Abstract
The granitoids of the northern part of Adamawa Massif in northeastern Nigeria have been differentiated based on field and petrochemical data into the granodiorite and granites. Although there are slight mineralogical and geochemical differences between the granodiorite and the granites (e.g. Rb/Sr ratios lower in granodiorite than the granites), the two rock units have similar geochemical characteristics. The rocks are characterized by a wide range in SiO₂, Calc-alkaline affinity, syn- to within-plate granite signatures, metaluminous to peraluminous composition and more K₂O-rich and hypersthene-poor comparable to fractionated I-type granitoids. The rocks display slightly fractionated to fractionated LREE, almost flat HREE patterns, with significant negative Eu and Ba anomalies. Linear major element trends and progressive rise in SiO₂, K₂O, Rb and Rb/Sr ratios with depleting MgO, Fe₂O₃, CaO, TiO₂, Sr and Ba consistent with removal of plagioclase during fractionation of basic melts to yield silicic magma. This linear trend is reflected in the normative mineralogy where orthoclase and quartz increase from granodiorite to the granites whereas other minerals behave in a reverse manner. Based on field and petrochemical features, the granodiorites and the granites of south Adamawa Massif are I-type, generated in a syn- to within-plate collision-related tectonic setting and genetically related to a common source by fractional crystallization dominated by the removal from the melt hornblende, plagioclase, biotite, K-feldspar and accessory phases such as apatite, epidote and zircon.

Keywords: Granitoids; Adamawa massif; Petrology; Geochemistry

Introduction
Adamawa Massif consists largely of granitoids and migmatites-gneisses complex (Figure 1) [1]. It is situated in eastern Nigeria and lies in an extensive area between the Benue Trough to the west and the Cameroon Line to the east. To the north, it is bordered by Hawal Massif and to the south, by Oban Massif (Figure 2) [2]. The three massifs extend into the Republic of Cameroon and form the Eastern Nigerian Basement Complex which is one of the three major basement complexes in Nigeria. The Oban Massif has been extensively studied [3-8]. Similarly the Hawal has recently received the attention of Bassey, Obienua et al and Baba [9-11]. Unlike its Oban and Hawal equivalents, little is known about the geology of Adamawa Massif and there is hardly any data on the major, trace and rare earth elements contents of these rocks. The scarcity of such data probably led Ogunleye and Okienji [12] to believed that the pockets of uranium in the sub adjacent Benue Trough were sourced from the volcanics within the Trough even though no evidence of uranium enrichment in these volcanics has been documented. Again, because of the paucity of research work on this massif, there is always a tendency to infer the geology of Adamawa Massif from that of the well-studied Oban Massif. This has always led to erroneous conclusions.

This paper combines field with major, trace and rare earth elements petrochemical data to expand information on the origin and tectonic environment of the basement geology of Adamawa Massif.

Regional Geological Setting and Tectonics
Nigeria is situated within the Pan African mobile belt and sandwiched between the West African Craton to the west, the Taureq shield to the north and the Congo Craton to the southeast (Figure 2) [2]. Opinions are divided concerning the evolution of the Nigerian Pan African terrain. The first and most popular opinion is that the Nigerian Pan African terrain is the result of tectonic processes involving continental collision between West African Craton and the Pan African mobile belt [13-17]. The resultant heat, deformation and partial melting of the upper mantle and lower crust led to the emplacement of the granites. This interpretation is based on the recognition of a suture along the eastern margin of the West African Craton. The second opinion suggests that the Pan African orogeny was more of aggregation of crustal blocks such as island arcs and older continental fragments than a simple collision between two entities – the West African Craton and the Pan African mobile belt [18-21]. This interpretation is predicated on the close association of calc-alkaline volcanics, ultramafic and basic rocks with the two major NE-SW trending fracture systems established in the western part of Nigeria.

Even though the former opinion has been widely accepted, some workers have observed that the Pan-African granites which extend to Nigeria and Cameroon, a distance of over 1500 km from the suture cannot be related to the same subduction zone [22,23].

The Granitoids
The granitoids of the study area are classified as granites and granodiorite based on the chemical classification of Cox et al. [24]. Such classification is consistent with the QAPF classification based on modal proportions of constituent minerals [25]. The granites are further subdivided based on field characteristics into migmatisites, equigranular granite, porphyritic granite and fine-grained granite.

The granodiorite presents a wide range in composition from basic granodiorite to quartz monzonite or adamellite. Distinction (in the field) between the various members of the group is difficult as they...
feldspar, quartz and biotite. Sericite and iron ore minerals constitute the alteration products.

The most striking characteristic of porphyritic granites is their porphyritic texture consisting of phenocrysts of microcline (mineral grains in the size range 20 mm×30 mm to 35 mm×40 mm) set in a medium- to coarse-grained mineral matrix ranging in size from 2 mm×3 mm to 4 mm×5 mm. They are relatively homogeneous, having predominantly gradational contacts (transitional) and restricted sharp contacts with equigranular granites and migmatite. These rocks are mainly potash granites, which grade into a fairly basic variety at the margins of the intrusions. Composition and texture of porphyritic granite changes as one traverse the intrusions from the center to the borders (margins). At the center, feldspar phenocrysts are crowded and the rock appears to be homogeneous biotite granite. This composition gradually changes to what appear to be syenite and monzonites at the margins, where the density of feldspar phenocryst is less.

The fine-grained granites are pale brown to grey, dominantly equigranular, fine-grained and show little variation in appearance. The rock consists of predominantly quartz, microcline and plagioclase. Similar rock forms enclaves which occur as irregular bodies and as vein-like lenses within the equigranular granites. In some places, veins of fine-grained granite interfinger and penetrate the porphyritic granites. Fine-grained granite, like the migmatite, is of subordinate occurrence in the study area.

**Sampling and Analytical Procedure**

The sampling procedure involved the collection of at least three individual samples of fresh rock from each outcrop. The samples, each
weighing about 5 kg, were subjected to preliminary preparation at the geochemical laboratory of Ashaka Cement Company. Each sample set was first crushed and manually sorted to obtain representative sample. Each representative sample was then pulverised in a disc mill. Finally the powdered samples were packaged, labelled and shipped to Activation Laboratory (ACTLABS), Canada where the samples were analysed for major elements using ICP and the trace elements and Rare Earth Elements using fusion ICP/MS package. The samples locations are shown in Figure 3 while the major and trace elements data contents for the granitoids are given in Table 1 and the normative mineralogy calculated therefrom presented on Table 2. Part of this data was earlier used by the authors to constraint the origin and processes of uranium in the northern part of Adamawa Massif.

Geochemistry

Major elements distinctions between the granites are subtle, however, the average granite has higher SiO₂, K₂O, Na₂O, Rb and lower MgO, CaO, TiO₂, Fe₂O₃(t), Al₂O₃, Ba and Sr than the granodiorites. Collectively, the granitoids have a wide range of SiO₂ (64.75 to 76.27 wt%), MgO (0.01 to 1.40 wt%), CaO (0.58 to 3.66 wt%), TiO₂ (0.02 to 1.44 wt%), Fe₂O₃(t) (0.46 to 8.20 wt%), MnO, (0.01 to 0.12 wt%), and a relatively narrow range of Al₂O₃ (12.91 to 16.37 wt%), Na₂O (2.46 to 4.28 wt%), K₂O (4.24 to 6.36 wt%).

In general, major and trace elements displayed display continuous trends with MgO, CaO, and Fe₂O₃ abundances decreasing with increasing SiO₂. Similarly, Sr and Ba decrease steadily with increasing SiO₂ while on the contrast, K₂O and Rb increase with increasing SiO₂. The remaining elements exhibit no clear patterns (Figure 4). There is clear absence of separate groups among the granitoids.

In general, the granitoids are characterized by very little foliation, mafic enclaves in granodiorite, low normative corundum (<1% in most samples), calc-alkaline affinity (Figure 5) [26], high Na₂O contents (generally more >3.5%), Al/Na₂O+CaO contents of ≤ 1.1 wt%, moderate values of Rb, Ba, LREE and Rb/Sr ratios. All these features, according to the nomenclature of Chappell and White [27] are typical of I-type granitoids.

On the SiO₂ versus Nb diagram of Kleeman and Twist [28] the granitoids plot in the orogenic field (Figure 6) [28]. A plot of A/NK versus Al saturation index (ASI) [Al₂O₃/(Na₂O+K₂O+CaO)] shows that the granitoids are metaluminous to peraluminous (Figure 7) [29]. On TiO₂ (wt %) versus Al₂O₃/TiO₂ diagram (Figure 8) [30] the plot indicates one curvilinear trend for all the granitoids characteristic of magmatic differentiation.
### Trace Elements

<table>
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<th>Major Elements</th>
<th>1</th>
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<td>2.17</td>
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<td>1.88</td>
<td>3.15</td>
<td>0.59</td>
<td>1.38</td>
<td>1.52</td>
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<td>0.08</td>
<td>0.121</td>
<td>0.042</td>
<td>0.044</td>
<td>0.028</td>
<td>0.031</td>
<td>0.005</td>
<td>0.04</td>
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<td>0.031</td>
<td>0.027</td>
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<td>1.08</td>
<td>0.29</td>
<td>0.57</td>
<td>0.71</td>
<td>0.13</td>
<td>0.01</td>
<td>0.18</td>
<td>0.24</td>
<td>0.02</td>
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<tr>
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<td>1.54</td>
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<td>0.11</td>
<td>0.15</td>
<td>0.05</td>
<td>0.01</td>
<td>0.05</td>
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<td>0.43</td>
<td>0.42</td>
<td>0.53</td>
<td>0.34</td>
<td>0.16</td>
<td>0.77</td>
<td>0.33</td>
<td>0.29</td>
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<tr>
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<td>99.88</td>
<td>100.6</td>
<td>101</td>
<td>99.27</td>
<td>99.09</td>
<td>99.74</td>
<td>100.4</td>
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<td>99.64</td>
<td>99.9</td>
<td>100.5</td>
<td>100.6</td>
<td>100.9</td>
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</table>

**Table 1:** Major (wt%) and Trace Elements (ppm) Analyses of the granitoids of north Adamawa Massif.
Plots of REE data for the granitoids on chondrite-normalised diagram of Boynton [31] display smooth coherent patterns from La to Lu. The REE distribution patterns for individual rock units (although not separately shown here) vary only slightly. The granodiorite displays appreciable negative Eu anomalies (Eu/Eu* = 0.44 on average). An almost flat HREE pattern [(Tb/Yb)N = 1.48 on average] and a near flat HREE pattern [(Tb/Yb)N = 1.58 on the average] with fractionated LREE-enriched trends [(La/Sm)N = 4.81 on the average]. They exhibit very small negative Eu anonalies (Eu/Eu* = 0.69 on the average). REE abundances in the granites are characterised by strongly fractionated LREE-enriched trends [(La/Sm)N = 4.81 on average]. The granitoids of the study area shows that the REE abundances are characterised by fractionated patterns [(La/Yb)N = 15.55 on average] and displays strongly fractionated LREE-enriched trends [(La/Sm)N = 3.62 on average] with less fractionated HREE patterns [(Tb/Yb)N = 1.52 on average] and significant negative Eu anomalies (Eu/Eu* = 0.41 on average). Trace elements distributions in which concentrations are normalised to average continental crust according to Weaver and Tarney [33] (Figure 10), may reflect the primary features of the melts and therefore give a general indication of the tectonic setting. On Figure 9 therefore, the granodiorites are characterized by enrichment in Nb, Sr and Nb and have high Y and Yb with pronounced negative EU anomalies. Collectively, this trend resembles that of post-collisional granites [34-36].

Discussion

Origin of the granitoids of zing-monkin area

Mantle and crust are two end member sources of granitoids. However, the two sources are not mutually exclusive. While most granitic rocks originate by contribution from both sources, some are derived purely from the end member sources [36,37]. The composition of the source and the physico-chemical processes that affect this source and the melt therefore control the chemistry of granitic rocks. Such characteristics have been described by Chappell and White [38]. Petrological and petrochemical investigation of the granitoids of the study area has led to recognition of two distinct granitoids types: the granodiorite and the granites (texturally subdivided into migmatite, equigranular granite, porphyritic granites and the fine-grained granites). The relatively uniform composition and overlapping ranges in most of their major, trace and rare earth elements contents indicates that they might have been derived from similar parental magma source. This notion of a genetic relationship is demonstrated on a plot of TiO2 versus Al2O3/TiO2 (Figure 7). The curvilinear trend for all the rock units is typical of magmatic differentiation and suggests that the rocks were generated from a chemically similar magma source [30]. It also suggests that the variation in the granitoids is probably the result of...
Figure 4: Selected Harker variation diagrams for major and trace from the granitoids of Northern Adamawa Massif.
of hybridization between the original magma and amphibolitic cover rocks [39]. Major and Rare earth elements chemistry of the granitoids suggest an evolutionary sequence from the more mafic granodiorite to the more evolved granites. Granitoids may be formed by fractional crystallization of mantle derived magmas, anatexis of crustal rocks or a combination of the two processes. Generally, there is an appreciable Eu anomalies (EU/EU’ = 0.41 on the average) probably produced by the removal of plagioclase consistent with fractionation of basic melts to yield silicic magmas. Liquids generated from melting of greywackes are of trondhjemitic composition and have low Al2O3, K2O, Ba and Rb contents [40]. Enrichment of these major and trace elements in the investigated granitoids argues against it formation by the melting of possible greywackes.

Geochemical modeling of Rb/Sr during melting suggest that a fluid present melting reaction of muscovite + plagioclase + quartz would
The REE patterns of the granitoids generally reflect the residual mineral assemblages of their source regions. The REE trends of the granodiorite and the granites are consistent with fractionation of biotite and plagioclase. The granitoids of the study area show REE trends that are characteristics of differentiated granites with moderate overall REE contents (TotREE = 492.66), a fractionated patterns [(La/Yb)N = 15.55 on average], strongly fractionated LREE-enriched trends [(La/Sm)N = 3.62 on average] with less fractionated HREE patterns [(Yb/Tb)N = 1.52 on average] and significant negative Eu anomalies (Eu/Eu* = 0.41 on average). These REE trends agree with other field characteristics that the granitoids are differentiated and can be explained by fractional crystallization. Rocks with LREE-enriched trends but characterized by negligible EU anomalies would be consistent with the generation by partial melting from a mafic source in which amphibole and/or garnet are present as residual phases in the source [42]. Negligible/minor EU anomalies and fractionated REE trends are mostly compatible with the control of amphibole with minor plagioclase crystalization [43]. Therefore the appreciable EU anomalies observed for the granitoids of the study area suggest plagioclase fractionation.

**Tectonic environment**

Methodical trace element variation plots encompassing granites from practically all possible tectonic environments have been developed by Pearce et al, Harris et al and Whalen et al [34,35,44]. According to Pearce et al [34] and Pearce [36] granites can be discriminated on the basis of Nb, Y, Ta, Yb, and Rb trace element data into volcanic-arc, ocean ridge, within-plate and collisional types. On Nb versus Y diagram (Figure 11) [34] the granitoids plot in the within-plate (WPG), Volcanic-arc (VAG) and syn-collisional granite (syn-COLG) fields. Granitoids have average Y/Nb ratios greater than 1.2 which according to Eby [45] correspond to I-subtype granites generated in a subduction-related environment. Further, the enrichment of the granitoids in Nb, Y and Yb indicates affinity to the post-collisional granitoids.

**Conclusion**

Although there are slight mineralogical and geochemical differences between the granodiorite and the granites (e.g. Rb/Sr ratios lower in granodiorite than the granites) which may be attributed to their different petrologic histories, in general, the two rock units have similar geochemical characteristics. The rocks are characterized by a wide range in SiO2, Calc-alkaline affinity, syn- to within-plate granite signatures, metaluminous to peraluminous composition and more K2O-rich and hypersthenes-poor comparable to fractionated I-type granitoids. The rocks display slightly fractionated to fractionated LREE, almost flat HREE patterns, with significant negative EU and Ba anomalies, Linear major element trends and progressive rise in SiO2, K2O, Rb and Rb/Sr ratios with depleting MgO, Fe2O3, CaO, TiO2, Sr and Ba consistent with removal of plagioclase during fractionation of basic melts to yield silicic magma.

Based on field and petrochemical features, the granodiorites and the granites of northern Adamawa Massif are I-type, generated in a syn- to within-plate collision-related tectonic setting and genetically related to a common source by fractional crystallization dominated by the removal of the melt hornblende, plagioclase, biotite, K-feldspar and accessory phases such as apatite, epidote and zircon.

**References**


