Geochemistry and Geotectonic Setting of the Post-orogenic granites at Qala En Nahal-Um Sagata Area, Gedarif State, Sudan

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Abstract. The survey area is located about 70 km southeast of Gedarif city, in Gedarif State east of Sudan, within two major lithological associations, representing two different crustal entities; Saharan Metacraton (SMC) in the west and the Arabian Nubian Shield (ANS) to the east. This study aims to investigate the post-orogenic granites at Qala En Nahal-Um Sagata. Geologically, both the petrographic characteristics and rock geochemistry investigation have been conducted in order to determine the tectonic environment and original protolith of these granites rocks. The area is made up of predominantly low-grade volcano-sedimentary rocks, ophiolite complex and belt of high-grade metasediments and gneiss into which voluminous granitic rocks have been emplaced. The post-orogenic granites of Ban-Balos are non foliated, high K calc-alkaline, I-type, post-dating the main collisional event emplacement at shallow levels intrusions.

1. Introduction
The study area of this research, lying some 70 km southeast of Gedarif city, Gerarif State, in eastern Sudan, between latitudes 13°15’ and 13° 43’ N and longitudes 34° 45’ and 35° 03’ E. With the exclusion of some sporadic outcrops of Mesozoic sandstones (Nubian Sandstone Formation and scattered Tertiary volcanics, most of the region south of Gedarif consists of exposed crystalline metamorphic rocks belonging to the Precambrian Basement Complex, which consists of two tectonostatigraphic terranes based on in the differences in metamorphic grades and the structural style: (1) high-grade schists and gneiss terrane and (2) ophiolitic fold and thrust belt known as Qala-En Nahal-Umm Saqata ophiolitic complex; structurally overlying, a layered sequence of low-grade metavolcano-sedimentary units. The syn-to late -orogenic and post-orogenic granites intrude the bovementioned sequences, usually forming conspicuous, hilly dissected massifs (Figure 1).

These two major lithological associations, representing two fundamentally different crustal entities; commonly referred to as the Saharan Metacraton (SMC) in the west and the Arabian Nubian Shield (ANS) to the east (Vail, 1985; Abdel-salam et al., 1995; Stern, 1994). The SMC represents a Palaeoproterozoic, continental crust, dominated by heterogeneous high-grade (amphibolite facies)
gneisses, migmatites and supracrustal rocks of ensialic geochemical affinities that remobilized during the Neoproterozoic time (Kroner et al., 1987; Kuster and Liegeois, 2001; Abdelsalam et al., 2002).

The Nubian Shield of NE Africa is well known for the abundant occurrences of post-orogenic and anorogenic plutonic complexes, mainly in the form of well developed central complexes. They penetrate the older Proterozoic basement, and in places, the Paleozoic cover rocks as well (Höhndorf et al., 1994). They are generally circular or oval in plan, sometimes occurring as ring dykes. Sillitoe (1979) considers them to have been emplaced between 620–500Ma during the Pan–African event. Vail (1978) discussed three episodes of intrusion of younger granites: approximately at 550Ma, 230Ma, and 100 – 50 Ma.

The younger granites are so named because they post-date the deformation, so they are essentially unfoliated. They include a range of compositional types from alkali granites, normal granites, quartz monzonites, syenites to gabbros.

Geochemically, the granites are typically alkaline, although some are calc-alkaline syenite, granites, and gabbros (Vail, 1982) and being always older in age (700 Ma, El-Nadi, 1984). They could possibly be regarded as high-level equivalents of the calc-alkaline arc batholithic granitoids (El-Nadi, 1984).

Figure 1. Regional geological map of the study area.

1.1. Geology, field relations and petrography
The post-orogenic granites of J. Balos and J. Ban can be respectively grouped into two types: one is medium-grained biotite granite, whose component minerals show oriented arrangements and a little foliation; the other is massive coarse-grained biotite granite which seemingly occur as apophyses. The contact relationship between both types is unclear, but the latter is possibly younger in time of formation. The coarse-grained biotite granite found at J. Ban is analogous to that at J. Balos in which xenoliths of various sizes and compositions are found. These xenoliths are comprised of gneisses, foliated granite and basic rocks (Figure 2 a, b). It obviously this rock is a younger intrusive mass,
whereas the two-mica granite that occurs in the banded or gneissoid form should be older in time of formation.

The granite is distributed at J. Miskin and J. Agamal both belong to the massive coarse-grained biotite granite, whose lithology similar to those coarse-grained biotite granites at J. Balos. A small hill northwest of J. Mahud is also belong to these intrusions.

The rock is light grey with a tint of flesh-red colour, showing a medium anhedral-subhedral granular texture and a massive structure. The mineral composition comprises mainly perthite, microcline, albite and quartz, with small amounts of biotite (Figure 2c) as well as trace amounts of accessory minerals such as apatite, magnetite and zircon. In the south-eastern part at El Asama area there are linear, small hilly outcrops of trending N-S. They are similar to the biotite granite of J. Ban in appearance but they differ in mineral compositions. Microscopically they are coarse-grained, anhedral-subhedral granular texture consist of microcline, plagioclase and quartz. Brown hornblende and biotite are the ferromagnesian minerals. Apatite and epidote are the accessories (Figure 2d).

Figure 2. Photomicrographs showing: (a) large xenoliths (raft) of foliated granite. (b) Xenoliths are consisted of gneisses, foliated granite. (c) The mineral composition comprises mainly perthite, microcline, albite and quartz, with small amounts of biotite. (d) Mineral composition of El Asama granite consists of plagioclase, microcline, quartz, hornblende and biotite.

2. Analytical methods
A number of 11 representative samples have been analyzed from the post-orogenic granitic rocks from the study area during surface geological mapping. However, fresh samples have been selected for this processing stage, the major, trace and some rare earth elements abundances of the granitic rocks.
The collected samples, covering a wide range of compositions, were further geochemically analyzed in order to decipher their geotectonic setting. The samples were submitted to Omac laboratory – Ireland to determine whole rock chemistry using X-Ray Fluorescence (XRF) and Inductively Coupled Plasma Mass spectrometry (ICP-MS). The discrimination and variation diagrams are conducted using these data in order to classify the rocks, interpret their geochemical affinity and illustrate their tectonic setting. Loss on Ignition (LOI) was determined from total weight loss after repeated ignition of the powdered samples at 1000°C for 1 h and cooling. Satisfying analytical accuracy was achieved by using replicate analyses and compared with rock standards. The geochemical plotting and CIPW norms have been calculated using Minpet software (Richard, 1995).

3. Results
The element oxides and selected trace and rare earth elements (Table 1 and 2) and their chemical data are used in the following interpretation.

3.1. Rock classification
On the total alkali-silica TAS, \{SiO\textsubscript{2} vs. (Na\textsubscript{2}O + K\textsubscript{2}O)\} geochemical rock classification diagram (Wilson, 1989) used for classification of the studied granitoid rocks, most samples are plotted in the granite fields (Figure 3a). in an agreement with the petrographic characteristics of the rocks. In Ab-An-Or classification diagram (Figure 3b) after O’ Connor (1965), the majority of the granitic rocks plot in the granitic field.

![Figure 3](image_url)

**Figure 3.** (a) The classification of the studied granitic intrusions according to the total alkali-silica (TAS), \{SiO\textsubscript{2} vs. (Na\textsubscript{2}O + K\textsubscript{2}O)\} geochemical rock classification diagram (Wilson, 1989). (b) The classification of the studied granitic intrusions according to their molecular normative An-Ab-Or composition. The fields of Barker (1979) are shown in heavy lines, while the original fields of O’ Connor (1965) are shown in faint lines.

3.2. Major element characteristics
Most samples have low iron content (Fe\textsubscript{2}O\textsubscript{3}) ranging between (1.05-2.56 wt%), with Fe\textsubscript{2}O\textsubscript{3}/MgO range (3.56-51.2). Other elements fall within the normal granitic abundancy limits (Nockolds, 1954). The major element chemistry for the studied granitoids show some characteristic features such as the > 1 wt\% of K\textsubscript{2}O, the <1 value of Fe\textsubscript{2}O\textsubscript{3}/(Fe\textsubscript{2}O\textsubscript{3}+MgO) ratio. According to aluminum saturation index (ASI = molar Al\textsubscript{2}O\textsubscript{3}/CaO+Na\textsubscript{2}O+K\textsubscript{2}O), the granitic intrusions have ASI<1.1. These features might indicate their probable arc environment of emplacement. Furthermore, this ASI ratio is also a distinctive according to Chappell and White (1974).
3.3. Trace and rare earth elements characteristics
The granitoid rocks from Ban-Balos are enrichment in some trace elements content (Figure 4) particularly; K, Rb, Sr, Th, Ce and Sm compared to Nb, Hf, Zr, Y and Yb with with distinct troughs at Nb and Zr, similar to the I-type granites from subduction zones.

![Figure 4. ORG-normalized diagram for the average analyzed granitoid rocks (The normalizing values are after Pearce et al., 1984).](image)

3.4. Magma characterization and geotectonic setting
The major element geochemistry indicates that most of the post-orogenic are dominantly high K calc-alkaline (Figure 5a). White and Chappell (1977) distinguished two granitoid types in eastern Australia on the basis of chemical, mineralogical and field data. They interpreted these types to be derived from two different sources, one igneous (I-type) and the other sedimentary (S-type). Thus, they defined the S-type granite as “one in which geochemical and isotopic characteristics are primary inherited through partial melting of a crustal sedimentary (or metasedimentary) source” (White et al., 1986), the I-type being derived from melting of igneous or meta-igneous protolith. A diagram (Figure 5b) proposed by Maniar and Picolli (1989) plots the aluminum saturation index (ASI = A/CNK = molar ((Al₂O₃) / (CaO) + (Na₂O) + (K₂O)) versus the anapatic index (AI = A/NK = molar ((Al₂O₃) / ((Na₂O) + (K₂O))) and characterizes the rocks as metaluminous (ASI < 1 and AI > 1), peraluminous (ASI > 1 and AI > 1), or peralkaline (ASI < 1 and AI < 1).

The granitic intrusions of Ban-Balos plot in the I-type metaluminous field. Presence of normative corundum in all samples (average 0.52 vol.%) also support Al-saturated behavior.

A bivariate plot of Nb and Y can provide three fields for oceanic granites (ORG), within-plate granites (WPG) and volcanic arc granites (VAG) together with syn-collision granites (syn-CLOG). Supra-subduction zone ocean ridge and post-collisional granites cannot be distinguished from volcanic arc granites on this basis (Pearce et al., 1984). The majority of Ban-Balos granites plot in the combined field of volcanic-arc granites (VAG), syn-collisional granites (syn-CLOG) (Figure 6a).

The plot of Rb Vs Y+Nb (after Pearce et al., 1984) separates more efficiently syn-collisional granites from volcanic arc granites. There is also a clear division between within-plate and oceanic ridge granites on this diagram. The studied granites of Ban-Balos granites plot in the overlap field of the post-collisional granite proposed by Pearce (1996) and the volcanic-arc granites (VAG) (Figure 6b).
Figure 5. (a): K$_2$O–SiO$_2$ plot showing the medium to high-K nature of studied granitoids. Calc-alkaline, shoshonitic and ultrapotassic fields are shown (modified from Peccerillo and Taylor, 1976 (dashed lines); solid lines are from Corriveau and Gorton, 1993). Line A and B separate the Shoshonitic field from Calc-alkaline and Ultrapotassic fields, respectively. (b): A/NK Vs A/CNK diagram classifying the analyzed granitic intrusions after Maniar and Picolli (1989).

Figure 6. (a) Nb Vs Y discriminant diagram for the analyzed granites. (b) Vs (Y+Nb) discrimination diagram for the analyzed granites. The fields: within-plate granites (WPG) + oceanic ridge granites (ORG) and volcanic arc granites (VAG) + Syn-collision granites (Syn-COLG) are after Pearce et al. (1984).

4. Discussion, conclusions and tectonic implications
The major element geochemistry of the post-orogenic of Ban-Balos indicates that they are dominantly high K calc-alkaline respectively (Figure 4a). They are metaluminous, with aegipaitic index more than 1 in accordance with the absence of alkali pyroxenes or amphiboles in these granitoids. The aluminum saturation index (ASI) does not exceed 1.1, and the normative corundum is less than 1 and then classified as metaluminous to slightly peraluminous, I-type granites (Figure 4b). Furthermore, the tectonic discrimination diagram proposed by Pearce et al., (1984), using Nb Vs Y (Figure 5a) classify these granitoids as volcanic arc, syn-collision granites. Using Rb Vs Y+Nb diagram, the studied granites of of Ban-Balos granites plot in the overlap field of the post-collision granite proposed by Pearce (1996) and the volcanic-arc granites (VAG) (Figure 5b). In the ocean ridge granite (ORG)-normalized diagrams, they are enrichment in some trace elements content (Figure 4) particularly; K, Rb, Sr, Th, Ce and Sm compared to Nb, Hf, Zr, Y and Yb with with distinct troughs at Nb and Zr, similar to the I-type granites from subduction zones. The volcanic arc granites nature for Ban-Balos granites is supported both by geochemical (metaluminous, medium and high K calc-alkaline) and petrographical evidence (presence of hornblende and biotite and absence of alkali pyroxenes and
amphiboles and absence of metamorphic minerals) such that these granites were emplaced as volcanic arc granites above a Neoproterozoic subduction zone during the post-collision stages of crust evolution.

Concerning the problem of the existence of some Post-orogenic complexes within plate as calc-alkaline rocks with volcanic arc granite setting (VAG), El Nadi (1984) suggested that these complexes could possibly be regarded as high-level equivalents of the batholithic granitoids. Abundant high-K calc-alkaline HKCA magmatism appears to be post-collisional and often shifts to shoshonitic or alkaline–peralkaline, often as ring complexes, both marking the end of the orogeny (Liegeois et al., 1998).

Depending on the above account derived from integrating the field relations, petrographical and mineralogical investigations substantiated with the geochemical interpretation, it is reasonable to conclude that, The post-orogenic granites of Ban-Balos are non foliated, circular shape, high K calc-alkaline, emplacement at shallow level-post-dating the main collisional event.

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