Crystalline inliers near Lake Iro (SE Chad): Post-collisional Ediacaran A2-type granitic magmatism at the southern margin of the Saharan Metacraton

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Abstract

The structure and evolution of the continental crust in the southern part of the Saharan Metacraton (central Africa) is poorly known due to extensive laterite and sediment cover as well as geographic isolation. We report on a series of five crystalline inliers newly discovered near Lake Iro (south-eastern Chad) that offered the opportunity to unravel the nature of the local basement in this area. Two spatially determined petrographic types are exposed in the inliers: a medium-grained porphyritic amphibole–biotite granite and a biotite microgranite with typical embayed (rhyolitic) quartz phenocrysts, both containing fine-grained melanocratic igneous enclaves. Some porphyritic granites display evidence for low temperature deformation along N60 shear zones. The Lake Iro igneous rocks are typified by their ferroan mineralogy, define a ferroan alkali-calcic metaluminous to weakly peraluminous potassic association, and exhibit elevated HFSE (Zr, Nb, Y) and REE contents. Therefore, they are best classified as A_2-type granites. They are variably ferromagnetic with total magnetization lower than 1 A/m. The Lake Iro granites most likely correspond to a single subvolcanic–plutonic silicic complex because: (i) first-order geochemical modelling indicates that the microgranites can be generated by 30% fractional crystallization of a two feldspar–amphibole assemblage from a porphyritic granite melt and (ii) both granite types yield zircon U–Pb emplacement ages consistent within a 575.3 ± 5.6 to 581.3 ± 3.8 Ma time frame. The Lake Iro granites thus represent the oldest of a series of post-collisional igneous associations exposed in southern Chad and nearby countries which, collectively, show that the amalgamation of the constituent blocks of the southern Saharan Metacraton is older than 580 Ma.

Keywords: A-type granites, post-collisional magmatism, Saharan Metacraton, Pan-African orogeny, southern Chad

Introduction

The geodynamic framework of Central Africa is not completely understood. In this area, the continental crust was assembled in the late Neoproterozoic (0.68 to 0.58 Ga) and built up by two main Neoarchean to Paleoproterozoic cratonic blocks (the West African Craton and the Congo Craton) ligatured by the so-called Pan-African mobile belts (Fig. 1a). These include the Trans Saharan Orogen, the East African Orogen and the Oubanguides (Abdelsalam et al., 2002; Black and Liegeois, 1993; Ennih and Liégeois, 2008; Garfunkel, 2015; Kennedy, 1964; Kröner, 1980; Liégeois et al., 2013; Stern, 1994). These mobile belts are intensively deformed crustal segments resulting from the amalgamation of reworked microcratonic domains and juvenile crust (extracted from the mantle not long before its incorporation into the belts). The juvenile crust formed between 0.8 and 0.65 Ga, during the closure of several oceanic domains, and encompasses a set of (meta)igneous and (meta)sedimentary rocks which collectively represent remnants of active margins (Bouyo et al., 2015; Caby, 2003; Liégeois et al., 2003; Triantafyllou et al., 2016). The intrinsically composite origin of the mobile belts is best reflected by the heterogeneous radiogenic isotope signature of their late Neoproterozoic igneous rocks which testifies to the tapping of two contrasting geochemical reservoirs: an old basement (Neoarchean to Paleoproterozoic cratonic fragments) and Neoproterozoic arc rocks (Errami et al., 2009; Liégeois et al., 2003, 1998; Toteu et al., 2001). The Arabian Nubian Shield within the East African Orogen (Fig. 1a) stands as a notable exception as it lacks any large remnant of pre-Neoproterozoic crust (Stern, 2002). These mobile belts also contain significant volumes of post-collisional igneous rocks and have been dissected by continent-scale (100s of km long) strike-slip shear zones which can be traced in the adjacent South American continent (Ngako et al., 2003; Njonfang et al., 2008; Toteu et al., 2004).

Among this geodynamic puzzle lies the Saharan metacraton (Abdelsalam et al., 2002) which is also termed the Central Saharan ghost craton (Black and Liegeois, 1993). This is a poorly known crustal domain which would encompass several Pan-African mobile belts suturing cratonic blocks. The latter have been imaged using geophysical methods (Murzuq, Al-Kufrah and Chad cratons, Fezaa et al., 2010; Liégeois et al., 2013) but detailed petrographic data on their constituent lithologies are restricted to one report (Bea et al., 2011). The S-SE region of Chad is located in a critical domain at the southern margin of the Saharan Metacraton and within the so-called Oubanguides or Central African Orogenic Belt (Fig. 1) which connects it to the Congo Craton (Abdelsalam et al., 2002; Pin and Poidevin, 1987; Toteu et al., 2004). However, the geology of the S-SE region of Chad is relatively unknown due to its geographical isolation and the large extension of laterite and recent sediment cover.

Field trips were conducted during the GELT Program on Lake Iro (10°10'N - 19°42'E) located in the southern part of Lake Chad Basin, about 100 km north of the border with the Central African Republic (Fig. 1b). The goals of the GELT project included description of the geological environment of the lake, assessment of its putative impact crater origin (Reimold and Koeberl, 2014), characterization of its sedimentary filling and determination of the hydrological and hydrogeological features of the area (Poulin et al., 2019). The present study focused on exploration of the lake surroundings and presents a description of newly discovered crystalline inliers where granitoids are exposed. Petrographic and geochemical investigations, as well as U-Pb zircon dating were conducted on selected samples. We also recorded basic magnetic properties of the constituent lithologies for application to aeromagnetic anomaly interpretation. This new set of data, coupled with the examination of geophysical regional anomalies, offers the opportunity to correlate the newly described igneous suite with geological formations located in neighboring sectors of the Oubanguides and position the Lake Iro region within the geodynamic framework of Central Africa.

1. Geological setting

Four main lithotectonic domains of the Oubanguides Pan-African mobile belt are exposed in southern Chad and nearby countries (Fig. 1b): the Ouaddaï massif to the North-East, the Guéra Massif to the North, the West Cameroon Domain and its Chadian continuation (termed the Mayo Kebbi massif and hereafter referred to as MK–WCD) and the Adamawa-Yadé domain (AYD) to the South. The AYD, mainly exposed in Cameroon and the Central African Republic (CAR), is composed of Neoproterozoic metavolcanosediments (Toteu et al., 2006) and features remnants of Archean to Paleoproterozoic crust metamorphosed during Neoproterozoic times (Ganwa et al., 2016; Penaye et al., 1989; Toteu et al., 2001). Abundant syn- to post-tectonic (mostly Ediacaran) granitoid plutons have been described in the AYD (Bessoles and Trompette, 1980; Soba et al., 1991; Tchameni et al., 2006; Toteu et al., 2004). Finally, the Central Cameroon Shear Zone (Fig. 1b) corresponds to a major late Pan-African structure dissecting the AYD (Njonfang et al., 2008).

The MK–WCD is regarded as a predominantly juvenile Neoproterozoic crust segment formed in an active margin setting (Bouyo et al., 2015; Penaye et al., 2006; Pouclet et al., 2006). It includes: (i) (meta)sediments deposited in the Cryogenian–Ediacaran and metamorphosed shortly afterwards (Bouyo et al., 2009; Toteu et al., 2006); (ii) very scarce fragments of reworked Paleoproterozoic crust (Bouyo et al., 2009); and (iii) several magmatic calc-alkaline plutonic suites, the earliest consisting of mafic to intermediate granitoids emplaced between 737 and 723 Ma while the second consists of more silicic terms and is dated at 665–640 Ma (Bouyo et al., 2016; Penaye et al., 2006). The MK–WCD was involved in a polyphase tectonic collage during the Pan-African orogeny. First the Mayo-Kebbi arc was juxtaposed against the AYD at c. 650-640 Ma, a contact corresponding to the sinistral Tcholliré-Banyo Shear Zone (Nomo et al., 2017; Pinna et al., 1994) (Fig. 1b). Then, this newly accreted block collided with a more western segment, the Neoproterozoic magmatic arc of Poli. As noted for the AYD, the MK–WCD rocks were intruded by Ediacaran c. 570 Ma-old post-collisional granites (Isseini et al., 2012; Pouclet et al., 2006).

Little is known about the Guéra massif which is primarily composed of granitoids (with minor gabbroic bodies) and metamorphic rocks (Isseini et al., 2013; Kusnir and Moutaye, 1997). A recent U–Pb dating survey of the igneous rocks revealed emplacement ages ranging between 595 and 545 Ma (Shellnutt et al., 2020, 2019, 2018, 2017) while a Neoproterozoic age is inferred for the metamorphic lithologies. Similarly, limited data are available on the southern Ouaddaï massif (Fig. 1b) which encompasses a range of c. 635–540 Ma-old granitoids (Djerossem et al., 2020; Kusnir and Moutaye, 1997; Liégeois, 1993) along with metamorphic rocks including amphibolites and Neoproterozoic metasediments which would have experienced metamorphism at 620–600 Ma (Djerossem et al., 2020). Results of detrital zircon geochronology performed on alluvium from the Chari river, which drains a large catchment covering most of SE Chad, yielded a date distribution clustered in the interval 550 – 650 Ma. This further indicates that the bulk of the local crust has been strongly affected by an Ediacaran magmatic episode (Shellnutt et al., 2019).

The post-Pan-African cover of the study area includes Cretaceous to Quaternary terrigenous sedimentary formations (Genik, 1993; Guiraud et al., 2005) which constitute notably thick, i.e. pluri-kilometric, sequences in four extensional to transtensional basins (Bongor, Doba, Doseo and Salamat, Fig. 1b). Sedimentation in these basins was partly controlled by normal to dextral brittle deformation along crustal structures parallel to the Pan-African shear zones thus suggesting a strong structural inheritance (Genik, 1993). Cretaceous to Pliocene protracted alkaline volcanic activity has also been recorded in the area (e.g. Nkouandou et al., 2008)

2. Materials and methods

2.1 Bedrock exposures around the Lake Iro

Most of the crystalline basement around the Lake Iro is hidden by an extensive lateritic cover (locally as thick as 20 m) and by recent sediments. Five bedrock occurrences were newly identified in the area and investigated during this study (Fig. 2, 3).

Two occurrences were discovered respectively 2 km S and 5 km SW of Lake Iro, close to the Massadjanga village (Fig. 2). Site G_1 *(10°01'36.84N/19°25'44.173E*) (Fig. 3a) is a massive outcrop forming two roughly 300 m-long and N60-trending ridges, together with smaller exposures being found southwards. Site G_2 *(10°00'59.02N/19°23'04.39E)* corresponds to a 50 m-round subcircular massif surrounded by large boulders. The Massadjanga outcrops are built-up by a medium-grained locally K–feldspar-porphyritic granite (samples A2, A3, A4, A5, Iro08) cut across by 15- to 20-cm wide aplite veins (sample Iro17, Fig. 3c) and hosting various enclaves (Fig. 3b and d). These encompass 30- to 40 cm large, fine- (Iro15) to medium-grained (Iro18), light-coloured and quartz-bearing varieties along with smaller, darker, fine-grained mafic types (Iro09) akin to mafic microgranular enclave (MME) (Didier and Barbarin, 1991).

Two outcrops are located *c.* 10.5 km NW of the lake, near the Karou village. Site G_3 *(10°12'50N/19°18'40E)* (Fig. 3e) corresponds to a rocky tip built-up by more-or-less loose blocks lacking clear orientation. Site G_4 *(10°12'52N/19°19'10E)* (Fig. 3f) is a 300 m-round subcircular massive outcrop showing N110 to N140-trending joints. Both outcrops feature as main rock type an unsheared biotite microgranite (samples A1, A6, A7, A8). The microgranite hosts rounded fine-grained melanocratic enclaves (Iro04) (Fig. 3g) and are locally cut across by pegmatite veins.

Site G_5 *(09°58.623'N/19°04.315'E)* (Fig. 3h) is located SW of Lake Iro, near the village of Malé. It features dome-shaped outcrops capped by large boulders composed of a medium-grained porphyritic granite (sample A9) locally cut across by aplite (Fig. 3i) veinlets. Two groups of joints strike N30 to 40 and N120, respectively.

2.2 Mineral chemistry

Mineral major element compositions were measured at the Laboratoire Magmas & Volcans (Clermont-Ferrand, France) using a Cameca SX100 electron microprobe with an accelerating voltage of 15 kV, a beam current of 15 nA, a beam size of 1 μm, and 20s counting times for all elements. The standards used were natural and synthetic minerals. Biotite and amphibole structural formulas (including ferric contents) were calculated using the approach and spreadsheets of Li et al. (2020a, 2020b) and the grains named following the classification schemes of Rieder et al. (1999) and Hawthorne et al. (2012), respectively. Feldspar formula were calculated using a Gabbrosoft spreadsheet. Representative mineral analyses are available in Supplementary Table 1.

2.3 Whole-rock geochemistry

Whole-rock major and trace element compositions were analysed at the Service d'Analyse des Roches et Minéraux (SARM, CNRS, Nancy) from powdered samples. Major element compositions were measured using an emission spectrometer ICP-OES (ICap 6500 Thermo Fischer), and trace elements by ICP-MS (Thermo Elemental X7) following the method detailed by Carignan et al., (2001). Typical analytical precisions were *c.* 2% for major elements and 5-8% for trace elements.

2.4 Zircon U-Pb dating

Zircon grains were separated from crushed rock samples at Saint-Etienne University using standard techniques (magnetic separator, heavy liquids), cast into epoxy mounts and polished down to equatorial sections. U–Th–Pb isotope data were measured by laser ablation inductively coupled mass spectrometry at the Laboratoire Magmas & Volcans (Clermont-Ferrand, France). Zircons were ablated using a Resonetics Resolution M-50 equipped with a 193 nm Excimer laser system coupled to a Thermo Element XR Sector Field ICP-MS. Helium carrier gas was supplemented with N_2 prior to mixing with Ar for sensitivity enhancement (Paquette et al., 2014). The laser was operated with a spot diameter of 27 µm, a repetition rate of 3 Hz, and a laser fluence of 2.5 J/cm^2. The alignment of the instrument and mass calibration were performed before every analytical session using a NIST SRM 612 reference glass, by inspecting the signals of ^{238}U, ^{232}Th and ^{208}Pb and by minimising the ThO^+/Th^+ ratio. The analytical method for isotope dating with laser ablation ICPMS is similar to that reported in Hurai et al., (2010) and Mullen et al., (2018). The ^{235}U signal is calculated from ^{238}U on the basis of the ratio ^{238}U/^{235}U = 137.818 (Hiess et al., 2012). Single analyses consisted of 30 seconds of background integration with the laser off followed by 60 seconds integration with the laser firing and a 20 seconds delay to wash out the previous sample and prepare the next analysis.

Data were corrected for U-Pb fractionation occurring during laser sampling and for instrumental mass bias by standard bracketing with repeated measurements of GJ-1 zircon reference material (Jackson et al., 2004). Repeated analyses of 91500 zircon reference material (Wiedenbeck et al., 1995) during each analytical session and treated as unknown, independently controlled the reproducibility and accuracy of the corrections. Data reduction was carried out with the software package GLITTER® (Van Achterbergh et al., 2001). Concentrations of U, Th, and Pb were calculated by normalization to the certified composition of GJ-1 (Jackson et al., 2004). Data were not corrected for common Pb. Tera-Wasserburg $^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$ diagrams were generated for each sample using Isoplot/Ex v. 2.49 software of Ludwig (2008). Error ellipses for each point are shown at the 2σ level and incorporate both internal and external uncertainties. Data points were pooled and Isoplot was used to calculate a date and associated 2σ error for each sample.

2.5 Magnetic properties

Low-field susceptibility (K, dimensionless in SI) was measured on large sub-samples (circa 24 to 72 g) using the KLY2 Kappabridge. Natural and saturation isothermal remanences (NRM and IRM, in A/m) were measured using a 2G cryogenic magnetometer on smaller subsamples (7 to 21 g). Measurements were normalized by mass but transformed into volume normalized units using an arbitrary density of 2.7. Using a present day ambient field H of 28 A/m, induced magnetization M_i=K*H was used to compute the total in situ magnetization (Mi + NRM) and Koenigsberger ratio NRM/M_i, which are typical parameters for magnetic anomaly interpretation. To evaluate the origin of NRM and possible bias by lightning, NRM/IRM ratios were computed before and after demagnetization in a 30 mT alternating field (AF).

3. Results

3.1 Petrography and mineral chemistry

3.1.1 The Massadjanga-Malé suite

The Massadjanga and Malé granites share a similar mineralogy and both will be described concomitantly in the following. They exhibit medium-grained (>1 mm) porphyritic textures and the common igneous assemblage includes quartz, microcline

(Or$_{90–94}$, Fig. 5a), oligoclase (An$_{14–27}$, Fig. 5a), amphibole, biotite and a large amount of accessories such as titanite, Fe-Ti oxides, zircon, apatite and epidote (Fig. 4a to c and h to i). The samples collected near Massadjanga display local evidence for strong deformation leading to protoclastic to mylonitic textures. Quartz appears as neo-crystals within polycrystalline mylonitic bands (Fig. 4c) or as partially restored phenoclasts. The K-feldspar occurs as phenocrysts and small laths in the matrix. The former are perthitic and poikilitic with inclusions of quartz and plagioclase. The plagioclase grains embedded in the K-feldspar are slightly more calcic than the crystals of the matrix. Calcic amphibole is a common mineral in the granite and is notably Fe-rich (3.5–4 a.p.f.u.) and ferroan (Mg-number lower than 25). This mineral displays several habitus. A former green-brown amphibole (Ti-rich hastingsite) partially recrystallized in blue-green amphibole (hastingsite). Part of the green-brown amphibole could derive from the breakdown of earlier Ca-pyroxene as suggested by the presence of amphibole-quartz symplectites. Finally, amphibole is partially replaced by biotite and epidote. Fe-rich (1.9–2.1 a.p.f.u.) and ferroan (Mg# <25) biotite (Fig. 4a) classified as annite (Fig. 5b) develop as large crystals that contain numerous zircons. Igneous compositions are commonly preserved but a third of the analysed grains plot in the field of reequilibrated biotite (Fig. 5c) in the diagram of Nachit et al. (2005). Feldspars, amphibole and biotite locally show undulatory extinction and/or fracturing. Apatite, oxides and zircons appear in clusters associated with ferromagnesian minerals. They are usually euhedral and well prismated. Fe-Ti oxides are partially replaced by titanite.

The mafic microgranular enclave (MME Iro09, Fig. 3b) has sliced contacts with the host granite. It shows a sub-doleritic texture well marked by plagioclase laths. Oligoclase, amphibole, and biotite are the dominant minerals while quartz and K-feldspar are subordinate. Post-magmatic deformation is underlined by undulatory extinction of crystals. Epidote, apatite, Fe-Ti oxides together with secondary titanite are abundant. However the thin section reveals a particular, several mm-thick zone at the granite–MME contact. This zone is enriched in amphibole, biotite, needle-shape apatite and large prisms of zircon. It could result from thermal–chemical exchanges between the MME and its host, related to magma mixing processes.

The aplite dyke (Iro17, Fig. 3c) and the leucocratic enclave (Iro15, Fig. 3d) both display sharp contacts with the host granite. They are similar to the main granite facies, regarding mineral assemblage and deformation features, but typified by a finer grain size of less than one mm.

3.1.2 The Karou suite

The Karou microgranite (A1, A6, A7, A8) is characterized by a microgranular texture with hypovolcanic features such as globular embayed (rhyolitic) quartz crystals and, less commonly, a slight “fluidal” fabric underlined by oriented euhedral laths of sodic plagioclase. No significant post-magmatic deformation features were observed (Fig. 4e and f). The mineral assemblage is consistent with a high degree of differentiation: quartz, microcline ($Or_{92–97}$, Fig. 5a) and albite ($An_{1–18}$) are abundant and occur both as phenocrysts and as major components of the mesostasis (Fig. 4e,f). Microcline phenocrysts often include globular quartz inclusions and plagioclase is mainly restricted to the groundmass. The only Fe-Mg mineral is Fe-rich (3.8–4.7 a.p.f.u.) and highly ferroan (Mg# <10) magmatic biotite (annite, Fig. 5b,cd). Epidote and titanite are present but always in lesser amounts. Zircon is embedded in biotite or occurs as anhedral grains in the groundmass. Sample A8 notably contains fluorite, which displays an interstitial habitus. Sample A6 is slightly coarser-grained than the typical facies (Fig. 4e). The melanocratic enclave Iro04 (Fig. 3g) is composite with a microgranular inner part surrounded by a narrow 3 cm-thick rim, with a coarser sub-millimeter grain, at the contact with the host granite. The mineralogy is mainly composed of quartz, dominant plagioclase (albite-oligoclase), K–feldspar and abundant biotite as large crystals.

3.2 Whole-rock geochemistry

The limited influence of post-magmatic alteration and weathering on whole-rock chemical signatures is evidenced by: (i) the relatively fresh aspect of the rocks at the hand-sample and thin-section scale; (ii) the weathering indexes W, calculated following the method of Ohta and Arai (2007), are always lower than 30% in a FMW diagram (see Couzinié et al., 2017); (iii) the positive correlations between fluid-mobile (Ba, Sr) and fluid-immobile (Zr, Hf) incompatible trace elements. Therefore, we will consider in the following that the range of observed chemical compositions exclusively results from igneous processes.

3.2.1 The Massadjanga-Malé suite

This suite shows a large compositional variation with SiO_2 contents mostly ranging between 68.4 and 77.0 wt, the MME Iro09 being less silicic (SiO_2: 61.9 wt.%). All samples plot in the field of granite and notably define a “subalkaline” trend in the P–Q cationic diagram (Fig. 6a) of Debon and Le Fort (1983). In the Q'–ANOR normative classification diagram of Streckeisen and Le Maitre (1979), all but two samples plot in the field of syenogranites (Fig. 6b). The Massadjanga–Malé granites are metaluminous to subaluminous (A/CNK: 0.90–1.04; A/NK: 1.08–1.36; Fig. 6c), alkali-calcic to alkalic (in the sense of Frost et al., 2001, Fig. 6d) and define a potassic and ferriferous association based on the cationic Fe+Mg+Ti vs. K/(Na+K) and Mg/(Mg+Fe) diagrams of Debon and Le Fort (1988) (Fig. 6e,f). Their agpaitic indexes (Na+K/Al) are in the range 0.74–0.86 apart for the aplite sample Iro 17 and the granite sample collected at Malé which was 0.93 (Supplementary Table 2).

The LREE are moderately fractionated with $(La/Sm)_{N\text{-chondrite}}$ ratios in the range 2.5–6.6 (Fig. 7). HREE patterns are nearly flat and Eu negative anomalies weak to marked (Eu/Eu*: 0.31–1.21). HFSE and REE contents are elevated (Zr: 210–717 ppm; Nb: 17–45 ppm; Ce: 105–403 ppm; Sum_{REE}: 249–884 ppm). All samples show Ti, Nb and Sr negative anomalies but only two granites display a Ba negative anomaly (Fig. 7). Three notable exceptions were pinpointed within the Massadjanga dataset: (i) the aplite sample (Iro 17) shows a strong Eu negative anomaly (Eu/Eu*: 0.24), a flat LREE and negative HREE patterns with a $(Gd/Yb)_N$ as low as 0.5 and a lower Zr content (96 ppm), consistent with fractionation of feldspar and accessory minerals including zircon; (ii) two leuco- (B values <38) granite samples (A5 and enclave Iro18) display strongly positive Eu anomalies (Eu/Eu*>2.5, Fig. 9a), a pronounced depletion in HREE (Yb contents below 1.4 ppm) and low HFSE and REE contents (Nb: 3–4 ppm; Zr: 59–68 ppm; Sum_{REE}: 165–168 ppm). These two leucogranites have markedly higher Ba and Sr compared to other fractionated specimens from the suite (A4, A9, Fig. 9a,b). Such signatures collectively indicate that they encompass a significant component of accumulated feldspar and deviate from melt compositions.

3.2.2 The Karou suite

Microgranite samples from the Karou suite show a narrower range of high SiO_2 contents (74.2–75.0 wt.%) and plot in the field of granites in the P–Q cationic diagram (Fig. 6a) of Debon and Le Fort (1983) and in the field of syenogranites in the Q' – ANOR classification diagram of Streckeisen and Le Maitre (1979) (Fig. 6b). They are subaluminous (A/CNK: 0.99–1.02; A/NK: 1.15–1.16, Fig. 6c), calc-alkalic to alkali-calcic (in the sense of Frost et al., (2001), Fig. 6d) and also define a potassic and ferriferous association (Fig 6e,f) (Debon and Le Fort, 1988). The enclave Iro04 is slightly less silicic (SiO_2: 69.5 wt.%), metaluminous (A/CNK: 0.93; A/NK: 1.22) but still exhibits the same ferroan and potassic character as its host (Fig. 6e,f).

As for major elements, trace element compositions are clustered (Fig. 7). LREE patterns are moderately fractionated with $(La/Sm)_{N\text{-chondrite}}$ ratios in the range 4.4–5.2. HREE patterns are nearly flat with $(Gd/Yb)_{N\text{-chondrite}}$ ranging between 1.1 and 1.36. All samples show a negative Eu anomaly (Eu/Eu*: 0.25–0.29) and exhibit elevated concentrations in HFSE (Zr: 203–249 ppm; Nb: 26–32 ppm) and REE (Ce: 211–242 ppm; Sum_{REE}: 473–533 ppm). The Karou microgranites display Sr, Nb, Ti and Ba negative anomalies (Fig. 7). Enclave Iro04 shows overall similar patterns but differs by its enrichment in Zr, Hf, Sr, Ba, Eu and depletion in U and Th compared to the host (Fig. 7, 9, 10).

3.3 Zircon U-Pb geochronology

Two samples (one from each igneous suite) were selected for zircon U–Pb geochronological investigations (Supplementary Table 3). The zircon crystals from the A3 Massadjanga granite sample are large, euhedral and often broken. They are poorly translucent, yellowish and filled with numerous undetermined dark inclusions. U and Th concentrations are generally lower than 100 ppm. High Th/U ratios are consistent with the magmatic origin of the zircons. Thirteen analyses were performed on the 7 available zircon grains defining a Discordia line with a lower intercept date of 575.3 ± 5.6 Ma (Fig. 8) interpreted as the crystallisation age of the zircon crystals.

In the A6 Karou granite sample, the zircon crystals are smaller but still euhedral, translucent and colorless. They contain rare clear undetermined inclusions. Th and U content are often lower than 50 ppm whereas Th/U ratios are high and up to 1.5. Nineteen analyses were performed on 13 zircon grains and yielded a Concordia date of 581.3 ± 3.8 Ma (Fig. 8) interpreted as the crystallization age of the zircon grains.

3.4 Magnetic properties

Table 1 summarizes the results of measurements made on the A1 to A9 samples. The three granitic suites Karou, Massandjana and Malé appear distinct regarding the intensity of their ferromagnetic signal. Based on susceptibility (Gleizes et al., 1993; Rochette, 1987) the Karou samples appear mostly paramagnetic (K<0.6 mSI, apart from A6), while Massandjana is mildly ferromagnetic (K from 1 to 2.3 mSI) except A5 which is paramagnetic, in agreement with its very low iron content (see Supplementary Table 2). Accordingly the NRM and IRM intensities increase from Karou to Malé. To propose a preliminary database for Chad granites aeromagnetic interpretation (such data do not currently exist) we first note that the Q ratio is always >>1 except in the two weakest Karou samples (A1, A7), thus justifying the need to consider remanence in anomaly interpretation. Total magnetization varies between 0.1 and 4.6 A/m (maximum for Malé). Such values are similar (although in the lower range) to values found in granitoids from central CAR and Western Cameroun (Ouabego et al., 2013). To confirm that the measured NRMs are not biased by lightning-induced remanence and thus reliable as a proxy for in-situ crustal magnetization, we computed the NRM/IRM ratio, that should be a few percent for non-lightning natural processes. Four samples (A3, 4, 8, 9) yield a ratio in the 12-16% range, and appear to be contaminated by lightning (Verrier and Rochette, 2002). After a 30 mT AF demagnetization these ratios decreased below 4% except for A3. Therefore we propose (as done in Ouabego et al., 2013) to use a modeled NRM by assuming that in situ NRM=0.02*IRM. This leads to lower total magnetization, at most 0.7 A/m (for the Malé granite). Still, Q ratio is >>1 (except for sample A7), consistent with data from granites in W Cameroon and CAR (Ouabego et al., 2013).

4. Discussion

4.1 Petrogenetic relationships between the Lake Iro granites

Several lines of evidence support a common origin for the granites exposed North (Karou) and South (Massadjanga-Malé) of Lake Iro. First, both igneous suites exhibit a ferroan mineralogy (including Fe-rich biotite) and define similar trends in geochemical diagrams (see section 4.3). One of the most silicic sample from the Massadjanga-Malé suite (A4) overlaps, in terms of major and trace element contents, with the Karou microgranites. The Karou enclave Iro04 is also chemically identical to the main Massadjanga-Malé granite type (Fig. 7, 8, 9). Second, trace element modelling indicates that the most fractionated samples (the Karou microgranites and sample A4) can be generated by c. 30% fractional crystallization of an assemblage of amphibole + plagioclase + K-feldspar + ilmenite starting from an average Massadjanga-Malé porphyritic granite composition (Fig. 9b). The fractionated granites exhibit lower zircon saturation temperatures (762–820°C depending on the calibration considered) than the porphyritic types (815–884°C). In the absence of inherited zircon cores among magmatic zircon grains, those values are regarded as minimum magma temperatures. These indicate that zircon was part of the fractionating assemblage and that the Karou microgranites, along with Massadjanga sample A4, represent lower temperature residual melts related to the main Massadjanga-Malé porphyritic granite type. Third, in addition to their geochemical kinship, the Karou and Massadjanga granites yielded zircon U–Pb emplacement ages which are consistent, within analytical uncertainties, at c. 580–575 Ma. We therefore suggest that the Lake Iro granites were part of a single igneous system active at the end of the Precambrian.

Petrographic evidence strongly suggests that, despite their petrogenetic relationships, the Karou and Massadjanga granites were emplaced at different crustal levels. The presence of “rhyolitic” globular quartz and the fine-grained microgranular texture of the Karou samples collectively demonstrate that the Karou magmas emplaced at very shallow crustal levels, which is consistent with their fractionated character. In contrast, the medium-grained texture of the Massadjanga-Malé granites is indicative of slow cooling in the middle crust. The aluminum content of calcic amphiboles is generally considered to be a reliable indicator of the pressure at which granite magmas crystallize (review in Anderson et al., 2008), but a calibration designed for ferroan calcic amphibole compositions is unavailable. Application of the Mutch et al. (2016) formulation to the hastingsite grains of the Massadjanga granites suggest emplacement pressures of 3.4 to 5.0 kbar, i.e. 13 to 19 km (considering an average crustal density of 2700 $kg.m^{-3}$).

In addition to their contrasting emplacement depths, the Karou and Massadjanga granites also differ with respect to their subsolidus tectonic evolution. The Karou samples display no evidence of solid-state deformation, in marked contrast to the Massadjanga (but not the Malé) granites. Petrographic features including recrystallized quartz and fractured feldspar/amphibole show that the latter experienced strong shearing at low temperature. The linear shape of the largest Massadjanga outcrop (G_1, section 2.1) may be closely related to this deformation event. The N60 trend of the two massive ridges that constitute the outcrop G_1 matches that of the main shear zones in the Oubanguides, notably the Central Cameroon Shear Zone (Toteu et al., 2004). It is most likely that the Lake Iro crustal segment experienced heterogeneous ductile shearing subsequent to the cooling of the late Ediacaran granites which had previously been emplaced at different crustal levels. The age of this deformation remains undetermined.

4.2 Typology of the Lake Iro igneous association

The Lake Iro granites are typified by their ferroan mineralogy and their major element composition matches that of A-type granitic suites (Bonin, 2007; Bonin et al., 2020; Collins et al., 1982; Eby, 1990; Frost and Frost, 2011) which feature: (i) high alkali and low CaO contents (the rocks are alkali-calcic to alkalic, Fig. 6d); (ii) low Mg# (Fig. 6f); (iii) moderate aluminosity (rocks are metaluminous to weakly peraluminous, Fig. 6c); (iv) a potassic character (Fig. 6e). The analogy is also supported by the trace element systematics and notably the elevated HFSE (Zr, Nb, Y) and REE concentrations. Consistently, the Lake Iro granites (discarding cumulate compositions) plot in the field of A-type granites in the discrimination diagrams (Fig. 10a,b) of Whalen et al. (1987) and in the field of Within Plate Granites (which encompasses A-type varieties) in the Nb vs. Y diagram (Fig. 10c) of Pearce et al. (1984). The affinity with A-type granite suites is further substantiated by the discrimination diagram (Fig. 10f) of Abdel-Rahman (1994) which is based on biotite compositions, regarded as repositories of magma chemistry. Similarly, the elevated Fe^{3+} contents of magmatic biotite (Fig. 10g) plot above the NNO buffer indicating that the magma were relatively oxidized, as commonly observed in A-type suites (Shabani et al., 2003). The presence of magmatic fluorite is also a typical feature of A-type granites (Collins et al., 1982). Finally, the Th–U contents of magmatic zircon grains from the Lake Iro suite are also consistent with those of alkalic magmas (Paquette et al., 2019).

Following the subdivision scheme of Eby (1992) and Grebennikov (2014), the Lake Iro samples are best classified as A_2-type granites (Fig. 10d,e). This group of igneous rocks shares chemical characteristics with a suite of metaluminous to weakly peraluminous alkali-calcic granitoids variously defined in the literature as “monzonitic”, “subalkaline” or “transalkaline” associations (de La Roche, 1980; Lameyre and Bonin, 1991; Stussi, 1989) and corresponding to the “K-rich calc-alkaline granitoids” (KCG) of Barbarin (1999). These associations encompass ferriferous varieties (sensu Debon and Le Fort, 1988) which are relatively similar to the A_2-type granites (Bonin et al., 2020) and have been extensively studied in the Variscan belt. Iconic examples include the Ploumanac’h complex (Barrière, 1977) or the Mont-Blanc granites (Debon and Lemmet, 1999). The kinship between A_2-type granites and the Fe–K “subalkaline” suite is well-illustrated in granite discrimination diagrams originally designed based on Variscan case studies, notably those based on biotite compositions (Nachit et al., 1985; Rossi and Chèvremont, 1987). For example, in the FeO_t–MgO–Al_2O_3 ternary and Mg vs. Al^{tot} binary discriminant diagrams (Fig. 10g,h), the Lake Iro samples dominantly plot in the field of “subalkaline” granites (or close to the subalkaline–alkaline boundary).

Several petrogenetic models have been proposed to account for the genesis of A-type granite suites. These include: (i) melting of mafic (D’Souza et al., 2006; Frost et al., 1999; Tagne-Kamga, 2003) to quartz–feldspar-rich (Breiter, 2012; Dall’Agnol and de Oliveira, 2007; Patiño Douce, 1997), and possibly residual (Collins et al., 1982; Creaser et al., 1991; Landenberger and Collins, 1996; Skjerlie and Johnston, 1992) crustal rocks; (ii) fractionation of mantle-derived magmas (Bogaerts et al., 2006; Duchesne et al., 2010; Eby, 1990; Ferré et al., 1998; Frost and Frost, 2011; Liégeois et al., 1998; Skridlaite et al., 2003; Turner et al., 1992). For the so-called “Fe-K subalkaline" associations, models involving melting of the lithospheric to asthenospheric mantle and subsequent fractionation of basic melts are preferred (Debon and Lemmet, 1999; Laurent et al., 2014; Schaltegger and Corfu, 1992). Discriminating between the different models for the Lake Iro granites is beyond the scope of this study.

4.3 Regional correlations and tectonic setting

Addressing the geodynamic significance of the Lake Iro association and its bearings on the evolution of the southern margin of the Saharan Metacraton would require a regional structural sketch of the Central African Orogen in southern Chad. Such a sketch is currently unavailable. In this poorly exposed area, geophysical data provide an opportunity to delineate crustal blocks and attempt regional correlations. In Central Chad, a major N45 lineament (the so-called Chad Lineament) has been identified by Bayer and Lesquer (1978) based on a gravimetric Bouguer anomaly map and its importance was reassessed by Braitenberg et al. (2011). Garfunkel (2015) interprets this structure as a possible oceanic suture zone. A revisit of this map reveals an overlooked, although prominent, N70 lineament in southern Chad (Fig. 11a; Bonvalot et al., 2012) that approximately connects the Lake Iro area with the Doba basin and the AYD massif to the SW and overlaps with the area of maximal Cretaceous–Paleogene extension. The magnetic anomaly map (Fig. 11b; Dyment et al., 2015, wdmam.org) is less resolved due to the lack of aeromagnetic surveys, but also shows N70 trending dipolar anomalies in southern Chad. This direction matches that of the major Bangui magnetic anomaly, which covers CAR just south of the present study area (Ouabego et al., 2013). These authors suggested that a Pan-African iron-rich crust may be the source of this anomaly. Therefore, we interpret the N70 lineament observed in southern Chad as the prolongation of the Central Cameroon Shear Zone, where the regional crust may possess reduced densities and be notably iron-rich. This major structure would thus juxtapose a northern block (comprising the MK–WCD, the northern part of the AYD, the Ouaddaï, Guéra massifs and Lake Iro inliers) against a southern block encompassing most of the southern part of the AYD and associated formations in CAR (see Fig. 2 of Toteu et al., 2004). Our new dataset on the Lake Iro inliers provide novel constraints on the orogenic evolution of this northern block.

As demonstrated by Bonin (2007), A_2-type granites are the hallmarks of the post-collisional stage of orogens (sensu Liégeois, 1998). The emplacement of the Lake Iro granites consistently post-dates the main tectonic-metamorphic events that shaped the northern block, which could be as old as 620–590 Ma (Bouyo et al., 2009; Djerossem et al., 2020, Fig. 12). Igneous suites similar to that of the Lake Iro inliers are exposed throughout this northern block (yellow stars, Fig. 11a). A-type volcanic-plutonic associations with emplacement ages ranging between 568 ± 6 and 545 ± 6 Ma have been described in the Guéra massif and two granitic inliers located 100 km to the NW (Pham et al., 2017; Shellnutt et al., 2018, 2017). In the WCD-MK, the A_2-type Zabili granite pluton was emplaced at 567 ± 10 Ma (Isseini et al., 2012) even though recent geochronological investigations performed on a hydrothermally altered facies (albitite) suggest it might be older (Vanderhaeghe et al., in press). No such rock types have been described in the Ouaddaï massif but the latter exposes 538 ± 5 Ma-old magnesian alkali-calcic potassic granites along with basic and intermediate igneous rocks (including two pyroxene monzonites). Together, they define a KCG-type (Barbarin, 1999) or “Mg–K subalkaline” (de La Roche, 1980) association (Djerossem et al., 2020, blue stars, Fig. 11a). As for A_2-type granites, such igneous suites are typically emplaced in post-collisional settings (Couzinié et al., 2016, 2014; Janoušek et al., 2019; Laurent et al., 2017). Similar rocks have been described in the MK–WCD (Pala suite, Penaye et al., 2006) and dated at 571 ± 1 and 567 ± 15 Ma. Besides, a diorite sample retrieved from the Karin-1 well in the Doba basin also yielded an intrusion age of 572.6 ± 0.3 Ma (Shellnutt et al., 2017). Collectively, the available petrological and geochronological data support a protracted post-collisional magmatic activity at the southern margin of the Saharan Metacraton, spanning the range 580–540 Ma (Fig. 12). The Lake Iro granites, first described in this contribution, would thus represent the oldest post-collisional intrusions in southern Chad.

Conclusion

The basement rocks exposed in the Lake Iro inliers correspond to cogenetic ferroan alkali-calcic A_2-type granites emplaced at contrasting crustal levels. The different components of this association are related by fractional crystallization processes. Investigation of the granite magnetic properties indicates that they are variably ferromagnetic, as observed in similar granites from West Cameroon and CAR, and may thus generate moderate magnetic anomalies (total magnetization of the order of 1 A/m). Emplacement of the Lake Iro granites at c. 580–575 Ma, i.e. less than 20 Ma after peak metamorphism related to arc accretion–collision (e.g. Bouyo et al., 2009). This demonstrates a rapid change in magma sources and geodynamic setting at the end of the Ediacaran in southern Chad. The onset of the post-collisional period was marked by large lateral displacements along shear zones such as the CCSZ. Further work is needed to identify the temporal evolution south of this structure, in CAR, and to clarify the timeframe of post-collisional magmatism in the southern part of the Saharan Metacraton

Figure and Table captions

Fig. 1: (a) Geological sketch delineating the main crustal domains of northern–central Africa (age and Nd–Hf isotope signature). Inspired from Garfunkel (2015) and adapted from Couzinié et al. (2019). (b) Geological map of southern Chad and adjacent countries. The map was redrawn and adapted from the geological map of Africa at a scale of 1/10 000 000 (Thieblemont, 2016). Dotted lines depict the outlines of the Cretaceous–Tertiary rift basins in southern Chad (redrawn from Genik, 1993). Abbreviations: C.A.R., Central African Republic; C., Cameroon; MK–WCD, Mayo Kebbi–West Cameroon domain, AYD, Adamawa–Yadé domain, TBSZ, Tcholliré–Banyo shear zone; CCSZ, Central Cameroon shear zone.

Fig. 2: Geological map centered on Lake Iro, depicting the location of the crystalline inliers.

Fig. 3: Field pictures of the studied bedrock exposures. (a) outcrop of the Massadjanga granite (G_1); (b) melanocratic enclave Iro09 in the Massadjanga granite; (c) aplite vein Iro17 cutting across the Massadjanga granite; (d) leucocratic enclave Iro15; (e,f) outcrops of the Karou microgranite (respectively G_3 and G_4); (g) melanocratic enclave Iro04 in the Karou microgranite; (h) outcrop of the Malé granite (G_5); (i) aplite dyke cutting across the Malé granite;

Fig. 4: Representative photomicrographs of studied samples. Massadjanga granite: (a,b) variably deformed granites with two feldspars, Ca-amphibole, biotite, titanite and apatite assemblage (plane-polarized); (c) strongly deformed, mylonitic facies with quartz ribbons (cross-polarized); (d) euhedral zircon crystal in a weakly deformed

facies (cross-polarized). Karou granites: (e) isotropic and medium-grained type (cross-polarized); (f) isotropic and fine-grained microgranite type (plane-polarized); (g) anhedral zircon within the fine-grained facies (plane-polarized). Malé granite (cross-polarized light): (h) weakly deformed two-feldspars, biotite, titanite and Fe-Ti oxides granite; (i) euhedral titanite crystal hosted by biotite.

Fig. 5: Mineral chemical compositions. (a) Feldspar ternary classification diagram; (b) binary classification diagram for micas after Tischendorf et al. (2007), *feal*=$^{VI}Fe_{tot}$+Mn+Ti-^{VI}Al and *mgli*=Mg-Li a.p.f.u. ; (c) FeO_t+MnO–10TiO_2–MgO ternary diagram of Nachit et al. (2005) discriminating between magmatic and reequilibrated biotites.

Fig. 6: Whole-rock geochemistry of the Lake Iro samples. (a) P–Q cationic classification diagram of Debon and Le Fort (1983); (b) Q'–ANOR classification diagram of Streckeisen and Le Maitre (1979); (c) B–A cationic classification diagram of Debon and Le Fort (1983); (d) SiO_2 vs. Na_2O+K_2O-CaO (MALI) diagram of Frost et al. (2001); (e) B vs. Mg/(Mg+Fe) diagram of Debon and Le Fort (1988) allowing discrimination between ferriferous and magnesian associations; (e) K/(K+Na) vs. B and (f) B vs. Mg/(Fe+Mg) cationic classification diagrams of Debon and Le Fort (1988). The subdivisions of Villaseca et al. (1998) are indicated in plot (c). SALK refers to the "potassic subalkaline" differentiation trend according to Debon and Le Fort (1988).

Fig. 7: Chondrite-normalized (Boynton, 1984) Rare Earth Elements and N-MORB-normalized trace elements patterns (Sun and McDonough, 1989) for the Karou

microgranites (left), Massadjanga-Malé granites (center) and peculiar facies (leucogranites A5 et Iro18 and aplite Iro17) of the Massadjanga suite (right).

Fig. 8: Tera–Wasserburg diagrams ($^{238}U/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$) showing Neoproterozoic zircon data for the Lake Iro granites. Error ellipses/ages are quoted at the 2σ level of uncertainty.

Fig. 9: Petrogenesis of the Lake Iro granitoids. (a) Eu/Eu* and (b) maficity (B parameter of Debon and Le Fort (1983) vs. Sr content for the Lake Iro granitoids. The red line depicts the evolving composition of a sample A2 melt undergoing fractional crystallization of an assemblage: 0.40 plagioclase An_{18} + 0.35 hastingsite + 0.23 K-feldspar + 0.02 ilmenite (in mol.%). The considered partition coefficients for Sr are 8.0, 4.2 and 0.6 for plagioclase, K-feldspar and amphibole, respectively. They correspond to the average values calculated from the results of Ewart and Griffin (1994). The blue dotted lines connect the melt compositions to those of the fractionating assemblage. (c) Zircon saturation temperatures calculated based on the calibrations of Watson and Harrison (1983) and Boehnke et al. (2013). Same legend as Fig. 7.

Fig. 10: Granitoid discrimination diagrams based on whole-rock (a to e) and biotite (f to h) chemical compositions (only grains plotting in the field of “magmatic biotite” in the diagram of Nachit et al. (2005) were retained). (a,b): Zr+Nb+Ce+Y (ppm) vs. FeO_t/MgO and (Na_2O+K_2O)/CaO discriminant diagrams for A-type granites from Whalen et al. (1987), OTG and FG stand for ordinary-type and fractionated granites, respectively; (c) Rb–(Y+Nb) geotectonic diagram of Pearce (1996)separating syn-collision (syn-COLG), post-collision (post-COLG), within-plate (WPG) and ocean ridge (ORG)

granites; (d,e) triangular plots of Eby (1992) and Grebennikov (2014) discriminating between A_1 and A_2-type granites; (f) FeO_t–MgO–Al_2O_3 diagram after Abdel-Rahman (1994) separating biotite crystallized in alkaline (A), calc-alkaline (C) and peraluminous (P) granites; (g) Fe^{2+}–Fe^{3+}–Mg ternary diagram of Wones and Eugster, (1965) indicative of the redox state of the melt from which biotite crystallized, with respect to the three common oxygen fugacity buffers: fayalite–magnetite–quartz (FMQ), nickel–nickel oxide (NNO) and hematite–magnetite (HM). (h) Mg vs Al^{tot} discriminant diagram (atoms per formula unit) after Nachit et al. (1985) and Stussi and Cuney (1996); (i) FeO_t–MgO–Al_2O_3 discriminant diagram after Rossi and Chèvremont (1987).

Fig. 11: Maps of the Bouguer gravimetric (a) and magnetic (b) anomalies in southern Chad and adjacent countries. Source grids correspond to Bonvalot et al. (2012)'s model for gravimetric anomaly, and to the WDMAM 2.0's grid for magnetic field anomaly (Dyment et al., 2015, wdmam.org). Yellow and blue stars depict the location of post-collisional igneous suites identified in the area: A-type granites and magnesian K-rich calc-alkaline granitoids, respectively (see references in text).

Fig. 12: Timeline summarizing available chronological constrains on the orogenic events in southern Chad and nearby countries based on the geological record of each massif (from the MK–WCD to the West to the Ouaddaï massif to the East). Yellow and blue stars depict the emplacement ages of typical post-collisional igneous associations: A_2-type granites and magnesian KCG suites, respectively. See references in text.

Table 1: Magnetic properties of Lake Iro granite samples. α(30) is initial NRM/IRM (after 30 mT AF demagnetization).

Supplementary Table 1: Mineral major element compositions for the Lake Iro granitoid samples. Feldspar structural formulas were calculated with a Gabbrosoft spreadsheet on an 8 O basis. Amphibole formulas are in the form $A_{0-1}B_2C_5T_8O_{22}W_2$ and were calculated using the method of Li et al. (2020a). Biotite has a general formula of $A_1M_3T_4O_{10}W_2$ estimated following Li et al. (2020b).

Supplementary Table 2: Whole-rock geochemical data for the Lake Iro granitoid samples in this study.

Supplementary Table 3: Zircon U-Pb data for the Lake Iro granites (SE Chad), obtained by in situ Laser Ablation ICP-MS.

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References

Abdel-Rahman, A.-F.M., 1994. Nature of Biotites from Alkaline, Calc-alkaline, and Peraluminous Magmas. J Petrology 35, 525–541. https://doi.org/10.1093/petrology/35.2.525

Abdelsalam, M.G., Liégeois, J.-P., Stern, R.J., 2002. The Saharan Metacraton. Journal of African Earth Sciences 34, 119–136. https://doi.org/10.1016/s0899-5362(02)00013-1

Anderson, J.L., Barth, A.P., Wooden, J.L., Mazdab, F., 2008. Thermometers and Thermobarometers in Granitic Systems. Reviews in Mineralogy and Geochemistry 69, 121–142. https://doi.org/10.2138/rmg.2008.69.4

Barbarin, B., 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. Lithos 46, 605–626.

Barrière, M., 1977. Le complexe de Ploumanac'h (Massif Armoricain), essai sur la mise en place et l'évolution pétrologique d'une association plutonique subalcaline tardi-orogénique (phdthesis). Université de Bretagne Occidentale.

Bayer, R., Lesquer, A., 1978. Les anomalies gravimetriques de la bordure orientale du craton ouest africain; geometrie d'une suture pan-africaine. Bulletin de la Société Géologique de France S7-XX, 863–876. https://doi.org/10.2113/gssgfbull.S7-XX.6.863

Bea, F., Montero, P., Anbar, M.A., Talavera, C., 2011. SHRIMP dating and Nd isotope geology of the Archean terranes of the Uweinat-Kamil inlier, Egypt–Sudan–Libya. Precambrian Research 189, 328–346. https://doi.org/10.1016/j.precamres.2011.07.017

Bessoles, B., Trompette, R., 1980. Géologie de l'Afrique. La chaîne panafricaine: "zone mobile d'Afrique Centrale (partie sud) et zone mobile soudanaise" (Mém. B.R.G.M. No. 92).

Black, R., Liegeois, J.-P., 1993. Cratons, mobile belts, alkaline rocks and continental lithospheric mantle: the Pan-African testimony. Journal of the Geological Society 150, 89–98. https://doi.org/10.1144/gsjgs.150.1.0088

Boehnke, P., Watson, E.B., Trail, D., Harrison, T.M., Schmitt, A.K., 2013. Zircon saturation re-revisited. Chemical Geology 351, 324–334. https://doi.org/10.1016/j.chemgeo.2013.05.028

Bogaerts, M., Scaillet, B., Auwera, J.V., 2006. Phase Equilibria of the Lyngdal Granodiorite (Norway): Implications for the Origin of Metaluminous Ferroan Granitoids. Journal of Petrology 47, 2405–2431. https://doi.org/10.1093/petrology/egl049

Bonin, B., 2007. A-type granites and related rocks: Evolution of a concept, problems and prospects. Lithos, IGCP project 510: A-type granites and related rocks through time 97, 1–29. https://doi.org/10.1016/j.lithos.2006.12.007

Bonin, B., Janoušek, V., Moyen, J.-F., 2020. Chemical variation, modal composition and classification of granitoids. Geological Society, London, Special Publications 491, 9–51. https://doi.org/10.1144/SP491-2019-138

Bonvalot, S., Balmino, G., Briais, A., Kuhn, M., Peyrefitte, A., Vales, N., Biancale, R., Gabalda, G., Reinquin, F., Sarrailh, M., 2012. World Gravity Map, BGI-CGMW-CNES-IRD. ed, Commission for the Geological Map of the World. Paris.

Bouyo, M.H., Penaye, J., Njel, U.O., Moussango, A.P.I., Sep, J.P.N., Nyama, B.A., Wassouo, W.J., Abaté, J.M.E., Yaya, F., Mahamat, A., Ye, H., Wu, F., 2016. Geochronological, geochemical and mineralogical constraints of emplacement depth of TTG suite from the Sinassi Batholith in the Central African Fold Belt (CAFB) of northern Cameroon: Implications for tectonomagmatic evolution. Journal of African Earth Sciences 116, 9–41. https://doi.org/10.1016/j.jafrearsci.2015.12.005

Bouyo, M.H., Toteu, S.F., Deloule, E., Penaye, J., Van Schmus, W.R., 2009. U–Pb and Sm–Nd dating of high-pressure granulites from Tchollíré and Banyo regions: Evidence for a Pan-African granulite facies metamorphism in north-central Cameroon. Journal of African Earth Sciences 54, 144–154. https://doi.org/10.1016/j.jafrearsci.2009.03.013

Bouyo, M.H., Zhao, Y., Penaye, J., Zhang, S.H., Njel, U.O., 2015. Neoproterozoic subduction-related metavolcanic and metasedimentary rocks from the Rey Bouba Greenstone Belt of north-central Cameroon in the Central African Fold Belt: New insights into a continental arc geodynamic setting. Precambrian Research 261, 40–53. https://doi.org/10.1016/j.precamres.2015.01.012

Boynton, W.V., 1984. Cosmochemistry of the rare earth elements: meteorite studies, in: Henderson, P. (Ed.), Rare Earth Element Geochemistry. Elsevier, Amsterdam, pp. 63–114.

Braitenberg, C., Mariani, P., Ebbing, J., Sprlak, M., 2011. The enigmatic Chad lineament revisited with global gravity and gravity-gradient fields. Geological Society, London, Special Publications 357, 329–341. https://doi.org/10.1144/SP357.18

Breiter, K., 2012. Nearly contemporaneous evolution of the A- and S-type fractionated granites in the Krušné hory/Erzgebirge Mts., Central Europe. Lithos 151. https://doi.org/10.1016/j.lithos.2011.09.022

Caby, R., 2003. Terrane assembly and geodynamic evolution of central-western Hoggar: a synthesis. Journal of African Earth Sciences 37, 133–159. https://doi.org/10.1016/j.jafrearsci.2003.05.003

Carignan, J., Hild, P., Mevelle, G., Morel, J., Yeghicheyan, D., 2001. Routine Analyses of Trace Elements in Geological Samples using Flow Injection and Low Pressure On-Line Liquid Chromatography Coupled to ICP-MS: A Study of Geochemical Reference Materials BR, DR-N, UB-N, AN-G and GH. Geostandards Newsletter 25, 187–198. https://doi.org/10.1111/j.1751-908X.2001.tb00595.x

Collins, W.J., Beams, S.D., White, A.J.R., Chappell, B.W., 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. Contr. Mineral. and Petrol. 80, 189–200. https://doi.org/10.1007/BF00374895

Couzinié, S., Laurent, O., Chelle-Michou, C., Bouilhol, P., Paquette, J.-L., Gannoun, A.-M., Moyen, J.-F., 2019. Detrital zircon U–Pb–Hf systematics of Ediacaran metasediments from the French Massif Central: Consequences for the crustal evolution of the north Gondwana margin. Precambrian Research 324, 269–284. https://doi.org/10.1016/j.precamres.2019.01.016

Couzinié, S., Laurent, O., Moyen, J.F., Zeh, A., Bouilhol, P., Villaros, A., 2016. Post-collisional magmatism: Crustal growth not identified by zircon Hf-O isotopes. Earth and Planetary Science Letters 456, 182–195.

Couzinié, S., Laurent, O., Poujol, M., Mintrone, M., Chelle-Michou, C., Moyen, J.-F., Bouilhol, P., Vezinet, A., Marko, L., 2017. Cadomian S-type granites as basement rocks of the Variscan belt (Massif Central, France): Implications for the crustal evolution of the north Gondwana margin. Lithos 286–287, 16–34. https://doi.org/10.1016/j.lithos.2017.06.001

Couzinié, S., Moyen, J.F., Villaros, A., Paquette, J.L., Scarrow, J.H., Marignac, C., 2014. Temporal relationships between Mg-K mafic magmatism and catastrophic melting of the Variscan crust in the southern part of Velay Complex (Massif Central, France). Journal of GEOsciences 69–86. https://doi.org/10.3190/jgeosci.155

Creaser, R.A., Price, R.C., Wormald, R.J., 1991. A-type granites revisited: Assessment of a residual-source model. Geology 19, 163–166. https://doi.org/10.1130/0091-7613(1991)019<0163:ATGRAO>2.3.CO;2

Dall'Agnol, R., de Oliveira, D.C., 2007. Oxidized, magnetite-series, rapakivi-type granites of Carajás, Brazil: Implications for classification and petrogenesis of A-type granites. Lithos, Granites and Crustal Anatexis 93, 215–233. https://doi.org/10.1016/j.lithos.2006.03.065

de La Roche, H., 1980. Granites chemistry through multicationic diagrams. Sciences de la Terre, Série Informatique Géologique 13, 65–88.

Debon, F., Le Fort, P., 1988. A cationic classification of common plutonic rocks and their magmatic associations : principles, method, applications. Bulletin de Minéralogie 111, 493–510. https://doi.org/10.3406/bulmi.1988.8096

Debon, F., Le Fort, P., 1983. A chemical-mineralogical classification of common plutonic rocks and associations. Transactions of the Royal Society of Edinburgh 73, 135–149.

Debon, F., Lemmet, M., 1999. Evolution of Mg/Fe ratios in Late Variscan plutonic rocks from the External Crystalline Massifs of the Alps (France, Italy, Switzerland). Journal of Petrology 40, 1151–1185.

Didier, J., Barbarin, B., 1991. The different types of enclaves in granites. Nomenclature., in: Didier, J., Barbarin, B. (Eds.), Enclaves and Granite Petrology. Elsevier, Amsterdam, pp. 19–23.

Djerossem, F., Berger, J., Vanderhaeghe, O., Isseini, M., Ganne, J., Zeh, A., 2020. Neoproterozoic magmatic evolution of the southern Ouaddaï Massif (Chad). BSGF. https://doi.org/10.1051/bsgf/2020032

D'Souza, M., Prasad, A., Ravindra, R., 2006. Genesis of Ferropotassic A-Type Granitoids of Mühlig- Hofmannfjella, Central Dronning Maud Land, East Antarctica. https://doi.org/10.1007/3-540-32934-X_6

Duchesne, J.C., Martin, H., Bagiński, B., Wiszniewska, J., Auwera, J., 2010. The origin of the ferroan-potassic A-type granitoids: the case of the hornblende-biotite granite suite of the Mesoproterozoic Mazury Complex, Northeastern Poland. The Canadian Mineralogist 48. https://doi.org/10.3749/canmin.48.4.947

Dyment, J., Lesur, V., Hamoudi, M., Choi, Y., Thebault, E., Catalan, M., the WDMAM Task Force, the WDMAM Evaluators, the WDMAM Data, the WDMAM Data, the WDMAM Providers, 2015. World Digital Magnetic Anomaly Map version 2.0.

Eby, G.N., 1992. Chemical subdivision of the A-type granitoids:Petrogenetic and tectonic implications. Geology 20, 641–644. https://doi.org/10.1130/0091-7613(1992)020<0641:CSOTAT>2.3.CO;2

Eby, G.N., 1990. The A-type granitoids: A review of their occurrence and chemical characteristics and speculations on their petrogenesis. Lithos, Alkaline Igneous Rocks and Carbonatites 26, 115–134. https://doi.org/10.1016/0024-4937(90)90043-Z

Ennih, N., Liégeois, J.-P., 2008. The boundaries of the West African craton, with special reference to the basement of the Moroccan metacratonic Anti-Atlas belt, in: Ennih, N., Liégeois, J.-P. (Eds.), The Boundaries of the West African Craton. Geological Society, London, Special Publications, pp. 1–17. https://doi.org/10.1144/SP297.1

Errami, E., Bonin, B., Laduron, D., Lasri, L., 2009. Petrology and geodynamic significance of the post-collisional Pan-African magmatism in the Eastern Saghro area (Anti-Atlas, Morocco). Journal of African Earth Sciences, Aspects of geological knowledge for sustainable development in Africa: Women in African Geoscience 55, 105–124. https://doi.org/10.1016/j.jafrearsci.2009.02.006

Ewart, A., Griffin, W.L., 1994. Application of proton-microprobe data to trace-element partitioning in volcanic rocks. Chemical Geology 117, 251–284.

Ferré, E.C., Caby, R., Peucat, J.J., Capdevila, R., Monié, P., 1998. Pan-African, post-collisional, ferro-potassic granite and quartz–monzonite plutons of Eastern Nigeria. Lithos 45, 255–279. https://doi.org/10.1016/S0024-4937(98)00035-8

Fezaa, N., Liégeois, J.-P., Abdallah, N., Cherfouh, E.H., De Waele, B., Bruguier, O., Ouabadi, A., 2010. Late Ediacaran geological evolution (575–555Ma) of the Djanet Terrane, Eastern Hoggar, Algeria, evidence for a Murzukian intracontinental episode. Precambrian Research 180, 299–327. https://doi.org/10.1016/j.precamres.2010.05.011

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A Geochemical Classification for Granitic Rocks. J Petrology 42, 2033–2048. https://doi.org/10.1093/petrology/42.11.2033

Frost, C.D., Frost, B.R., 2011. On Ferroan (A-type) Granitoids: their Compositional Variability and Modes of Origin. J Petrology 52, 39–53. https://doi.org/10.1093/petrology/egq070

Frost, C.D., Frost, B.R., Chamberlain, K.R., Edwards, B.R., 1999. Petrogenesis of the 1.43 Ga Sherman Batholith, SE Wyoming, USA: a Reduced, Rapakivi-type Anorogenic Granite. J Petrology 40, 1771–1802. https://doi.org/10.1093/petroj/40.12.1771

Ganwa, A.A., Klötzli, U.S., Hauzenberger, C., 2016. Evidence for Archean inheritance in the pre-Panafrican crust of Central Cameroon: Insight from zircon internal structure and LA-MC-ICP-MS UPb ages. Journal of African Earth Sciences 120, 12–22. https://doi.org/10.1016/j.jafrearsci.2016.04.013

Garfunkel, Z., 2015. The relations between Gondwana and the adjacent peripheral Cadomian domain—constrains on the origin, history, and paleogeography of the peripheral domain. Gondwana Research 28, 1257–1281. https://doi.org/10.1016/j.gr.2015.05.011

Genik, G.J., 1993. Petroleum Geology of Cretaceous-Tertiary Rift Basins in Niger, Chad, and Central African Republic. Bulletin 77. https://doi.org/10.1306/BDFF8EAC-1718-11D7-8645000102C1865D

Gleizes, G., Nédélec, A., Bouchez, J.-L., Autran, A., Rochette, P., 1993. Magnetic susceptibility of the Mont-Louis andorra ilmenite-type granite (Pyrenees): A new tool for the petrographic characterization and regional mapping of zoned granite plutons. Journal of Geophysical Research: Solid Earth 98, 4317–4331. https://doi.org/10.1029/92JB01590

Grebennikov, A.V., 2014. A-type granites and related rocks: Petrogenesis and classification. Russian Geology and Geophysics 55, 1353–1366. https://doi.org/10.1016/j.rgg.2014.10.011

Guiraud, R., Bosworth, W., Thierry, J., Delplanque, A., 2005. Phanerozoic geological evolution of Northern and Central Africa: An overview. Journal of African Earth Sciences, Phanerozoic Evolution of Africa 43, 83–143. https://doi.org/10.1016/j.jafrearsci.2005.07.017

Hawthorne, F.C., Oberti, R., Harlow, G.E., Maresch, W.V., Martin, R.F., Schumacher, J.C., Welch, M.D., 2012. Nomenclature of the amphibole supergroup. American Mineralogist 97, 2031–2048. https://doi.org/10.2138/am.2012.4276

Hiess, J., Condon, D.J., McLean, N., Noble, S.R., 2012. 238U/235U Systematics in terrestrial uranium-bearing minerals. Science 335, 1610–1614. https://doi.org/10.1126/science.1215507

Hurai, V., Paquette, J.L., Huraiová, M., Konečný, P., 2010. U–Th–Pb geochronology of zircon and monazite from syenite and pincinite xenoliths in Pliocene alkali basalts of the intra-Carpathian back-arc basin. Journal of Volcanology and Geothermal Research 198, 275–287. https://doi.org/10.1016/j.jvolgeores.2010.09.012

Isseini, M., André-Mayer, A.-S., Vanderhaeghe, O., Barbey, P., Deloule, E., 2012. A-type granites from the Pan-African orogenic belt in south-western Chad constrained using geochemistry, Sr–Nd isotopes and U–Pb geochronology. Lithos, Seventh Hutton Symposium on Granites and Related Rocks 153, 39–52. https://doi.org/10.1016/j.lithos.2012.07.014

Isseini, M., Hamit, A., Abderamane, M., 2013. The tectonic and geologic framework of the Mongo area, a segment of the Pan-African Guera Massif in Central Chad: evidences from field observations and remote sensing. Revue Scientifique du TCHAD 1, 4–12.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology 211, 47–69. https://doi.org/10.1016/j.chemgeo.2004.06.017

Janoušek, V., Holub, F.V., Verner, K., Čopjaková, R., Gerdes, A., Hora, J.M., Košler, J., Tyrrell, S., 2019. Two-pyroxene syenitoids from the Moldanubian Zone of the Bohemian Massif: Peculiar magmas derived from a strongly enriched lithospheric mantle source. Lithos 342–343, 239–262. https://doi.org/10.1016/j.lithos.2019.05.028

Kennedy, W., 1964. The Structural Differentiation of Africa in the Pan-African (500 ± m.y.) Tectonic Episode, 8th Annual Report of the Research Institute of African Geology. University of Leeds.

Kröner, A., 1980. Pan African crustal evolution. Episodes 3–8.

Kusnir, I., Moutaye, H.A., 1997. Ressources minérales du Tchad: une revue. Journal of African Earth Sciences 24, 549–562. https://doi.org/10.1016/S0899-5362(97)00080-8

Lameyre, J., Bonin, B., 1991. Granites in the main plutonic series, in: Didier, J., Barbarin, B. (Eds.), Enclaves in Granite Petrology. p. 601.

Landenberger, B., Collins, W., 1996. Derivation of A-type Granites from a Dehydrated Charnockitic Lower Crust: Evidence from the Chaelundi Complex, Eastern Australia. Journal of Petrology - J PETROL 37, 145–170. https://doi.org/10.1093/petrology/37.1.145

Laurent, O., Couzinié, S., Zeh, A., Vanderhaeghe, O., Moyen, J.-F., Villaros, A., Gardien, V., Chelle-Michou, C., 2017. Protracted, coeval crust and mantle melting during Variscan late-orogenic evolution: U–Pb dating in the eastern French Massif Central. International Journal of Earth Sciences 106, 421–451. https://doi.org/10.1007/s00531-016-1434-9

Laurent, O., Rapopo, M., Stevens, G., Moyen, J.F., Martin, H., Doucelance, R., Bosq, C., 2014. Contrasting petrogenesis of Mg–K and Fe–K granitoids and implications for post-collisional magmatism: Case study from the Late-Archean Matok pluton (Pietersburg block, South Africa). Lithos 196–197, 131–149. https://doi.org/10.1016/j.lithos.2014.03.006

Li, X., Zhang, C., Behrens, H., Holtz, F., 2020a. Calculating amphibole formula from electron microprobe analysis data using a machine learning method based on principal components regression. Lithos 362–363, 105469. https://doi.org/10.1016/j.lithos.2020.105469

Li, X., Zhang, C., Behrens, H., Holtz, F., 2020b. Calculating biotite formula from electron microprobe analysis data using a machine learning method based on principal components regression. Lithos 356–357, 105371. https://doi.org/10.1016/j.lithos.2020.105371

Liégeois, J.-P., 1998. Preface - Some words on the post-collisional magmatism. Lithos 45, xv–xvii.

Liégeois, J.-P., 1993. Mesures des isotopes du Sr en vue de détermination d'âges des roches magmatiques du Centre du Tchad (région du Ouaddaï) (Rapport inédit). Musée Royal Afrique Centrale, Tervuren, Belgique.

Liégeois, J.-P., Abdelsalam, M.G., Ennih, N., Ouabadi, A., 2013. Metacraton: Nature, genesis and behavior. Gondwana Research, Construction and Destruction of Cratons 23, 220–237. https://doi.org/10.1016/j.gr.2012.02.016

Liégeois, J.P., Latouche, L., Boughrara, M., Navez, J., Guiraud, M., 2003. The LATEA metacraton (Central Hoggar, Tuareg shield, Algeria): behaviour of an old passive margin during the Pan-African orogeny. Journal of African Earth Sciences, The Precambrian of Hoggar, Tuareg Shield-Dedicated to Louis Latouche 37, 161–190. https://doi.org/10.1016/j.jafrearsci.2003.05.004

Liégeois, J.-P., Navez, J., Hertogen, J., Black, R., 1998. Contrasting origin of post-collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline granitoids. The use of sliding normalization. Lithos 45, 1–28. https://doi.org/10.1016/s0024-4937(98)00023-1

Ludwig, K.R., 2008. A Geochronological Toolkit for Microsoft Excel, Berkeley Geochronology Central Special Publication.

Mullen, E.K., Paquette, J.-L., Tepper, J.H., McCallum, I.S., 2018. Temporal and spatial evolution of Northern Cascade Arc magmatism revealed by LA–ICP–MS U–Pb zircon dating. Can. J. Earth Sci. 55, 443–462. https://doi.org/10.1139/cjes-2017-0167

Mutch, E.J.F., Blundy, J.D., Tattitch, B.C., Cooper, F.J., Brooker, R.A., 2016. An experimental study of amphibole stability in low-pressure granitic magmas and a revised Al-in-hornblende geobarometer. Contrib Mineral Petrol 171, 85. https://doi.org/10.1007/s00410-016-1298-9

Nachit, H., Ibhi, A., Abia, E.H., Ben Ohoud, M., 2005. Discrimination between primary magmatic biotites, reequilibrated biotites and neoformed biotites. Comptes Rendus Geoscience 337, 1415–1420. https://doi.org/10.1016/j.crte.2005.09.002

Nachit, H., Razafimahefa, N., Stussi, J.M., Carron, J.-P., 1985. Composition chimique des biotites et typologie magmatique des granitoïdes. Comptes Rendus de l'Académie des Sciences, Paris 813–818.

Ngako, V., Affaton, P., Nnange, J.M., Njanko, Th., 2003. Pan-African tectonic evolution in central and southern Cameroon: transpression and transtension during sinistral shear movements. Journal of African Earth Sciences 36, 207–214. https://doi.org/10.1016/S0899-5362(03)00023-X

Njonfang, E., Ngako, V., Moreau, C., Affaton, P., Diot, H., 2008. Restraining bends in high temperature shear zones: The "Central Cameroon Shear Zone", Central Africa. Journal of African Earth Sciences 52, 9–20. https://doi.org/10.1016/j.jafrearsci.2008.03.002

Nkouandou, O.F., Ngounouno, I., Déruelle, B., Ohnenstetter, D., Montigny, R., Demaiffe, D., 2008. Petrology of the Mio-Pliocene volcanism to the North and East of Ngaoundere (Adamawa, Cameroon). Comptes Rendus Geosciences 340, 28–37. https://doi.org/10.1016/j.crte.2007.10.012

Nomo, E.N., Tchameni, R., Vanderhaeghe, O., Sun, F., Barbey, P., Tekoum, L., Tchunte, P.M.F., Eglinger, A., Fouotsa, N.A.S., 2017. Structure and LA-ICP-MS zircon U–Pb dating of syntectonic plutons emplaced in the Pan-African Banyo-Tchollіré shear zone (central north Cameroon). Journal of African Earth Sciences 131, 251–271. https://doi.org/10.1016/j.jafrearsci.2017.04.002

Ohta, T., Arai, H., 2007. Statistical empirical index of chemical weathering in igneous rocks: A new tool for evaluating the degree of weathering. Chemical Geology 240, 280–297. https://doi.org/10.1016/j.chemgeo.2007.02.017

Ouabego, M., Quesnel, Y., Rochette, P., Demory, F., Fozing, E.M., Njanko, T., Hippolyte, J.-C., Affaton, P., 2013. Rock magnetic investigation of possible sources of the Bangui magnetic anomaly. Physics of the Earth and Planetary Interiors 224, 11–20. https://doi.org/10.1016/j.pepi.2013.09.003

Paquette, J.-L., Médard, E., Francomme, J., Bachèlery, P., Hénot, J.-M., 2019. LA-ICP-MS U/Pb zircon timescale constraints of the Pleistocene latest magmatic activity in the Sancy stratovolcano (French Massif Central). Journal of Volcanology and Geothermal Research 374, 52–61. https://doi.org/10.1016/j.jvolgeores.2019.02.015

Paquette, J.-L., Piro, J.-L., Devidal, J.-L., Bosse, V., Didier, A., Sanac, S., Abdelnour, Y., 2014. Sensitivity enhancement in LA-ICP-MS by N_2 addition to carrier gas: Application to radiometric dating of U–Th–bearing minerals. Agilent ICP-MS Journal 58, 1–5.

Patiño Douce, A.E., 1997. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. Geology 25, 743–746. https://doi.org/10.1130/0091-7613(1997)025<0743:GOMATG>2.3.CO;2

Pearce, J.A., 1996. Sources and settings of granitic rocks. Episodes 19, 120–125.

Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. J Petrology 25, 956–983. https://doi.org/10.1093/petrology/25.4.956

Penaye, J., Kröner, A., Toteu, S.F., Van Schmus, W.R., Doumnang, J.-C., 2006. Evolution of the Mayo Kebbi region as revealed by zircon dating: An early (ca. 740Ma) Pan-African magmatic arc in southwestern Chad. Journal of African Earth Sciences, The Precambrian of Central Africa 44, 530–542. https://doi.org/10.1016/j.jafrearsci.2005.11.018

Penaye, J., Toteu, S.F., Michard, A., Bertrand, J.-M., Dautel, D., 1989. Reliques granulitiques d'âge Protérozoïque inférieur dans la zone mobile panafricaine d'Afrique Centrale au Cameroun; géochronologie U/Pb sur zircons. Comptes Rendus de l'Académie des Sciences, Paris 315–318.

Pham, N.H.T., Shellnutt, J.G., Yeh, M.-W., Lee, T.-Y., 2017. A-type granites from the Guéra Massif, Central Chad: Petrology, geochemistry, geochronology, and petrogenesis. 19, 6211.

Pin, C., Poidevin, J.L., 1987. U-Pb zircon evidence for a pan-african granulite facies metamorphism in the central african republic. a new interpretation of the high-grade series of the northern border of the congo craton. Precambrian Research 36, 303–312. https://doi.org/10.1016/0301-9268(87)90027-1

Pinna, P., Calvez, J.Y., Abessolo, A., Angel, J.M., Mekoulou-Mekoulou, T., Mananga, G., Vernhet, Y., 1994. Neoproterozoic events in the Tchollíré area: Pan-African crustal growth and geodynamics in central-northern Cameroon (Adamawa and North Provinces). Journal of African Earth Sciences 18, 347–353. https://doi.org/10.1016/0899-5362(94)90074-4

Pouclet, A., Vidal, M., Doumnang, J.-C., Vicat, J.-P., Tchameni, R., 2006. Neoproterozoic crustal evolution in Southern Chad: Pan-African ocean basin closing, arc accretion and late- to post-orogenic granitic intrusion. Journal of African Earth Sciences, The Precambrian of Central Africa 44, 543–560. https://doi.org/10.1016/j.jafrearsci.2005.11.019

Poulin, C., Hamelin, B., Vallet-Coulomb, C., Amngar, G., Loukman, B., Cretaux, J.-F., Doumnang, J.-C., Mahamat Nour, A., Menot, G., Sylvestre, F., Deschamps, P., 2019. Unraveling the hydrological budget of isolated and seasonally contrasted subtropical lakes. Hydrology and Earth System Sciences 23, 1705–1724. https://doi.org/10.5194/hess-23-1705-2019

Reimold, W., Koeberl, C., 2014. Impact structures in Africa: A Review. Journal of African Earth Sciences 93. https://doi.org/10.1016/j.jafrearsci.2014.01.008

Rieder, M., Cavazzini, G., D'yakonov, Y.S., Frank-Kamenetskii, V.A., Gottardi, G., Guggenheim, S., Koval', P.V., Müller, G., Neiva, A.M.R., Radoslovich, E.W., Robert, J.-L., Sassi, F.P., Takeda, H., Weiss, Z., Wones, D.R., 1999. Nomenclature of the micas. Mineralogical Magazine 63, 267–279. https://doi.org/10.1180/minmag.1999.063.2.13

Rochette, P., 1987. Magnetic susceptibility of the rock matrix related to magnetic fabric studies. Journal of Structural Geology 9, 1015–1020. https://doi.org/10.1016/0191-8141(87)90009-5

Rossi, P., Chèvremont, P., 1987. Classification des associations magmatiques granitoïdes. Géochronique 14–18.

Schaltegger, U., Corfu, F., 1992. The age and source of late Hercynian magmatism in the central Alps: evidence from precise U−Pb ages and initial Hf isotopes. Contr. Mineral. and Petrol. 111, 329–344. https://doi.org/10.1007/BF00311195

Shabani, A.A.T., Lalonde, A.E., Whalen, J.B., 2003. COMPOSITION OF BIOTITE FROM GRANITIC ROCKS OF THE CANADIAN APPALACHIAN OROGEN: A POTENTIAL TECTONOMAGMATIC INDICATOR? The Canadian Mineralogist 41, 1381–1396. https://doi.org/10.2113/gscanmin.41.6.1381

Shellnutt, J.G., Pham, N.H.T., Denyszyn, S.W., Yeh, M.-W., Lee, T.-Y., 2017. Timing of collisional and post-collisional Pan-African Orogeny silicic magmatism in south-central Chad. Precambrian Research 301, 113–123. https://doi.org/10.1016/j.precamres.2017.08.021

Shellnutt, J.G., Pham, N.H.T., Yeh, M.-W., Lee, T.-Y., 2020. Two series of Ediacaran collision-related granites in the Guéra Massif, South-Central Chad: Tectonomagmatic constraints on the terminal collision of the eastern Central African Orogenic Belt. Precambrian Research 347, 105823. https://doi.org/10.1016/j.precamres.2020.105823

Shellnutt, J.G., Yeh, M.-W., Lee, T.-Y., Iizuka, Y., Pham, N.H.T., Yang, C.-C., 2018. The origin of Late Ediacaran post-collisional granites near the Chad Lineament, Saharan Metacraton, South-Central Chad. Lithos 304–307, 450–467. https://doi.org/10.1016/j.lithos.2018.02.020

Shellnutt, J.G., Yeh, M.-W., Pham, N.H.T., Lee, T.-Y., 2019. Cryptic regional magmatism in the southern Saharan Metacraton at 580 Ma. Precambrian Research 332, 105398. https://doi.org/10.1016/j.precamres.2019.105398

Skjerlie, K.P., Johnston, A.D., 1992. Vapor-absent melting at 10 kbar of a biotite- and amphibole-bearing tonalitic gneiss: Implications for the generation of A-type granites. Geology 20, 263–266. https://doi.org/10.1130/0091-7613(1992)020<0263:VAMAKO>2.3.CO;2

Skridlaite, G., Wiszniewska, J., Duchesne, J.-C., 2003. Ferro-potassic A-type granites and related rocks in NE Poland and S Lithuania: west of the East European Craton. Precambrian Research, Origin and Evolution of Precambrian Anorogenic Magmatism 124, 305–326. https://doi.org/10.1016/S0301-9268(03)00090-1

Soba, D., Michard, A., Toteu, S.F., Norman, D.I., Penaye, J., Ngako, V., Nzenti, J.-P., Dautel, D., 1991. Données géochronologiques nouvelles (Rb-Sr, U-Pb et Sm-Nd) sur la zone mobile panafricaine de l’Est du Cameroun : âge protérozoïque supérieur de la série de Lom. Comptes Rendus de l’Académie des Sciences, Paris 1453–1458.

Stern, R.J., 2002. Crustal evolution in the East African Orogen: a neodymium isotopic perspective. Journal of African Earth Sciences 34, 109–117.

Stern, R.J., 1994. Arc Assembly and Continental Collision in the Neoproterozoic East African Orogen: Implications for the Consolidation of Gondwanaland. Annu. Rev. Earth Planet. Sci. 22, 319–351. https://doi.org/10.1146/annurev.ea.22.050194.001535

Streckeisen, A., Le Maitre, R.W., 1979. A Chemical Approximation to the Modal QAPF Classification of the Igneous Rocks. Neues Jahrbuch fur Mineralogie, Abhandlungen 169–206.

Stussi, J.-M., 1989. Granitoid chemistry and associated mineralization in the French Variscan. Economic Geology 84, 1363–1381. https://doi.org/10.2113/gsecongeo.84.5.1363

Stussi, J.M., Cuney, M., 1996. Nature of Biotites from Alkaline, Calcalkaline and Peraluminous Magmas by Abdel-Fattah M. Abdel-Rahman: A Comment. Journal of Petrology 1025–1029.

Sun, S. s, McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geological Society, London, Special Publications 42, 313–345. https://doi.org/10.1144/gsl.sp.1989.042.01.19

Tagne-Kamga, G., 2003. Petrogenesis of the Neoproterozoic Ngondo Plutonic complex (Cameroon, west central Africa): A case of late-collisional ferro-potassic magmatism. Journal of African Earth Sciences - J AFR EARTH SCI 36, 149–171. https://doi.org/10.1016/S0899-5362(03)00043-5

Tchameni, R., Pouclet, A., Penaye, J., Ganwa, A.A., Toteu, S.F., 2006. Petrography and geochemistry of the Ngaoundéré Pan-African granitoids in Central North Cameroon: Implications for their sources and geological setting. Journal of African Earth Sciences 44, 511–529. https://doi.org/10.1016/j.jafrearsci.2005.11.017

Thieblemont, D., 2016. An updated geological map of Africa at 1/10 000 000 scale. Presented at the 35th InternationalGeological Congress, Cape Town, South Africa.

Tischendorf, G., Förster, H.-J., Gottesmann, B., Rieder, M., 2007. True and brittle micas: composition and solid-solution series. Mineralogical Magazine 71, 285–320. https://doi.org/10.1180/minmag.2007.071.3.285

Toteu, S.F., Penaye, J., Deloule, E., Van Schmus, W.R., Tchameni, R., 2006. Diachronous evolution of volcano-sedimentary basins north of the Congo craton: Insights from U–Pb ion microprobe dating of zircons from the Poli, Lom and Yaoundé Groups (Cameroon). Journal of African Earth Sciences, The Precambrian of Central Africa 44, 428–442. https://doi.org/10.1016/j.jafrearsci.2005.11.011

Toteu, S.F., Penaye, J., Djomani, Y.P., 2004. Geodynamic evolution of the Pan-African belt in central Africa with special reference to Cameroon. Canadian journal of earth sciences 41, 73–85. https://doi.org/10.1139/e03-079

Toteu, S.F., Van Schmus, W.R., Penaye, J., Michard, A., 2001. New U–Pb and Sm–Nd data from north-central Cameroon and its bearing on the pre-Pan African history of central Africa. Precambrian Research 108, 45–73. https://doi.org/10.1016/S0301-9268(00)00149-2

Triantafyllou, A., Berger, J., Baele, J.-M., Diot, H., Ennih, N., Plissart, G., Monnier, C., Watlet, A., Bruguier, O., Spagna, P., Vandycke, S., 2016. The Tachakoucht–Iriri–Tourtit arc complex (Moroccan Anti-Atlas): Neoproterozoic records of polyphased subduction-accretion dynamics during the Pan-African orogeny. Journal of Geodynamics, Subduction and Orogeny 96, 81–103. https://doi.org/10.1016/j.jog.2015.07.004

Turner, S.P., Foden, J.D., Morrison, R.S., 1992. Derivation of some A-type magmas by fractionation of basaltic magma: An example from the Padthaway Ridge, South Australia. Lithos 28, 151–179. https://doi.org/10.1016/0024-4937(92)90029-X

Van Achterbergh, E., Ryan, C.G., Jackson, S.E., Griffin, W.L., 2001. Data reduction software for LA-ICP-MS: appendix, in: Sylvester, P.J. (Ed.), Laser Ablation-ICP-Mass Spectrometry in the Earth Sciences: Principles and Applications, Short Courses Series. Mineralog Assoc Canada (MAC), Ottawa, Ontario, Canada, pp. 239–243.

Vanderhaeghe, O., André-Mayer, A.-S., Diondoh, M., Eglinger, A., Ohnenstetter, M., Moussa, I., Cuney, M., Poujol, M., Van Lichtervelde, M., in press. Uranium mineralization associated with late magmatic ductile to brittle deformation and Na–Ca metasomatism of the Pan-African A-type Zabili syntectonic pluton (Mayo-Kebbi massif, SW Chad). Mineralium Deposita. https://doi.org/10.1007/s00126-020-00999-1

Verrier, V., Rochette, P., 2002. Estimating peak currents at ground lightning impacts using remanent magnetization. Geophysical Research Letters 29, 14-1-14–4. https://doi.org/10.1029/2002GL015207

Villaseca, C., Barbero, L., Herreros, V., 1998. A re-examination of the typology of peraluminous granite types in intracontinental orogenic belts. Transactions of the Royal Society of Edinburgh.

Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. Earth and Planetary Science Letters 64, 295–304.

Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology 95, 407–419.

Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Von Quadt, A., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards Newsletter 19, 1–23.

Wones, D.R., Eugster, H.P., 1965. Stability of biotite: experiment, theory, and application. American Mineralogist 50, 1228–1272.