinshan and Ordos blocks which are divided by the Khondalite Belt, composed of graphite-bearing sillimanite garnet gneiss, garnet quartzite, calc-silicate, and marble with minor mafic granulite and felsic paragneiss. The Khondalite Belt is derived from high-grade metamorphism of interlayered pelitic, psammitic, psammopelitic, and carbonaceous sediments deposited in a shallow sea on the cratonic shelf (Zhao et al., 2005; Xia et al., 2006). Numerous S-type granites, yielding zircon U–Pb ages of 1.97–1.84 Ga, indicate extensive partial melting of thick sedimentary rocks during the high-grade metamorphism (Yin et al., 2009). The TNCO consists predominantly of Late Archean to Paleoproterozoic TTG gneisses and granitoids, interleaved with plentiful metamorphosed volcanic and sedimentary rocks that formed in magmatic arc and intra-arc basin settings. These rocks experienced multiple episodes of high-pressure metamorphism and compressional deformation followed by rapid exhumation at ~1.8 Ga because of the collision between the Western and Eastern blocks, resulting in the final amalgamation of the NCC (Zhao et al., 2001; Zhao et al., 2012; Guo et al., 2005).

The Paleoproterozoic orogenic junctions between the Khondalite Belt and TNCO in Fengzhen and Huai'an areas are intruded by dikes (Fig. 1), which consist of a variety of contemporaneous rock types including carbonatites, pyroxenites, syenites, granites, and gneisses (Fig. 2a, b). These rocks are intimately associated and hybridise together locally, exhibiting complex field features. The granites are made up of medium to coarse-grained (0.5–15 mm) K-feldspar (50–70 vol%) and quartz (30–50 vol%) (Fig. 3a). The K-feldspar consists of predominant microcline and minor (<5 vol%) perthite. Clinopyroxene and titanite occur in the granite margin at the contact zones with pyroxenite and carbonatite (Fig. 2c; Fig. 3b, c). Furthermore, ovoid and rounded pyroxenite enclaves can be observed in the granite (Fig. 2d). The rock also presents as lenses and veins in the pyroxenite and shows plastic flow features (Fig. 2e, f), indicating that the granites and pyroxenites may have formed coevally. Rarely exposed gneisses are associated with the

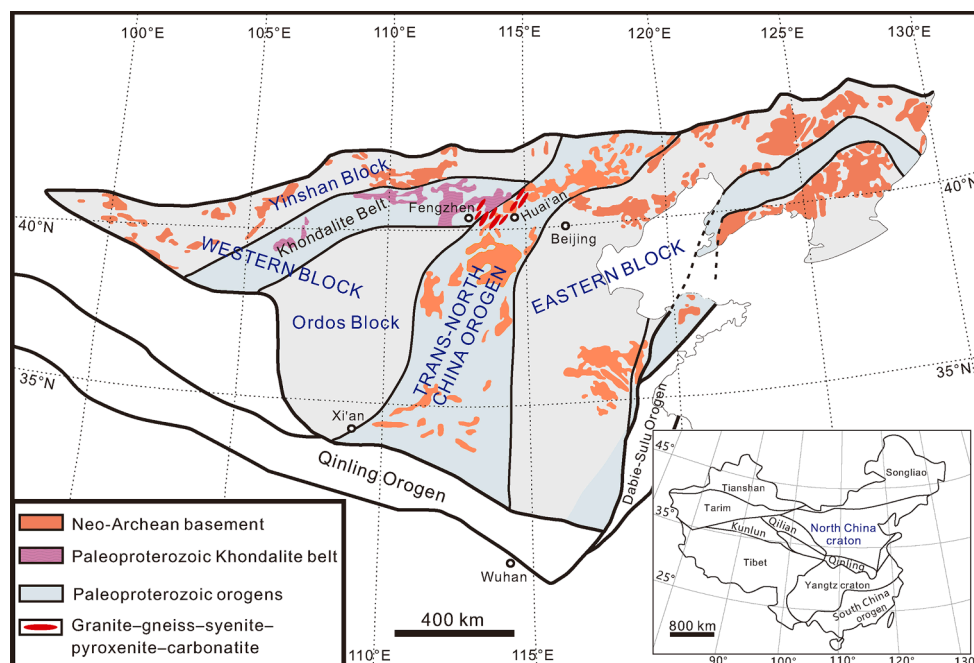


Fig. 1. Schematic geological map of the North China Craton (modified from Zhao et al., 2005; Xu et al., 2018; Xu et al., 2019).

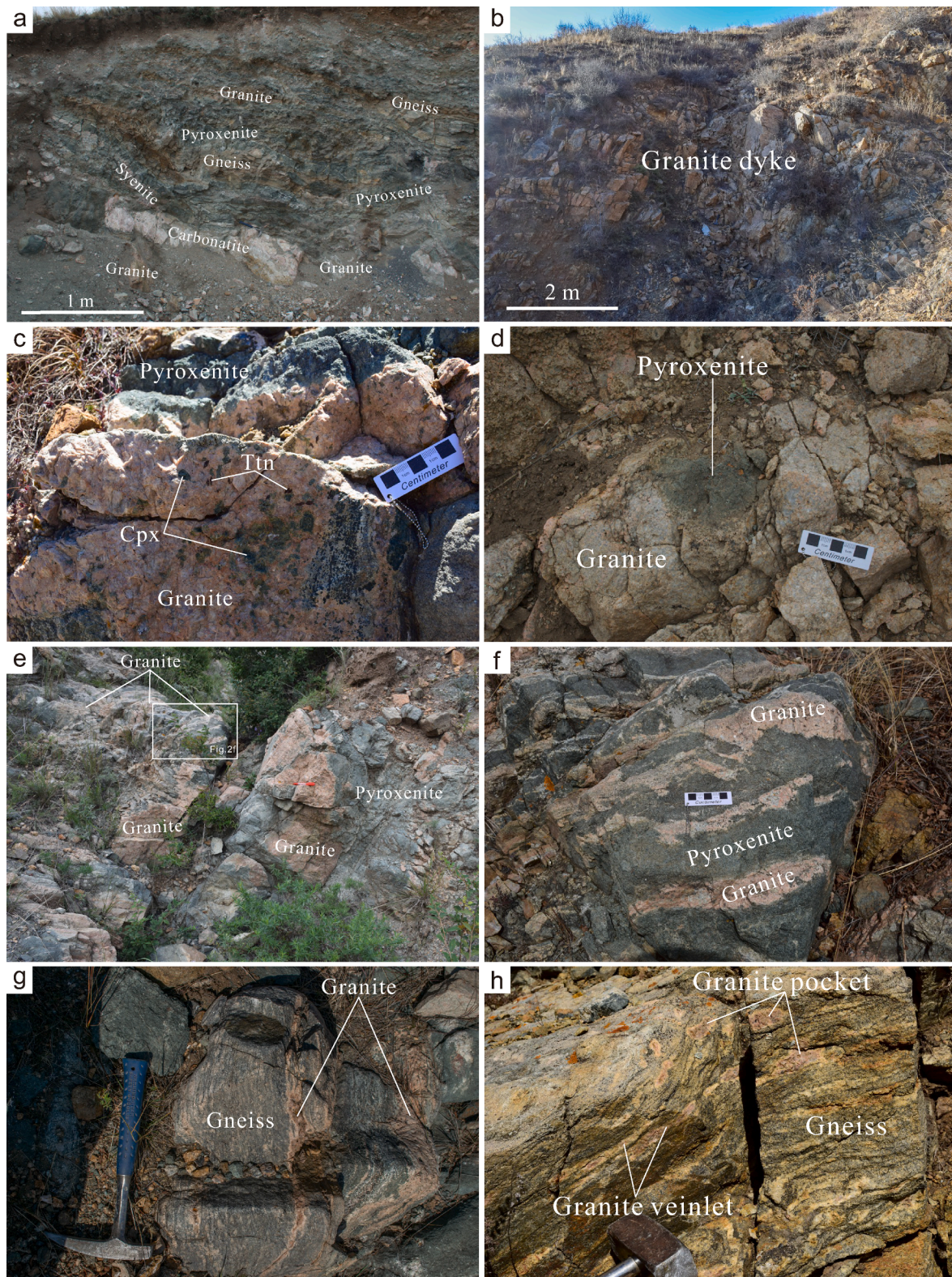


Fig. 2. Field photographs of granite, gneiss, and associated carbonatite–pyroxenite–syenite complex (a), single granite dyke (b), granite margin at the contact of pyroxenite (c), pyroxenite enclave in granite (d), granite lenses and veins in pyroxenite (e, f), granite associated with gneiss (g), and granite pockets and veinlets in gneiss (h) from Fengzhen area. Rectangle in (e) outlines the approximate position of Fig. 2f. Cpx, clinopyroxene; Ttn, titanite.

alkali-feldspar granites and occasionally contain granite pockets and veinlets (Fig. 2g, h), which are composed of K-feldspar and quartz (Fig. 3d). This suggests these two type rocks may have a genetic relationship. The gneisses are composed of K-feldspar (65–85 vol%), mica

(biotite and phlogopite: 10–20 vol%), and spinel (5–15 vol%) (Fig. 3e), and the accessory phases mainly include magnetite and corundum (Fig. 3f). The aluminium-rich spinel and corundum indicate that the protoliths of the gneisses are pelitic rocks. No plagioclase presents in the

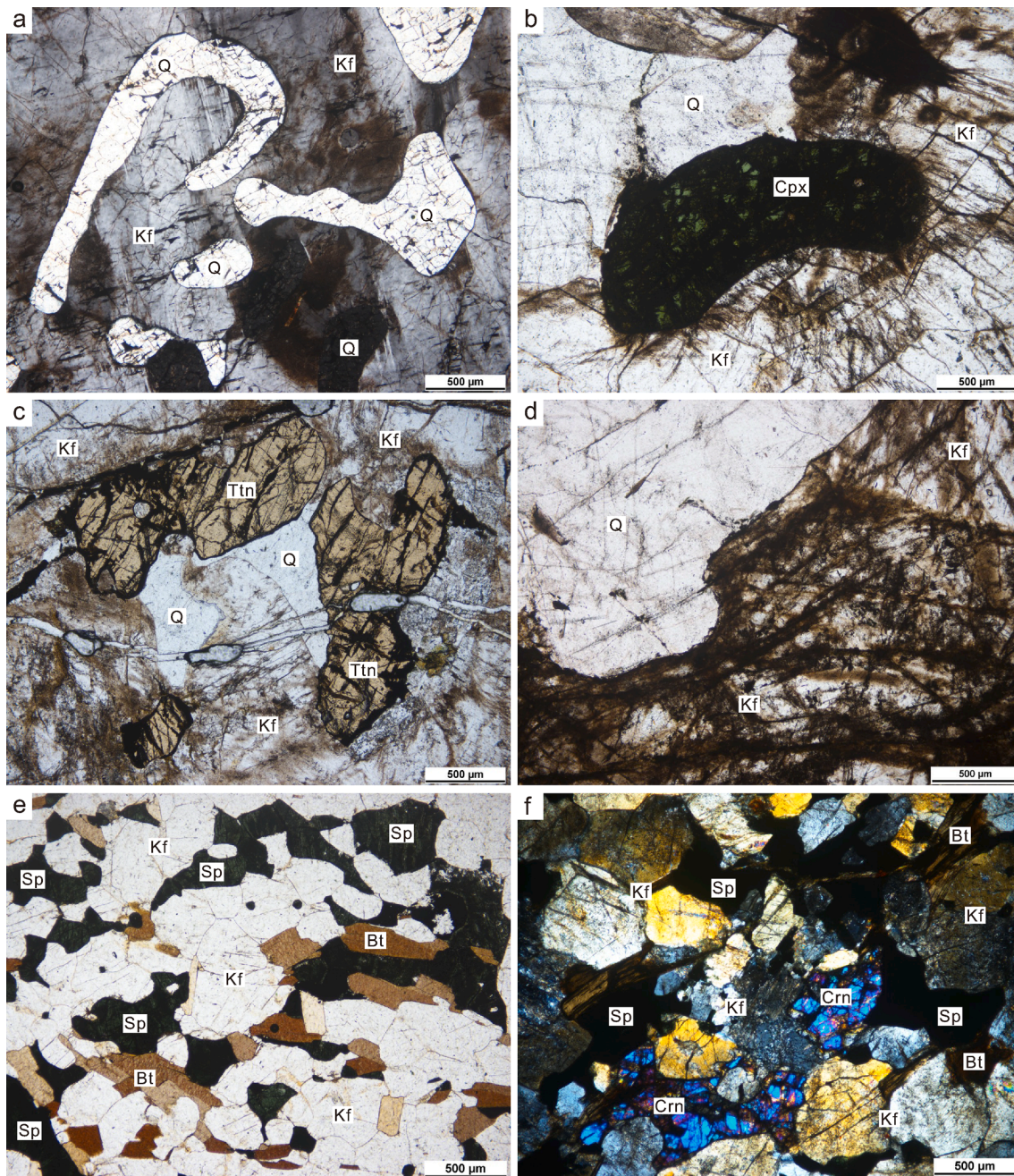


Fig. 3. Characteristic textures of granite (a), contaminated granite margin (b, c), granite pocket (d) in gneiss (e, f). Kf, K-feldspar; Q, quartz; Cpx, clinopyroxene; Ttn, titanite; Bt, biotite; Sp, spinel; Crn, corundum.

granites, gneisses, and granite pockets or veinlets in gneisses. Syenites usually occur at the contact of pyroxenites, and some are associated with granites, with variable alkali-feldspar (50–80 vol%), clinopyroxene (10–40 vol%), and minor titanite and apatite. Pyroxenites are strongly associated with carbonatites, composed predominantly of clinopyroxene (>90 vol%) and minor calcite and phlogopite, whilst carbonatites generally comprise calcite (>90 vol%) and minor clinopyroxene, phlogopite, forsterite, and apatite.

3. Analytical methods

3.1. Mineral analyses

The major element composition of representative mineral phases in the granites and gneisses was determined on carbon-coated polished

sections using a JXA-8230 electron microprobe (EMP) with wavelength-dispersive X-ray spectrometry (WDS) at the Laboratory of Orogenic Belts and Crustal Evolution, Peking University. The instrument was operated at an accelerating voltage of 15 kV and a beam current of 10 nA, with an electron beam defocused to 2–10 µm. Based on the components and sizes of the separated minerals, a set of appropriate matrix-specific standards (including natural and synthetic) and corresponding instrumental conditions (including beam diameter, detector type, and counting statistics) were adopted. All raw data were corrected with standard ZAF (Z, atomic number; A, absorption; and F, fluorescence) correction procedures. Repeated measurements of the standards showed that the precision of the EMP analysis was $\pm 2\%$ or better for most elements. Further details regarding the instrument and methodology are described by Li et al. (2018b).

3.2. Zircon dating analyses

U–Th–Pb dating zircons were separated from representative samples using conventional magnetic and density techniques, mounted into the epoxy resin, and polished. Reflected and transmitted light photomicrographs and cathodoluminescence (CL) images were used to reveal the internal structures of the zircon crystals. Age determination was conducted using laser ablation inductively coupled plasma mass spectrometry (ICP-MS) with an Agilent 7700x mass spectrometer coupled to a 193 nm ArF excimer laser at the Laboratory of Orogenic Belts and Crustal Evolution, Peking University. The laser beam was focused on the sample with a flux of 10 J/cm² and a spot size of 32 µm in diameter at a repetition rate of 5 Hz for 40 s. Helium was used as the carrier gas to transport the ablated aerosol to the mass spectrometer. Zircon Nancy 91,500 was employed as an external calibration standard to correct for instrumental mass bias and elemental fractionation. Zircon standards Plešovice and GJ-1 were used for quality control. The lead content of zircon was externally calibrated against NIST 610 with Si as an internal standard, whilst other trace elements were measured with Zr as an internal standard. Raw data reduction was conducted using the GLITTER software. An average Pb isotope composition of present-day crustal Pb was taken for the common Pb correction (Stacey and Kramers, 1975).

3.3. Whole-rock analyses

The major and trace elements of the whole-rock samples were determined using X-ray fluorescence spectrometry (XRF) and ICP-MS, respectively, at the Laboratory of Orogenic Belts and Crustal Evolution, Peking University. The details for the whole-rock analyses are described by Qi et al. (2000). Whole-rock powder (50 mg) was dissolved in a Teflon beaker using 1 mL of HF (38%) and 1 mL of HNO₃ (68%). The sealed beaker was placed in an electric oven and heated at 180 °C for 24 h. A 1 µg/mL Rh solution (1 mL) was added to the cooled solution as an internal standard, and the solution was evaporated to dryness. Another 1 mL of HNO₃ (68%) was added, and the solution was evaporated to dryness, followed by a repeated addition of HNO₃ (68%) and evaporation. The final residue was redissolved in a 5 mL HNO₃ (2%). The beaker was sealed and heated in an electric oven at 180 °C for 12 h. The final solution was diluted to 50 mL using distilled deionised water for ICP-MS measurements. The analytical values for all elements were <10% in error compared to the standard values.

3.4. Sr–Nd isotope analyses

The Sr–Nd isotope composition of the whole-rock samples was analysed in solution using a VG Axiom multi-collector ICP-MS at the Laboratory of Orogenic Belts and Crustal Evolution, Peking University. The analytical procedures for Sr and Nd isotope measurements were similar. Representative granite samples were dissolved in an acid solution, and Rb, Sr, and REEs were separated on AGW50-X12 cation exchange columns. REEs were further dissolved in 0.25 N HCl, and then Sm and Nd were separated on the Ln-Spec resin ion exchange columns. The total procedural blanks were <100 and 50 pg for Sr and Nd, respectively. Mass fractionation effects for the Sr and Nd isotope ratios were corrected to ⁸⁶Sr/⁸⁸Sr and ¹⁴⁶Nd/¹⁴⁴Nd ratios of 0.1194 and 0.7219, respectively. Before the isotope measurements, the Rb/Sr and Sm/Nd ratios in the solution were acquired using ICP-MS. Repeated measurements of Sr standard NBS987 and Nd standard JNdi yielded an average ⁸⁷Sr/⁸⁶Sr = 0.710215 ± 31 (2σ) and ¹⁴³Nd/¹⁴⁴Nd = 0.512087 ± 20 (2σ). The results were normalised to the accepted in-house values of 0.710248 (NBS987) and 0.512113 (JNdi). Additional corrections were applied to the Sr and Nd data of the granites.

3.5. Zircon O–Hf isotope analyses

Zircon oxygen isotopes were analysed using the Cameca IMS-1280

SIMS at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The instrument is equipped with a primary beam of Cs ions accelerated at 10 kV and an intensity of ~2 nA with a spot size of 15 µm in diameter. Oxygen isotopes, ¹⁶O and ¹⁸O, were measured simultaneously in multi-collector mode using two off-axis Faraday cups. Measured ¹⁸O/¹⁶O ratios were normalised to Vienna standard mean ocean water (V-SMOW). Zircon reference standards Nancy 91500, Penglai, and Qinghu were repetitively analysed to correct and monitor the instrumental mass fractionation. All obtained ¹⁸O/¹⁶O ratios and calculated δ¹⁸O_{SMOW} values are therefore reported relative to the zircon Nancy 91,500 standard with a reference δ¹⁸O_{SMOW} value of 9.9‰ (Wiedenbeck et al., 2004). The internal precision of a single measurement was generally better than 0.2‰ (1σ) for the ¹⁸O/¹⁶O ratio. Further details on the methodology are given by Li et al. (2010).

Zircon Lu–Hf isotopes were analysed using a NU plasma II MC-ICP-MS at the Laboratory of Orogenic Belts and Crustal Evolution, Peking University. An ArF excimer laser ablation system, Geolas HD (193 nm), was employed with a 44 µm spot size. Raw data reduction was performed using the IOLITE software (Paton, et al., 2011). The typical ablation time for 200 cycles of each measurement was approximately 30 s with a repetition rate of 5 Hz. The laser power was 100 mJ/pulse. During the analysis, the isobaric interferences of ¹⁷⁶Lu and ¹⁷⁶Yb on ¹⁷⁶Hf were corrected by taking recommended values of ¹⁷⁶Lu/¹⁷⁵Lu (0.02655) and ¹⁷⁶Yb/¹⁷²Yb (0.5887), and assuming that the instrumental mass fractionation of Lu and Yb is identical to that of Hf. Zircon Nancy 91,500 was employed as the internal standard with a reference ¹⁷⁶Hf/¹⁷⁷Hf = 0.282307 ± 31 (2σ) (Wu et al., 2006). Penglai and Plešovice standards were analysed to assess the reliability of the analytical data, which gave weighted mean ¹⁷⁶Hf/¹⁷⁷Hf ratios of 0.282913 ± 25 (2σ) and 0.282490 ± 18 (2σ), respectively. The results are within the margin of error of reported values of 0.282906 ± 16 and 0.282482 ± 13 for the Penglai and Plešovice standards, respectively (Sláma et al., 2008; Li et al., 2010). For the calculation of initial Hf isotope composition, ¹⁷⁶Lu/¹⁷⁷Hf and ¹⁷⁶Hf/¹⁷⁷Hf values of chondritic uniform reservoir (CHUR) and depleted mantle (DM) were cited from Blichert-Toft and Albarede (1997) and Griffin et al. (2000), respectively. The accepted decay constant (λ) of ¹⁷⁶Lu → ¹⁷⁶Hf is 1.867 × 10^{−11} y^{−1} (Scherer et al., 2001).

4. Results

Representative mineral chemical compositions, zircon U–Pb isotope data, and whole-rock major and trace element concentrations are listed in Tables 1–3, respectively. The Sr–Nd, Hf, and O isotope data are shown in Tables 4–6, respectively.

4.1. Mineral compositions

The feldspar in granites is typical K-feldspar with a composition of An_{0.1}Ab_{1.7–9.5}Or_{90.2–98.3} (An = mol.% CaAl₂Si₂O₈, Ab = mol.% NaAlSi₃O₈, Or = mol.% KAlSi₃O₈). The granite pockets in gneiss also show similar feldspar compositions (An_{0.2}Ab_{2.1–4.3}Or_{95.7–97.8}). Clinopyroxene and titanite were identified in the granite margin (Fig. 2c; Fig. 3b, c). The clinopyroxene is represented by hedenbergite with Wo_{46.7–48.5}En_{18.5–22}Fs_{30.7–34.3} (Wo = mol.% CaSiO₃, En = mol.% MgSiO₃, Fs = mol.% FeSiO₃), showing low MgO (~6.5 wt%) and Al₂O₃ (~0.3 wt%) and high FeO (~18.6 wt%) and MnO (~0.5 wt%) contents. In the contact zone from pyroxenite and syenite to granite, clinopyroxenes are characterised by a good transition from diopside (Wo_{50.5–53.7}En_{37.8–40.9}Fs_{7.4–9}; Kuang et al., 2020) to hedenbergite. The titanite in granite contains relatively higher TiO₂ (~36.4 wt%) and FeO (~2.2 wt%) and lower Al₂O₃ (~0.4 wt%) and CaO (~26 wt%) abundances (Table 1) than that in syenite (Kuang et al., 2020).

In gneisses, the K-feldspar has a chemical composition of An_{0.1–0.9}Ab_{0.1–10.6}Or_{89.9–99.8}, which is similar to that in the granites. The mica has variable compositions and comprises biotite and phlogopite,

Table 1
Electron microprobe analyses (wt%) of representative minerals in the granites and gneisses from Fengzhen area.

	Granite		Granite margin		Granite pocket	Gneiss			Corundum					
	K-feldspar n = 28	Magnetite n = 2	Clinopyroxene n = 28	Titanite n = 8	K-feldspar n = 8	Phlogopite n = 3 (FZ1906)	Biotite n = 5 (FZ1903)	n = 4 (FZ1911)	Spinel n = 3 (FZ1906)	n = 4 (FZ1903)	n = 4 (FZ1911)	K-feldspar n = 10	Magnetite n = 4	Corundum n = 3
SiO ₂	66.20(53)	0.02(3)	51.35(36)	29.84 (31)	65.82(41)	35.42(20)	35.57(22)	35.54(38)	0.03(2)	0.02(3)	bd	64.82(40)	0.04(3)	bd
TiO ₂	0.03(3)	0.05(1)	0.12(5)	36.39 (34)	0.01(3)	3.59(65)	5.81(50)	4.84(10)	0.03(4)	0.02(3)	0.03(3)	0.06(2)	0.08(6)	bd
Al ₂ O ₃	18.16(23)	0.04(2)	0.26(7)	0.44(19)	17.68(23)	20.20(45)	17.08(40)	16.49(14)	64.04(13)	58.75(25)	56.72(71)	19.10(15)	0.29(20)	101.54(7)
FeO	0.28(19)	92.43(30)	18.64(51)	2.18(9)	0.66(22)	8.50(66)	12.28(55)	14.43(82)	21.25(40)	31.24(45)	35.56(114)	0.03(2)	91.22(21)	0.63(16)
MnO	0.01(2)	0.02(3)	0.49(5)	0.03(0)	0.02(2)	0.23(3)	0.08(3)	0.03(1)	0.93(6)	0.32(2)	0.11(4)	0.01(1)	0.02(3)	bd
MgO	bd	0.02(0)	6.46(26)	0.02(1)	bd	16.64(22)	14.40(31)	13.35(86)	13.31(22)	8.61(23)	6.29(17)	bd	0.03(2)	0.01(1)
CaO	0.01(5)	0.01(1)	21.79(25)	25.99 (29)	0.01(2)	bd	bd	bd	bd	bd	0.01(1)	0.09(5)	bd	0.01(1)
Na ₂ O	0.64(22)	0.02(2)	0.74(8)	0.04(1)	0.40(8)	0.01(1)	0.06(2)	0.09(3)	bd	bd	0.01(1)	0.55(45)	0.04(3)	0.02(2)
K ₂ O	14.77(45)	0.01(1)	0.01(1)	bd	16.75(36)	9.81(22)	9.58(29)	9.52(16)	bd	0.01(1)	bd	15.36(62)	0.01(1)	0.01(1)
Cr ₂ O ₃	0.01(2)	bd	0.01(2)	bd	bd	0.03(3)	0.02(2)	bd	0.02(2)	0.06(1)	0.06(3)	0.01(1)	0.10(3)	0.06(4)
NiO	0.02(3)	bd	0.02(3)	bd	0.01(2)	0.03(1)	0.02(3)	0.02(3)	0.02(3)	bd	0.04(2)	0.01(2)	0.07(6)	0.01(1)
Total	100.15 (54)	92.60(31)	99.88(41)	94.93 (40)	101.37(24)	94.47(79)	94.89(57)	94.30(50)	99.63(39)	99.01(52)	98.83(47)	100.02 (51)	91.89(26)	102.28(3)

Gneiss samples FZ1906 and FZ1903 are closely associated with carbonates and pyroxenites, and FZ1911 is distant from the alkaline rocks. Number in parenthesis represents one standard deviation of multiple analyses of several spots. bdl, below detection limit.

yielding an $Mg^{\#}$ value [molar $Mg/(Mg + Fe)$] of 0.59–0.79. It records different Al_2O_3 (16.3–20.7 wt%), FeO (7.7–15.4 wt%), MgO (12.4–16.9 wt%), and TiO_2 (3.0–6.7 wt%) abundances. The spinel is represented by pleonaste, exhibiting variable compositions with wide ranges of Al_2O_3 (55.7–64.2 wt%), FeO (20.9–37.2 wt%), and MgO (6.1–13.5 wt%) contents. Three groups of mica and spinel have been distinguished based on different samples (Table 1). From the gneiss samples closely associated with carbonates and pyroxenites to those distant from the alkaline rocks, the mica changes from phlogopite to biotite with decreasing MgO (16.6 vs. 13.4 wt%) and Al_2O_3 (20.2 vs. 16.5 wt%) and increasing FeO (8.5 vs. 14.4 wt%), and the spinel shows similar chemical variations (13.3 vs. 6.3 wt%, 64.0 vs. 56.7 wt%, and 21.3 vs. 35.6 wt% for MgO , Al_2O_3 , and FeO , respectively), suggesting the influence of coeval mantle-derived magmas.

4.2. Zircon geochronology

Zircon crystals from the granites exhibit magmatic oscillatory zoning (Fig. 4a). They are 100–250 μm in length and show variable Th (75–848 ppm) and U (95–560 ppm) contents with high Th/U ratios ranging from 0.5 to 2.8. Twenty-two crystals yielded a weighted $^{207}Pb/^{206}Pb$ age of 1805 ± 11 Ma with a mean square weighted deviation (MSWD) of 0.54 and a well-constrained concordant U–Pb age of 1809 ± 3 Ma (MSWD = 0.04) (Fig. 4b). Some inherited zircons with magmatic oscillatory zoning and accretionary rim were identified in the granites, characterised by relatively lower Th/U ratios of 0.5–0.7 and older ages of 2.0–2.1 Ga (Table 2). The granite samples dated in this study are close to the carbonatite–pyroxenite–syenite complexes and have a similar age to the associated syenites (1810 ± 3 Ma; Xu et al., 2019). A single granite dyke in Fengzhen area showed a consistent age of 1808 ± 6 Ma (Kuang et al., 2020).

Zircons from the gneisses are represented by predominantly metamorphic patches and minor magmatic oscillatory zonings and generally have oval shapes with a length of 50–100 μm (Fig. 4c). They exhibit wide ranges of Th (18–664 ppm), U (161–1544 ppm), and Th/U (0.01–1.82) values. Forty LA-ICP-MS analyses gave an upper intercept age of 1827 ± 14 Ma (MSWD = 1.4), and sixteen among them define a concordant U–Pb age of 1832 ± 4 Ma (MSWD = 3.4; Fig. 4d). The gneisses are consistent in age with the granites. Moreover, the inherited zircon cores in the gneisses record $^{207}Pb/^{206}Pb$ ages of 2.0–2.1 Ga (Table 2), which are also similar to those in the granites.

4.3. Major and trace element geochemistry

The granites contain high SiO_2 (63–75 wt%), Al_2O_3 (12–18 wt%), and K_2O (10–14 wt%) and low CaO (0.3–2.3 wt%) and Na_2O (0.3–0.8 wt%) abundances, with extremely elevated K_2O/Na_2O ratios of 18–42 (Table 3). A plot of A/NK vs. A/CNK [A/CNK = molar ratios of $Al_2O_3/(CaO + Na_2O + K_2O)$] (Maniar and Piccoli, 1989) exhibits a metaluminous to weakly peraluminous character (Fig. 5a). In the $Na_2O + K_2O$ vs. 10,000 Ga/Al discrimination diagram (Whalen et al., 1987), the granite samples differ from M-, S-, and I-type granites, but are similar to A-type rock (Fig. 5b).

The granites have high concentrations of Rb (276–434 ppm), Sr (176–2067 ppm), Ba (2028–7282 ppm) and low levels of total REEs (18–100 ppm) and high field-strength elements (e.g., Nb, Ta, Zr, Hf; Table 3). They show positive anomalies of Ba, K, Pb, Sm, and Hf and negative anomalies of Th, U, Nb, P, and Ti in primitive mantle normalised patterns. The Ta, Sr, and Zr present variable negative and positive anomalies (Fig. 6a). Chondrite-normalised REE patterns show evident enrichment in LREE relative to HREE [$(La/Yb)_{CN} = 44–128$] with strongly positive Eu anomalies ($\delta Eu = 1.6–10.2$; Fig. 6b).

4.4. Isotope geochemistry

Because of high Rb/Sr ratios, the Sr isotopes of granites were not well

Table 2

Zircon U–Th–Pb data of the Fengzhen granites and gneisses.

Sample	Th ppm	U ppm	Pb ppm	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	σ	²⁰⁷ Pb/ ²³⁵ U	σ	²⁰⁶ Pb/ ²³⁸ U	σ	²⁰⁷ Pb/ ²⁰⁶ Pb Ma	σ
<i>Granite</i>												
FZ1802_01	144	113	54	1.27	0.10978	0.00186	4.84767	0.08903	0.31950	0.00417	1795	31
FZ1802_02	556	302	153	1.84	0.11072	0.00146	4.83292	0.07152	0.31567	0.00376	1813	24
FZ1802_03	848	317	170	2.67	0.10951	0.00145	4.84691	0.08513	0.32090	0.00558	1791	24
FZ1802_04	301	152	82	1.98	0.11036	0.00161	4.97931	0.08634	0.32602	0.00412	1805	21
FZ1802_05	430	154	94	2.79	0.10888	0.00157	4.83537	0.08638	0.32033	0.00413	1781	27
FZ1802_06	218	221	100	0.99	0.10981	0.00149	4.92096	0.08036	0.32370	0.00405	1796	24
FZ1802_07	425	167	99	2.55	0.11004	0.00174	5.01921	0.10359	0.32912	0.00504	1811	28
FZ1802_08	301	176	91	1.71	0.11105	0.00184	4.97495	0.08983	0.32467	0.00451	1816	30
FZ1802_09	502	247	134	2.03	0.11078	0.00173	4.95557	0.09501	0.32306	0.00452	1813	28
FZ1802_10	316	276	124	1.14	0.10995	0.00149	4.81005	0.07607	0.31642	0.00391	1798	30
FZ1802_11	523	381	180	1.37	0.10944	0.00146	4.83076	0.07985	0.31904	0.00412	1791	24
FZ1802_12	154	161	72	0.96	0.10767	0.00177	4.77629	0.08490	0.32127	0.00412	1761	30
FZ1802_13	453	314	157	1.44	0.11104	0.00158	5.01057	0.09086	0.32660	0.00492	1816	26
FZ1802_14	374	209	109	1.79	0.10808	0.00180	4.72683	0.09198	0.31625	0.00449	1769	31
FZ1802_15	251	222	109	1.13	0.11138	0.00180	5.12749	0.10692	0.33295	0.00570	1822	29
FZ1802_16	575	348	179	1.65	0.11020	0.00166	5.06628	0.10468	0.33211	0.00558	1803	28
FZ1802_17	75	95	41	0.80	0.10935	0.00178	4.89241	0.08644	0.32400	0.00421	1789	30
FZ1802_18	342	240	120	1.43	0.11057	0.00153	5.07300	0.09165	0.33098	0.00464	1809	26
FZ1802_19	569	217	128	2.62	0.11153	0.00161	5.08185	0.09280	0.32894	0.00487	1824	26
FZ1802_20	785	516	264	1.52	0.11175	0.00155	5.04843	0.08304	0.32620	0.00439	1828	25
FZ1802_21	159	130	63	1.23	0.11216	0.00198	5.12548	0.09669	0.32974	0.00422	1835	32
FZ1802_22	249	135	74	1.84	0.11311	0.00179	5.16909	0.09059	0.32998	0.00429	1850	29
FZ1802_23h	134	184	86	0.73	0.12517	0.00419	6.35490	0.19870	0.36814	0.00513	2031	36
FZ1802_24h	131	184	90	0.71	0.12762	0.00427	6.78369	0.21136	0.38541	0.00531	2065	36
FZ1802_25h	272	560	256	0.49	0.12770	0.00432	6.72325	0.21086	0.38173	0.00523	2067	36
FZ1802_26h	188	274	130	0.68	0.13137	0.00433	6.85684	0.21079	0.37844	0.00515	2116	35
FZ1802_27h	151	229	115	0.66	0.13381	0.00451	7.39796	0.23171	0.40087	0.00552	2149	35
FZ1802_28h	95	181	88	0.53	0.13476	0.00461	7.43395	0.23597	0.39999	0.00558	2161	36
<i>Gneiss</i>												
FZ1911_01	77	426	158	0.18	0.11095	0.00261	5.13615	0.11642	0.33576	0.00377	1815	25
FZ1911_02	87	471	172	0.18	0.11095	0.00262	5.05549	0.11526	0.33047	0.00371	1815	25
FZ1911_03	18	448	160	0.04	0.11091	0.00263	5.13999	0.11729	0.33612	0.00378	1814	25
FZ1911_04	78	477	176	0.16	0.11148	0.00276	5.15481	0.12244	0.33535	0.00384	1824	27
FZ1911_05	93	429	155	0.22	0.11145	0.00278	4.99857	0.11949	0.32528	0.00375	1823	27
FZ1911_06	91	606	219	0.15	0.11114	0.00277	5.07226	0.12086	0.33099	0.00379	1818	27
FZ1911_07	32	418	148	0.08	0.11046	0.00278	5.04046	0.12164	0.33095	0.00383	1807	27
FZ1911_08	43	322	119	0.13	0.11143	0.00283	5.19074	0.12606	0.33783	0.00394	1823	27
FZ1911_09	122	516	190	0.24	0.11263	0.00285	5.11579	0.12373	0.32939	0.00381	1842	27
FZ1911_10	81	596	214	0.14	0.11108	0.00283	5.04057	0.12248	0.32909	0.00381	1817	27
FZ1911_11	96	657	198	0.15	0.11099	0.00262	4.21972	0.09614	0.27576	0.00310	1816	25
FZ1911_12	97	743	250	0.13	0.10940	0.00263	4.68220	0.10844	0.31040	0.00352	1789	26
FZ1911_13	98	560	189	0.17	0.11022	0.00267	4.65382	0.10856	0.30623	0.00349	1803	26
FZ1911_14	38	504	172	0.08	0.11612	0.00296	5.06155	0.12334	0.31612	0.00368	1897	27
FZ1911_15	46	326	127	0.14	0.11142	0.00268	5.45131	0.12668	0.35485	0.00410	1823	26
FZ1911_16	139	308	125	0.45	0.11283	0.00271	5.38567	0.12462	0.34619	0.00394	1845	26
FZ1911_17	155	810	299	0.19	0.11251	0.00194	5.11103	0.08029	0.32959	0.00300	1840	16
FZ1911_18	91	1078	373	0.08	0.11127	0.00210	4.92425	0.08644	0.32105	0.00309	1820	18
FZ1911_19	318	184	93	1.72	0.10919	0.00222	4.89342	0.09409	0.32508	0.00337	1786	20
FZ1911_20	210	161	75	1.30	0.11096	0.00228	4.96051	0.09645	0.32428	0.00338	1815	21
FZ1911_21	316	191	93	1.67	0.10998	0.00282	4.96258	0.12467	0.32721	0.00396	1799	28
FZ1911_22	228	166	78	1.37	0.11141	0.00294	5.09068	0.13196	0.33134	0.00410	1823	29
FZ1911_23	379	1144	406	0.33	0.11573	0.00189	4.83293	0.07102	0.30304	0.00267	1891	14
FZ1911_24	271	187	85	1.45	0.11081	0.00198	4.66261	0.07653	0.30533	0.00292	1813	16
FZ1911_25	18	1368	430	0.01	0.11131	0.00185	4.50372	0.06743	0.29360	0.00261	1821	15
FZ1911_26	125	1544	468	0.08	0.10925	0.00184	4.20714	0.06408	0.27943	0.00250	1787	15
FZ1911_27	255	438	163	0.58	0.10533	0.00299	4.24666	0.11283	0.29240	0.00289	1720	53
FZ1911_28	541	296	142	1.82	0.11125	0.00205	4.59881	0.07828	0.29992	0.00290	1820	17
FZ1911_29	172	825	261	0.21	0.11749	0.00213	4.53641	0.07596	0.28012	0.00265	1918	17
FZ1911_30	273	1117	351	0.24	0.11408	0.00218	4.55142	0.08128	0.28942	0.00281	1865	19
FZ1911_31	87	1063	306	0.08	0.10707	0.00216	3.97722	0.07557	0.26946	0.00271	1750	20
FZ1911_32	195	687	215	0.28	0.11254	0.00237	4.35928	0.08724	0.28097	0.00292	1841	21
FZ1911_33	116	1091	342	0.11	0.11049	0.00253	4.45655	0.09842	0.29252	0.00321	1807	24
FZ1911_34	81	1146	366	0.07	0.10793	0.00262	4.47486	0.09752	0.30070	0.00324	1765	45
FZ1911_35	300	437	161	0.69	0.11250	0.00266	4.74522	0.10852	0.30589	0.00344	1840	25
FZ1911_36	216	164	69	1.32	0.11288	0.00287	4.65225	0.11518	0.29888	0.00363	1846	27
FZ1911_37	307	666	179	0.46	0.10757	0.00418	3.24640	0.11965	0.21889	0.00269	1759	73
FZ1911_38	37	916	277	0.04	0.10815	0.00275	4.33622	0.10795	0.29073	0.00345	1768	28
FZ1911_39	23	1022	374	0.02	0.11269	0.00189	5.28586	0.07997	0.34034	0.00304	1843	15
FZ1911_40	41	888	325	0.05	0.11368	0.00231	5.41085	0.10391	0.34526	0.00349	1859	20
FZ1911_41h	74	170	81	0.43	0.13185	0.00255	7.18938	0.13009	0.39555	0.00398	2123	18
FZ1911_42h	183	309	147	0.59	0.13157	0.00276	7.05108	0.14031	0.38871	0.00407	2119	20
FZ1911_43h	664	640	283	1.04	0.12453	0.00264	6.34126	0.12785	0.36933	0.00385	2022	21

(continued on next page)

Table 2 (continued)

Sample	Th ppm	U ppm	Pb ppm	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	σ	$^{207}\text{Pb}/^{235}\text{U}$	σ	$^{206}\text{Pb}/^{238}\text{U}$	σ	$^{207}\text{Pb}/^{206}\text{Pb}$ Ma	σ
FZ1911_44h	200	455	183	0.44	0.12305	0.00294	5.85595	0.13579	0.34513	0.00392	2001	25
FZ1911_45h	535	723	291	0.74	0.12414	0.00324	5.77425	0.14791	0.33728	0.00409	2017	28

FZ1802_23h to FZ1802_28h and FZ1911_41h to FZ1911_45h are inherited zircons. The σ is the within-run error of a single spot analysis.

Table 3

Whole rock major (wt%) and trace (ppm) element compositions of the Fengzhen granites.

Sample	FZG01	FZG02	FZG03	FZG04	FZG05	FZG06	FZG07	FZG08
SiO ₂	74.68	67.76	65.65	65.24	62.57	73.01	68.88	72.06
TiO ₂	0.01	0.03	0.16	0.04	0.03	0.01	0.04	0.02
Al ₂ O ₃	12.97	16.05	16.19	17.22	18.21	12.06	15.86	13.52
Fe ₂ O ₃	0.58	0.86	0.45	0.64	0.65	0.64	0.33	0.50
MnO	0.03	0.03	0.02	0.02	0.02	0.01	bdl	0.01
MgO	0.02	0.02	0.02	0.03	0.02	0.27	0.22	0.41
CaO	0.41	0.92	2.27	1.92	1.40	1.68	0.28	0.78
Na ₂ O	0.25	0.54	0.42	0.51	0.81	0.52	0.48	0.59
K ₂ O	10.22	12.45	12.66	12.77	14.34	9.96	13.16	11.09
P ₂ O ₅	0.02	bdl	bdl	bdl	0.07	0.03	0.04	0.02
LOI	0.47	0.73	1.88	1.24	1.07	1.48	0.45	0.58
Total	99.66	99.39	99.74	99.62	99.20	99.66	99.75	99.58
Ga	10.9	18.0	15.0	20.3	19.3	21.7	11.9	22.1
Rb	326	371	365	380	434	276	292	327
Ba	3614	5815	2607	3271	7282	2434	2028	3198
Th	3.10	4.22	2.30	1.33	7.95	4.16	3.43	5.20
U	0.49	0.45	0.97	0.44	1.46	0.77	0.78	1.02
Nb	1.04	0.87	3.71	1.36	0.60	2.33	0.87	5.30
Ta	0.93	0.38	0.44	0.33	0.22	0.13	0.21	0.24
Pb	11.6	73.7	55.1	73.5	64.2	8.28	26.4	5.80
Sr	789	1851	462	1078	2067	359	176	294
Zr	4.70	14.8	44.2	8.12	17.3	35.7	15.5	109
Hf	0.12	0.39	1.28	0.27	0.46	0.87	0.48	2.74
Y	0.52	1.37	1.89	1.10	3.55	2.73	1.85	1.04
La	4.63	15.5	13.0	19.6	28.9	26.4	9.93	5.82
Ce	8.32	21.9	19.8	29.3	47.0	45.6	18.7	12.0
Pr	0.80	1.94	1.90	2.56	4.50	4.46	1.77	1.28
Nd	2.54	5.67	5.98	7.15	13.7	13.6	6.05	4.27
Sm	0.34	0.61	0.81	0.72	1.59	1.55	0.90	0.61
Eu	1.10	1.57	1.22	1.20	2.02	0.74	1.08	0.63
Gd	0.32	0.65	0.78	0.76	1.58	1.28	0.80	0.49
Tb	0.02	0.05	0.07	0.05	0.13	0.11	0.09	0.04
Dy	0.10	0.22	0.35	0.19	0.58	0.46	0.41	0.19
Ho	0.02	0.05	0.07	0.04	0.12	0.09	0.06	0.03
Er	0.05	0.14	0.19	0.10	0.37	0.26	0.16	0.08
Tm	0.01	0.02	0.03	0.02	0.06	0.04	0.02	0.01
Yb	0.05	0.16	0.19	0.11	0.40	0.29	0.16	0.09
Lu	0.01	0.03	0.03	0.02	0.06	0.05	0.02	0.01

bdl, below detection limit. LOI, loss on ignition.

Table 4

Sr–Nd isotope compositions of the granites from Fengzhen area.

Sample	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	$\epsilon\text{Nd}_{(t)}$	T_{DM} (Ga)
FZ17G01	2.20	0.755597	5	< 0.70	0.0690	0.510833	7	0.510012	−5.6	2.43
FZ17G02	4.07	0.801524	23	< 0.70	0.0789	0.510933	12	0.509994	−5.9	2.50
FZ17G03	3.64	0.793447	12	< 0.70	0.1005	0.511244	12	0.510048	−4.9	2.56
FZ17G04	4.74	0.822140	9	< 0.70	0.0880	0.511135	10	0.510088	−4.1	2.44
FZ17G05	2.63	0.763195	8	< 0.70	0.0599	0.510800	6	0.510087	−4.1	2.32
FZ17G06	3.14	0.779682	12	< 0.70	0.0683	0.510904	22	0.510091	−4.0	2.35
FZ17G07	3.24	0.781872	10	< 0.70	0.0825	0.510963	16	0.509981	−6.2	2.53

Initial Sr and Nd isotope ratios of the granites are calculated assuming an age of 1809 Ma. The $\epsilon\text{Nd}_{(t)}$ values are calculated based on present-day $(^{147}\text{Sm}/^{143}\text{Nd})_{\text{CHUR}} = 0.1967$ and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$. The σ is the within-run error of a single measurement.

separated and measured. Their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were found to be lower than the Earth's primordial value of 0.699. The granites are characterised by negative $\epsilon\text{Nd}_{(t)}$ values (−4.0 to −6.2) with Nd isotope model ages (T_{DM}) of 2.32–2.56 Ga (Fig. 7a; Table 4). The Hf isotope compositions of zircons from the granites show consistently low $\epsilon\text{Hf}_{(t)}$ values (−3.7 to −7.1) with an Hf model age (T_{DM}) of 2.35–2.48 Ga (Fig. 7b; Table 5), which are similar to those from the gneisses ($\epsilon\text{Hf}_{(t)}$ =

−3.3 to −8.4, T_{DM} = 2.36–2.55 Ga) and syenites ($\epsilon\text{Hf}_{(t)}$ = −5.0 to −8.8, T_{DM} = 2.40–2.55 Ga; Xu et al., 2019). High $\delta^{18}\text{O}_{\text{SMOW}}$ values ranging from 9.9‰ to 10.9‰ are recorded by the zircons from the granites (Fig. 7c; Table 6).

Table 5

Zircon Hf isotope data of the Fengzhen granites and gneisses.

Sample	$^{176}\text{Hf}/^{177}\text{Hf}$	2 σ	$^{176}\text{Lu}/^{177}\text{Hf}$	2 σ	$^{176}\text{Hf}/^{177}\text{Hf}_{\text{initial}}$	$\varepsilon\text{Hf}_{(t)}$	T_{DM} (Ga)
<i>Granite</i>							
FZ1802-01	0.281440	41	0.000225	1	0.281432	−7.09	2.48
FZ1802-02	0.281449	39	0.000305	4	0.281438	−6.87	2.47
FZ1802-03	0.281442	45	0.000251	7	0.281433	−7.05	2.48
FZ1802-04	0.281458	42	0.000305	6	0.281447	−6.55	2.46
FZ1802-05	0.281454	47	0.000330	3	0.281442	−6.72	2.47
FZ1802-06	0.281476	42	0.000201	3	0.281469	−5.78	2.43
FZ1802-07	0.281463	38	0.000265	3	0.281454	−6.32	2.45
FZ1802-08	0.281493	41	0.000263	4	0.281484	−5.25	2.41
FZ1802-09	0.281497	45	0.000226	2	0.281489	−5.06	2.40
FZ1802-10	0.281514	49	0.000220	1	0.281506	−4.45	2.38
FZ1802-11	0.281536	38	0.000223	1	0.281528	−3.67	2.35
FZ1802-12	0.281488	44	0.000269	4	0.281478	−5.44	2.42
FZ1802-13	0.281484	40	0.000178	1	0.281478	−5.46	2.42
FZ1802-14	0.281514	44	0.000297	2	0.281503	−4.55	2.39
FZ1802-15	0.281499	42	0.000246	1	0.281490	−5.02	2.40
FZ1802-16	0.281463	42	0.000265	2	0.281454	−6.32	2.45
<i>Gneiss</i>							
FZ1911-01	0.281389	51	0.000166	1	0.281383	−8.41	2.55
FZ1911-02	0.281408	83	0.000226	6	0.281400	−7.82	2.52
FZ1911-03	0.281451	41	0.000551	14	0.281431	−6.70	2.49
FZ1911-04	0.281467	64	0.000592	5	0.281446	−6.19	2.47
FZ1911-05	0.281420	67	0.000203	4	0.281413	−7.36	2.51
FZ1911-06	0.281432	54	0.000376	7	0.281418	−7.16	2.50
FZ1911-07	0.281491	59	0.001572	67	0.281435	−6.58	2.50
FZ1911-08	0.281413	52	0.000223	2	0.281405	−7.63	2.52
FZ1911-09	0.281488	60	0.000136	1	0.281483	−4.86	2.41
FZ1911-10	0.281497	54	0.000192	2	0.281490	−4.61	2.40
FZ1911-11	0.281494	68	0.001104	8	0.281454	−5.88	2.46
FZ1911-12	0.281469	76	0.000684	19	0.281444	−6.23	2.47
FZ1911-13	0.281439	54	0.000318	8	0.281428	−6.83	2.49
FZ1911-14	0.281421	56	0.000524	5	0.281402	−7.73	2.53
FZ1911-15	0.281500	73	0.000143	1	0.281495	−4.44	2.40
FZ1911-16	0.281483	62	0.000884	16	0.281451	−5.99	2.47
FZ1911-17	0.281471	59	0.000175	1	0.281465	−5.51	2.44
FZ1911-18	0.281491	67	0.000640	57	0.281468	−5.40	2.44
FZ1911-19	0.281499	59	0.000684	2	0.281474	−5.17	2.43
FZ1911-20	0.281488	65	0.001238	14	0.281444	−6.27	2.48
FZ1911-21	0.281557	80	0.003266	64	0.281440	−6.40	2.52
FZ1911-22	0.281491	62	0.000033	1	0.281490	−4.62	2.40
FZ1911-23	0.281559	86	0.001946	64	0.281489	−4.65	2.43
FZ1911-24	0.281610	110	0.002935	25	0.281505	−4.10	2.42
FZ1911-25	0.281538	61	0.000825	15	0.281508	−3.96	2.39
FZ1911-26	0.281556	62	0.001032	13	0.281519	−3.59	2.37
FZ1911-27	0.281572	59	0.001230	4	0.281528	−3.27	2.36

Initial isotope ratios were calculated assuming an age of 1809 Ma and 1827 Ma for the granites and gneisses, respectively. The $\varepsilon\text{Hf}_{(t)}$ values are calculated based on present-day ($^{176}\text{Lu}/^{177}\text{Hf}$)_{CHUR} = 0.0332 and ($^{176}\text{Hf}/^{177}\text{Hf}$)_{CHUR} = 0.282772. The σ is the within-run error of a single spot analysis.

Table 6

Zircon O isotope data of the Fengzhen granites.

Sample	FZ1802-01	FZ1802-02	FZ1802-03	FZ1802-04	FZ1802-05	FZ1802-06	FZ1802-07	FZ1802-08	FZ1802-09	FZ1802-10	FZ1802-11	FZ1802-12	FZ1802-13
$\delta^{18}\text{O}$	10.59	10.70	10.92	10.63	10.92	10.59	10.53	10.28	10.25	10.65	10.34	10.35	10.29
2 σ	0.15	0.13	0.14	0.22	0.16	0.14	0.18	0.23	0.24	0.16	0.21	0.22	0.25
Sample	FZ1802-14	FZ1802-15	FZ1802-16	FZ1802-17	FZ1802-18	FZ1802-19	FZ1802-20	FZ1802-21	FZ1802-22	FZ1802-23	FZ1802-24	FZ1802-25	FZ1802-26
$\delta^{18}\text{O}$	10.71	10.63	10.26	10.41	10.25	10.58	10.78	10.90	10.60	10.55	10.61	10.03	9.94
2 σ	0.26	0.21	0.13	0.16	0.23	0.15	0.23	0.23	0.23	0.20	0.18	0.21	0.20

The σ is the within-run error of a single spot analysis.

5. Discussion

5.1. Granite origin

The Fengzhen Paleoproterozoic alkali-feldspar granites are strongly associated with coeval carbonated alkaline complexes. The latter contains similar Sr–Nd isotope compositions of ($^{87}\text{Sr}/^{86}\text{Sr}$)_i = 0.7028–0.7036, 0.7029–0.7035, and 0.7027–0.7039 and $\varepsilon\text{Nd}_{(t)}$ = −4.1 to −5.9, −4.6 to −6.2, and −3.7 to −5.0 for carbonatites, pyroxenites,

and syenites, respectively (Xu et al., 2019). The granites also show consistent Nd isotope compositions with $\varepsilon\text{Nd}_{(t)}$ ranging from −4.0 to −6.2, implying that the four rock types were possibly derived from a common parental source (Fig. 7a). Liquid immiscibility and fractional crystallisation from a carbonated silicate melt are the main mechanisms for the petrogenesis of silicate rocks associated with carbonatites (Veksler et al., 1998; Halama et al., 2005). However, the carbonate–silicate complexes are commonly silica-undersaturated, and silicate magmas usually stop differentiation as syenite instead of granite

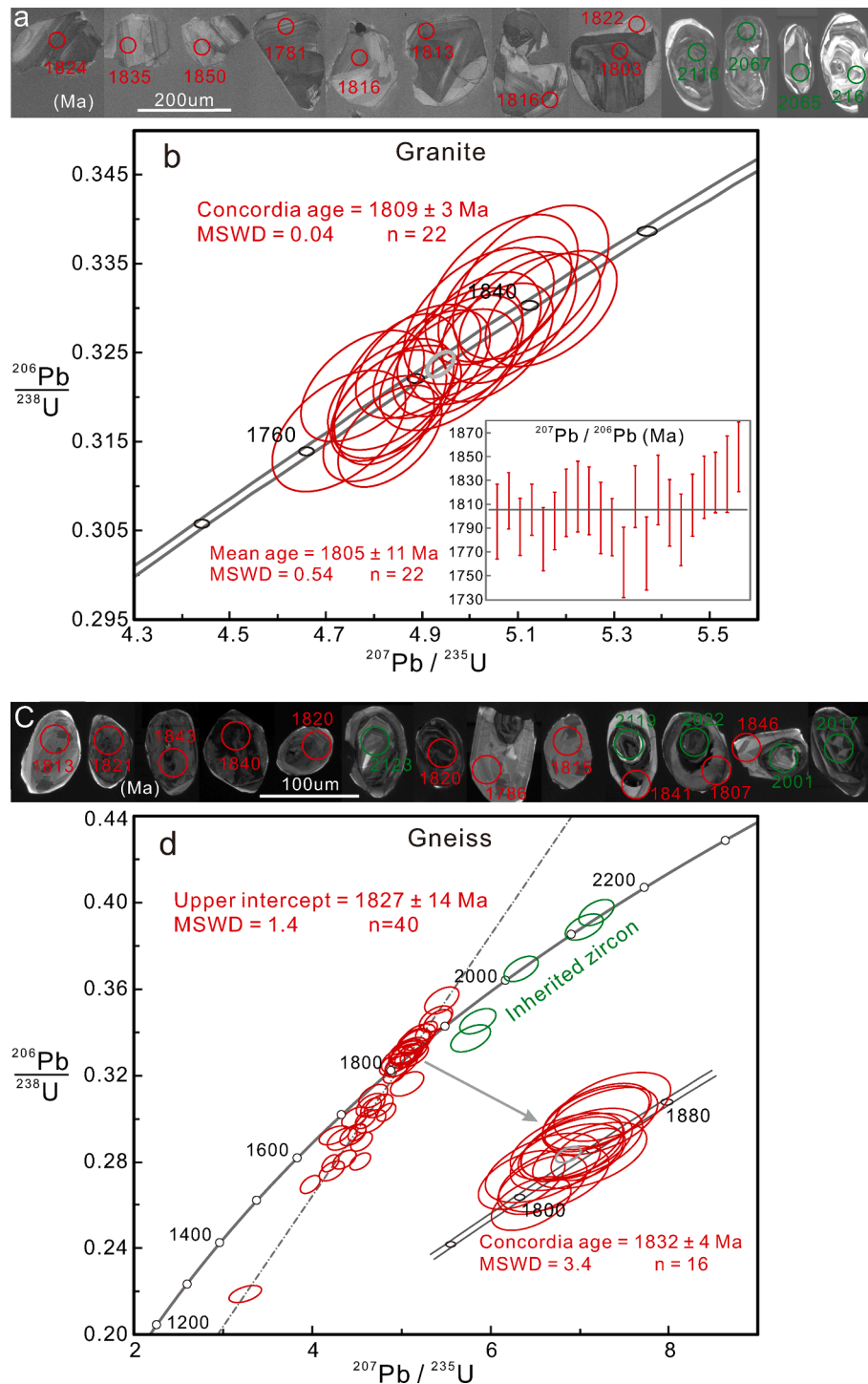


Fig. 4. Representative zircon cathodoluminescence images and U-Pb concordia diagrams of granite (a, b) and gneiss (c, d) from Fengzhen area.

(Wolff, 2017). Experiments also show that the silicate melts produced by liquid immiscibility are characterized by silica-undersaturation (Veksler et al., 2012; Nabyi et al., 2020). Fractional crystallisation of syenites would form granites but result in high REE contents and negative Eu anomalies because of the low REE partitioning coefficients (except Eu) between feldspar and silicate melts (Bédard, 2006). This is inconsistent with the geochemical features of the granites, which show low REE contents and positive Eu anomalies ($\delta\text{Eu} = 1.6\text{--}10.2$; Fig. 6b). Therefore, the alkali-feldspar granites have no petrogenetic relationship with the alkaline rocks.

The granites have high K_2O and low CaO and Na_2O contents

(Table 3), exhibiting metaluminous to slightly peraluminous characteristics (Fig. 5a). Nevertheless, typical Al-rich minerals (e.g., garnet and cordierite) of S-type granites are absent in the rock. The petrological and geochemical features of the granites are also inconsistent with I-type granites, which usually show high Na_2O and CaO contents and $\text{Na}_2\text{O}/\text{K}_2\text{O} > 1$ and contain abundant amphibole and accessory titanite (Chappell and White, 1992; Chappell and White, 2001). In the $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. 10,000 Ga/Al diagram, the rock plots in the field of A-type granite (Fig. 5b). A-type granites are characterized by Fe-rich mafic minerals and high levels of high field strength elements as well as high Ga/Al ratios (>2.6) (Whalen et al., 1987; Eby, 1990; Frost and Frost,

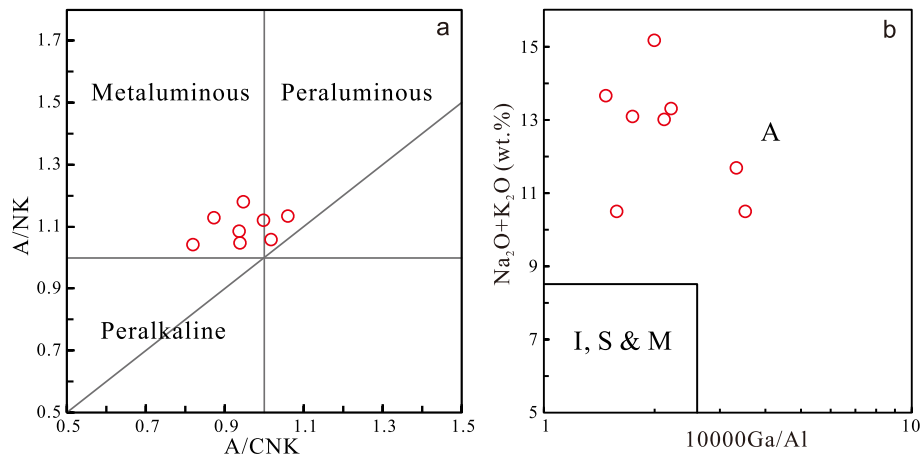


Fig. 5. A/NK vs. A/CNK (a) and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. 10,000 Ga/Al (b) diagrams for the Fengzhen granite.

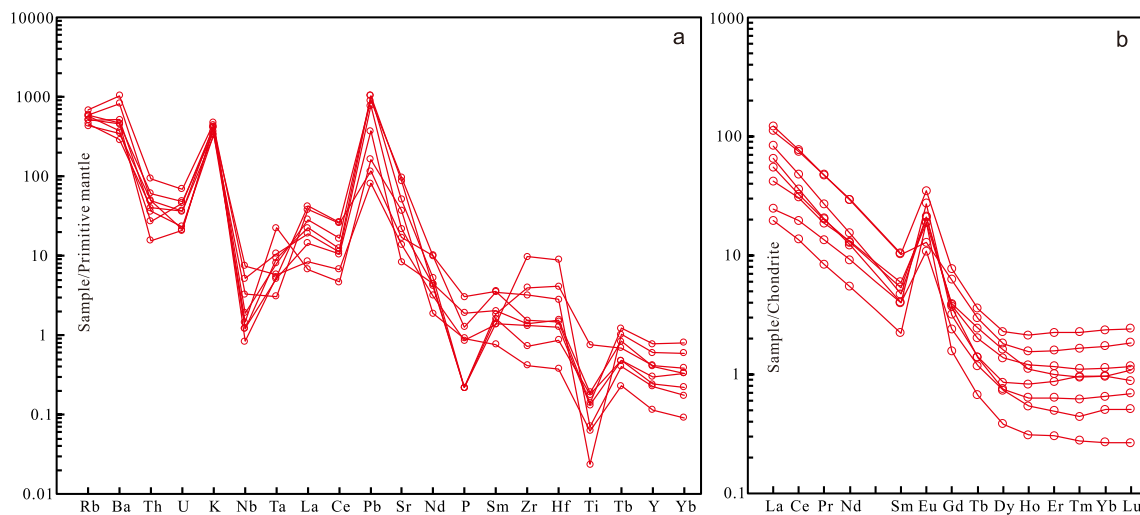


Fig. 6. Distributions of selected trace elements normalised to the primitive mantle (a) and REE normalised to chondrite (b) in Fengzhen granites. The normalisation values are from McDonough and Sun (1995).

2011; Dall' Agnol et al., 2012). However, the alkali-feldspar granites show low Nb, Ta, Zr, Hf, and REE compositions and positive Eu anomalies (Fig. 6; Table 3), distinct from typical A-type rocks. This indicates that they may not undergo strong fractional crystallization. Clinopyroxene and titanite in the rock generally occur at the contact zone with pyroxenite and pyroxene syenite (Fig. 2c; Fig. 3b, c). The minerals are exotic and captured from the associated alkaline complexes.

The granites were found to associate with the rarely exposed gneisses (Fig. 2a, g). They also occur as pockets and veinlets, consisting of K-feldspar and quartz, in the gneisses (Fig. 2h; Fig. 3d). Zircons from the two rock types record similar U–Pb ages (Fig. 4) and initial Hf isotopes (Fig. 7b). The inherited zircons also show similar ages of 2.0–2.1 Ga (Table 2). Such lines of evidence indicate that the alkali-feldspar granites have a genetic relationship with the gneisses. Al-rich minerals of spinel and corundum are present in the gneisses (Fig. 3e, f), indicating a pelitic sediment source. The metasedimentary rocks in the Khondalite Belt close to the studied area show detrital and metamorphic zircon ages of 2.3–2.0 Ga and 1.95–1.85 Ga, respectively (Wan et al., 2006; Xia et al., 2008; Yin et al., 2009; Cai et al., 2014). The granites record considerably higher zircon $\delta^{18}\text{O}_{\text{SMOW}}$ values (9.9–10.9 ‰) than in contemporary zircons from granitoid rocks worldwide and the associated syenites (Fig. 7c). The 2.2 Ga I-type granites in Fengzhen area also show relatively lower $\delta^{18}\text{O}_{\text{SMOW}}$. The O isotope data strongly support that the Paleoproterozoic (~1.8 Ga) granite sources contain supracrustal

materials. Therefore, we propose that the alkali-feldspar granites and associated Al-rich gneisses were formed by anatexis of the pelitic rocks. The melt compositions depend on the protolith compositions, pressure and temperature (P–T) conditions during melting, integration of residuum, and melt differentiation (Sawyer, 2001; Sawyer, 2008). The occurrence of spinel and corundum requires Si-poor and Al-rich sources and high temperatures. Segregation and extraction of melts (i.e., granite) from the sources carry the fusible components, such as Si and alkali, and leave refractory components of Al_2O_3 , FeO, MgO, and TiO_2 in the residuum (i.e., gneiss) (Sawyer et al., 2011). This results in chemical composition changes of the system, and thus the Al-rich minerals are present in the gneisses but absent in the granites.

5.2. Heat source for partial melting

Normal geothermal gradients are seldom sufficient to provide necessary heat for partial melting of the crust. Mantle-derived magmas may be an alternative heat source. The mantle heat may be provided through mantle upwelling and crustal thinning and through the intra- and underplating of mafic magmas (Clemens, 2003). The carbonated alkaline magmas arose from the mantle and provided sufficient heat for the partial melting of metasedimentary rocks in the crust, generating the anatexis melts of alkali-feldspar granites and Al-rich gneiss residuum. Ultra-high temperature granulites (>1000 °C) have been found 10 km

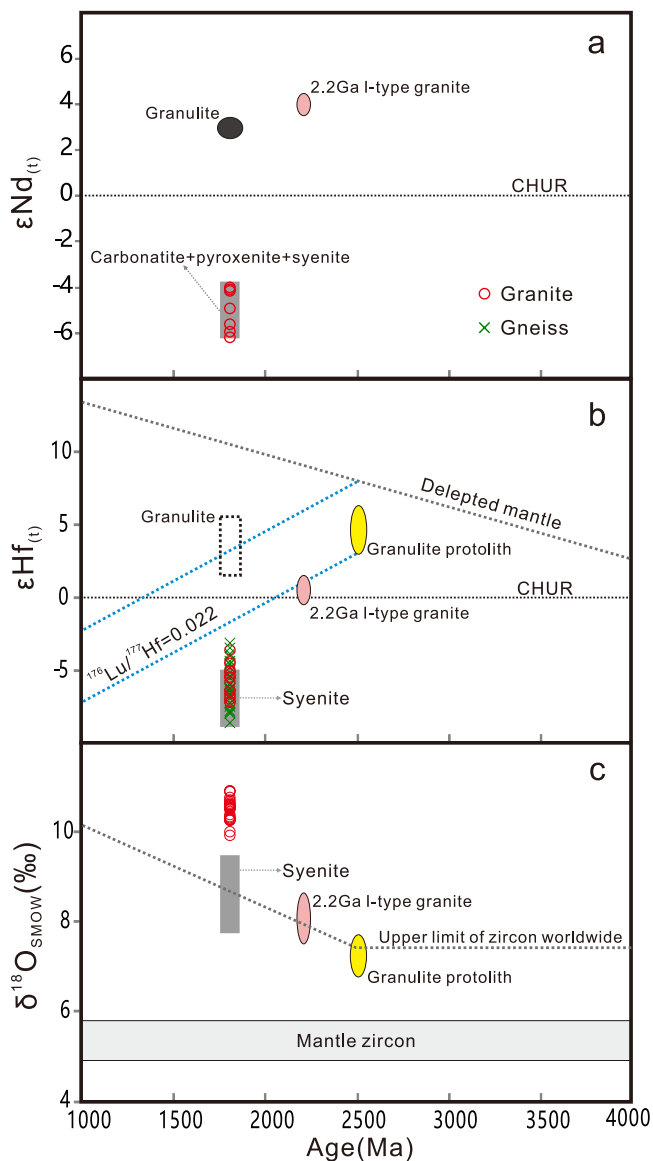


Fig. 7. Variation of whole-rock $\epsilon\text{Nd}(t)$ values in the granites (a), zircon $\epsilon\text{Hf}(t)$ values in the granites and gneisses (b), and zircon $\delta^{18}\text{O}_{\text{SMOW}}$ values in the granites (c) shown in comparison to 1.8 Ga carbonatites, pyroxenites, and syenites from Fengzhen and Huai'an areas, and 2.2 Ga I-type granites from Fengzhen area. Data sources: 1.8 Ga carbonatites (Nd), pyroxenites (Nd), and syenites (Nd–Hf–O) are from Xu et al. (2019); 2.2 Ga I type granites (Nd–Hf–O) are from Zeng et al. (2017) and Xu et al. (2019); 1.8 Ga granulites (Nd–Hf) are from Guo et al. (1993) and Zhang et al. (2016); 2.5 Ga granulite protoliths (Hf–O) are from Zhang (2014); $^{176}\text{Lu}/^{177}\text{Hf}$ ratio for mafic crust is taken from Amelin et al. (1999), and the depleted mantle evolution curve is based on the average modern-day values of $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ (Griffin et al., 2000); the upper limit of zircon and mantle zircon $\delta^{18}\text{O}_{\text{SMOW}}$ values (worldwide) are from Valley et al. (2005); and CHUR, chondritic uniform reservoir.

away from the studied area, which recorded the mantle-derived CO_2 metasomatism (Santosh et al., 2007; Santosh et al., 2008). Due to the contamination of the ultramafic magmas, clinopyroxene and titanite occur in the granite margin, and the mica and spinel in gneisses close to the alkaline rocks show variable Fe–Mg compositions (Table 1). The carbonatite–pyroxenite–syenite complexes have relatively high REE and Hf contents (Xu et al., 2019). The Nd and Hf isotope compositions of the alkali-feldspar granites may have been assimilated by the coeval carbonated alkaline magmas and therefore show similar isotope values

(Fig. 7a, b), resulting in ambiguity issue of the granite origin.

Zeng et al. (2017) reported Paleoproterozoic I-type leucogranites (2.2 Ga), S-type garnet granites (2.0 Ga), and high-pressure granulites (1.97 Ga) in the studied area. These rock assemblages suggest that this region may have underwent arc–continental collision at ~ 2.2 Ga and the continent–continent collision between the Eastern and Western blocks of the NCC began at ~ 2 Ga. Gneiss in the TNCO records 1.82–1.84 Ga metamorphic event and clockwise P–T paths with peak conditions of 8.2–13 kbar and 695–822 °C, which was involved in the Paleoproterozoic subduction and/or collision activities (Liu et al., 2021). Rare eclogite and garnet pyroxenite xenoliths hosted by the Fengzhen carbonatites also show the metamorphism age of ~ 1.8 Ga and cold thermal gradients of 250 ± 15 °C/GPa (2.5–2.8 GPa and 650–670 °C) and 307 ± 35 °C/GPa (2.6–3.3 GPa and 890–962 °C), respectively, indicating a typical deep subduction in the Paleoproterozoic (Xu et al., 2018; Li et al., 2021). The carbonatite has a sediment-derived C isotope signature and enriched initial Sr–Nd isotope compositions, indicative of recycled ocean crust components in the mantle sources (Xu et al., 2019). The intrusion of the alkali carbonatite–pyroxenite–syenite complex indicates a post-orogenic setting in the Paleoproterozoic. The mantle-derived carbonated alkaline magmas catalysed the melting of pelitic rocks, which produced the alkali-feldspar granites and residual Al-rich gneisses.

6. Conclusion

The Paleoproterozoic alkali-feldspar granites in the Trans-North China Orogen show temporally and spatially close association with alkaline rocks (carbonatites, pyroxenites, and syenites) and gneisses. They have extremely high K_2O and low REE contents with positive Eu anomaly, and are not fractional products of the associated syenites. Zircon from the granites has high $\delta^{18}\text{O}_{\text{SMOW}}$ value and similar U–Pb age and initial Hf isotope to that in the associated gneisses. The Paleoproterozoic carbonated alkaline magmas arising from the mantle were the dominant heat source that induced the partial melting of pelitic rocks, which produced the alkali-feldspar granite melt and Al-rich gneiss residuum. Granitoid rocks showing alkaline affinity in orogenic belts, may not originate from the fractionation of mantle-derived intermediate magmas but may have formed from reworked sedimentary materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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