

GEOCHEMICAL CHARACTERIZATION AND PROTOLITH OF THE MIGMATITE-GNEISSES OF TANDAMA AREA, KATSINA STATE, NW NIGERIA

Abstract

Migmatite-gneisses, which include migmatite, granite gneiss, and augen gneiss, underlie more than 70% of Tandama area, in North-western Nigeria. They are associated with schists, and are intruded by granites and pegmatites. These rocks are thought to have undergone a reworking during the Pan-African Orogeny. Whole rock geochemical analyses have been used to evaluate the characteristics, petrogenesis and mode of emplacement of the protoliths. Geochemically, these rocks show granitic affinities. They are peraluminous, I-type, magnesian to ferroan and alkali calcic and calcic. With these varying features, the protoliths are derived from magma source which mixed or mingled with crustally derived melt. The rocks display varying REEs and trace elements patterns but, their LREEs and LILE enrichment with the noticeable enrichment in Rb, K, Pb and negative Nb, Ta, Ti observed among majority of the samples are typical signature of "arc rocks" or continental crustal materials. The incompatible trace element ratios in Th/U (2.21 – 12.4), Th/Yb (2.60 – 90.95), Ta/Yb (0.03 - 1.43), Ce/Pb (mainly 0.30 – 29.23) and high Ba/Nb (8.56 – 2402), are similar to those of the continental crust. The rocks are characterised by subduction related Sr/Y content (< 100). The magnesian affinity reflects relatively hydrous, oxidizing source which is consistent with origins that are broadly subduction related. Their high – K nature also points to an important petrogenetic role of remelting and differentiation of arc – accretionary complex crust. The rare earth element (REE) distribution shows that the migmatite-gneisses are enriched in the lighter rare earth elements (LREE) Sm, Pr, Nd, La and Ce, in that order of increasing abundance, with average values of 4.81 ppm, 7.90 ppm, 27.50 ppm, 38.44 ppm, 68.22ppm, respectively; and relatively depleted in the heavy rare earth elements (HREE) Lu, Tm, Tb, Ho, Yb and Er, with average values ranging 0.28 ppm, 0.30 ppm, 0.58 ppm, 0.65ppm, 1.91 ppm and 1.88 ppm respectively, and they exhibit negative EU anomaly, indicating that the rocks are highly fractionated. REE-chondrite normalized spider plot and plots in the chemical discrimination diagrams including the Y versus Nb plot, show that the protoliths were derived from partial melting and differentiation of granitic magma of hybrid origin which were emplaced in volcanic arc (VAG) to Syn-collision granite (Syn-COLG) tectonic setting. Variations thus, suggest igneous precursors for the migmatite-gneisses of this area, were derived from differing sources and depths.

1. INTRODUCTION

The Migmatite–Gneiss Complex of the study area is one of the four major petro-lithological units that constitute the Basement complex of Nigeria which forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons and south of the Tuareg Shield (Black, 1980). It is intruded by the Younger Granites and is unconformably overlain by Cretaceous and younger sediments. The Migmatite – Gneiss Complex is the most widespread of the component units in the Nigerian basement. It has a heterogeneous assemblage comprising migmatites, orthogneisses, paragneisses, and a series of basic and ultrabasic metamorphosed rocks. Petrographic evidence indicates that the Pan-African reworking led to recrystallization of many of the constituent minerals of the Migmatite– Gneiss Complex by partial melting with majority of the rock types displaying medium to upper amphibolite facies metamorphism (Dada, 1998).

The Migmatite-Gneiss Complex of the study area is located in north-western part of Nigeria and has heterogeneous assemblages of migmatites, gneiss and augen gneiss. Some authors have attributed the Migmatite-Gneiss Complex of Nigeria to be of sedimentary origin while others view them as rocks of igneous origin. According to Rahaman (1988), the geochemical data available were insufficient to equivocally distinguish between sedimentary and igneous gneisses. Grant (1970) on the basis of $^{87}\text{Sr}/^{86}\text{Sr}$ studies of the Ibadan granite gneiss supported an igneous origin while Burke et al. (1972) argued that the granite gneiss were derived from isochemical metamorphism of a shale-graywacke sequence (a sedimentary origin). Onyeagocha (1984) on the basis of field and geochemical evidence proposed an igneous origin by partial melting of crustal rocks for the granite gneisses of north-central Nigeria. Supportive of the igneous origin are also works of Ekwere and Ekwueme (1991); Imeokparia and Emofurieta (1991) while Freeth (1971) support a sedimentary origin. Elueze and Bolarinwa, (2004) studies of the granite gneiss of Abeokuta area gives a wide range of Ba and Zr concentration, concluded that the gneisses were of igneous parentage but with sedimentary input. This made it difficult to propose a single mode of origin for the granite gneisses in the Nigerian basement due to their variable compositions from location to location (Elueze and Bolarinwa, 2004).

Works done on the genetics of migmatite-gneisses are restricted to the south-western basement of Nigeria (Olawajolu, 1988; Elueze et al., 2004; Oyinloye, 1998; 2002; 2004; 2011 and Okonkwo and Ganev, 2012). However, the gneisses of the Malumfashi schist belt where the study area is situated were earlier identified by McCurry (1976) on the basis of petrography and not geochemistry, and were on a regional scale. This paper therefore presents results of geochemical investigation of Migmatite-Gneiss Complex, around Tandaman area of north-western Nigeria, with a view to determine their geochemical characteristics and petrogenesis, in order to improve on the existing knowledge.

2. GEOLOGY OF THE AREA

The study area lies between latitude 11° 22' to 11° 30'N and longitude 07° 23' to 07° 30'E and covers a total area of 195km² and falls within the north western zone of the Nigerian basement complex. The Migmatite-Gneiss Complex of the study area has heterogeneous assemblages of migmatites, granite gneiss and augen gneiss (Figure 1).

The migmatites occur as low-lying outcrops and boulders that are medium-grained with bandings, and they are associated with granite gneiss. The bandings are regular in form and consist of palaeosome and neosome, with stromatic and pygmatitic structures. The Granite gneiss comprises the main body of the palaeosome which consists of medium grained gneissic fabric of feldspar, quartz and biotite distributed into darker laminae. The neosome consists of light grey medium grained granitic constituents that were introduced into the pre-existing gneissic parent's rock. They include quartz, feldspar, and little biotite and muscovite. The migmatitic gneiss outcrops at the centre of the western portion of the area, especially around Tudun Ibat, Dan Zaki and Dan Kauye as low lying outcrops and boulders. The gneissic palaeosome is highly foliated with simple fold structure. It is marked by alternating light leucosome band that is rich in quartz-feldspathic minerals and dark melanosome band, which is composed of mafic minerals. The bands are generally discontinuous, thin and somewhat weak. The neosomes which are marked by veins of pegmatitic constituents of quartz and feldspars form a pygmatitic structure. They form 30% of the migmatite-gneiss rock. The pegmatite veins are common and may be concordant or cross cutting and contain mostly pinkish feldspar, quartz and mica.

The granite gneiss occurs in association with migmatites, especially in the central area of the western portion of the study area. It outcrops as more resistant low-lying rock bodies and boulders along the north-western and south-western portion of the study area. Those along the river channels are highly weathered. The rock is medium-grained light grey to grey in colour and it is well foliated. The foliation is marked by segregation of quartz-feldspar and biotite-rich successions in a north-south direction. The ferromagnesian minerals tending to concentrate in parallel alignment of darker bands, the coloured minerals consist of biotite and hornblende, while the light coloured bands are quartz and feldspar rich. The granite gneiss around Ungwan Balarabe in the north has green amphibole along the darker bands. The rocks are jointed with one set of jointing system trending north-south and the others trending east-west. The quartz-feldspar veins are concordant and sometimes develop pinch and swell structures. The pegmatite veins run parallel to the foliation of these rocks, some few are discordant. There are portions of the granite gneiss that has folded banding, somewhat complexly, within the migmatite, and there are areas where the granite gneiss consists of weakly foliated granite rock which gives the granite gneiss a migmatitic feature, thus called migmatitic granite gneiss. The folding gives the leucocratic portion pygmatitic structure. It is a light grey leucocratic rock with the banding varying in thickness and continuity. The individual bandings vary in thickness from fraction of a centimetre to several centimetres, the banding in some places are split into smaller units.

The Augen gneiss occupies about 20% of the area, and it occurs as boulders and low lying outcrops in the north-east and extends towards the centre of the study area. They are prominent around part of Rafin Gora, Ungwan Sambo, and Tandaman area as boulders and low-lying outcrops. The rock is dark grey in colour and weakly foliated, and bounded by mica schist. It is characterized by feldspathic augens enclosed in a finer grained groundmass of feldspar, quartz and ferromagnesian minerals which are weakly foliated. Generally, the shape of the feldspar porphyroblasts is irregular, the colour of the porphyroblasts is pale pink and they are embedded in a groundmass of flattened quartz crystals, chlorite and biotite. The feldspar augen has inclusion of wisps and small blebs of the groundmass, especially quartz. The grain size of the rock is finer, more foliated and less porphyroblastic in the north, while those in the central area are more porphyroblastic and less foliated. This shows that the rock experienced more shearing in the north than in the central area.

3. ANALYTICAL METHODS

Rock samples collected from the field were taken to the laboratory of the Department of Geology and Mining, University of Jos, for sample preparation. The samples were broken into smaller pieces using geologic hammer so that they can be grinded easily in the pulveriser. The smaller fragments were crushed and reduced to powder using FRITSCH Pulverisette 7. The equipment has two grinding bowls and each of them has grinding steel balls which crush and rip apart the rock fragments while rotating for 30 minutes at 400 revolutions per minute (400rpm). The powdered samples, pulverised to 85% passing 200 mesh, and measured to 5g were transferred into labelled dispersing gloves for transportation to Acme laboratory at Vancouver, Canada, where whole-rock analyses were carried out using X-ray fluorescence (XRF) for major oxides and Inductively coupled plasma mass spectrometry (ICP-MS) for trace elements determination.

4. RESULTS

4.1 Chemical Alteration

Studies have shown that, even for rocks of prehistoric inheritance, the concentrations of such ‘mobile’ (major and large ion lithophile elements (LILE)) elements do not significantly change from their background abundances (e.g. Whalen et al., 1999). Due to the relatively immobile nature of high field strength (HFSE) and rare earth elements (REEs) under most conditions (e.g., Pearce and Cann, 1973; Whalen et al., 1999), they have often been used for igneous petrogenetic and tectonic studies. On the other hand, due to high susceptibility to mobility *during processes such as metamorphism and hydrothermal activities*, major elements have mostly been used to give background information. However, if the dispersion of the major elements is minor, they could still reveal the principal igneous processes involved in the formation of the rocks. Nevertheless, the extent to which the Dahomeyide granitoid gneisses had been altered was investigated using the chemical index of alteration (CIA) calculations of Nesbitt and Young (1982). According to Nesbitt and Young (1982), CIA value of any rock above 60 indicates alteration. The CIA values for the migmatite-gneiss samples range between 51.83% and 62.49% (average of 56.67%) which indicates that the rocks have not gone through much alteration.

4.2 Major Oxides

In the K_2O - SiO_2 diagram (Figure 2), the samples of granite gneiss mostly fall in the field of shoshonite series while most of the augen gneiss fall in the field of high-K series, the migmatite spread across them. These migmatite-gneisses are mostly of peraluminous character and only a sample of granite gneiss and augen gneiss show metaluminous character (Figure 3). The rocks contain high K_2O content (> 2.0). The total alkalis A/NK [molar $(Al_2O_3 / Na_2O + K_2O)$] and A/CNK [molar $(Al_2O_3 / CaO + Na_2O + K_2O)$] contents range from 1.46–2.12 and 1.08–1.67 respectively (Table 1). The alumina saturation index [ASI= molar $[Al / (Ca + Na + K)]$] contents also range from 1.08–1.67 which is typical I-type signature.

According to the classification of granitoid rocks by Frost et al. (2001) using SiO_2 (wt.%) vs. Fe^* -number [molar $Fe_2O_3 / (Fe_2O_3 + MgO)$], most of the plots of migmatite-gneisses lie in the compositional field for Caledonian post-collisional plutons (Figure 4a). This diagram shows that the augen gneiss belong to the magnesian group (only 1 sample of augen gneiss belong to ferroan group) while migmatite and granite gneiss belong to the ferroan group (only 1 sample of migmatite and granite gneiss belong to magnesian group).

In SiO_2 (wt.%) vs. $(Na_2O + K_2O + CaO)$ (wt.%) diagram (modified alkali lime index, MALI) of Frost et al. (2001), with increasing SiO_2 composition, the granite gneiss and augen gneiss are of alkali-calcic and the migmatite mainly of calc-alkalic (Figure 4b).

In the migmatite-gneiss rocks, Al_2O_3 , CaO , MgO , TiO_2 , Fe_2O_3 , P_2O_5 , Ba and Sr display a linear negative correlation with SiO_2 in the Harker plot suggesting fractional crystallization. The variations of Na_2O correlate positively with SiO_2 up to 70% SiO_2 and then correlate negatively (Fig. 6). K_2O is broadly positively correlated with SiO_2 (Figure 5).

The analyzed samples of the migmatite-gneisses plot in the granitic field in the normative Ab–An–Or diagram (Figure 6a). They follow a classical calc-alkaline trend in the AFM diagram (Figure 6b), and fall on the volcanic arc field in $\log(-Ta)$ vs. $\log(Yb)$ tectonic discrimination diagram (Figure 6c).

4.3 Trace Elements

In the incompatible trace-element concentrations normalized to the primitive mantle using Sun and McDonough (1989) normalized values (Figure 7a), the migmatite-gneisses display nearly linear distribution characterised by decreasing abundance from large ion lithophile elements (LILE) down to high field strength elements (HFSE).

The migmatite show gentle slope pattern with noticeable positive Rb, U, Th, Ta, K, Pb, Sr, Nd, Zr, Sm, Hf, La, Dy, with slightly Cs, Th, enrichment, there are depletion in Ba, Ce, Pr, P, Ti, Nb. The granite gneiss show enrichment in Rb, Th, U, Pb, K, Pr, Sr, Nd, La, Sm, Dy and negative Ba, Nb, Ta, Ce, P, Zr, Ti, Cs anomaly. Augen gneiss is characterised by negative Ba, Nb, Ce, Ti, Ta, Sr, P and enriched in Cs, Rb, Th, U, Pb, Pr, Nd, La, Zr, Sm, Dy.

The trace elements characteristics give indication of varying sources for the migmatite-gneisses protolith, but the depletion in Nb, Ta, and Ti and enrichment in K, especially Pb, are typical signatures of “arc rocks” or continental crustal materials (i.e., the familiar “arc signature” or “crustal signature”). Lavecchia et al. (2006) suggested this distribution requires a high oxygen (O_2) fugacity in the source region to allow HFSE fractionation which could also produce the Eu anomaly. While this interpretation may be possible, the negative Eu anomaly is more likely a source inheritance (Guo et al., 2013).

Their incompatible trace element ratios, such as Th/U (2.21 – 12.4), Th/Yb (2.60 – 90.95), Ta/Yb (0.03 - 1.43), Ce/Pb (mainly 0.30 – 29.23) and high Ba/Nb (8.56 – 2402), are similar to those of the continental crust (Rudnick and Fountain, 1995; Rudnick and Gao, 2003), and resemble the values recorded by magmas that formed in active continental margins (Wilson, 1989).

On the other hand, the Eu anomalies may be attributed to the varying concentration of plagioclase minerals observed among the samples which is typical of processes in crustal magma chambers and matches field and petrographic evidence of the abundance of plagioclase phenocrysts. Generally, Eu anomalies are negative ($Eu/Eu^* = 0.24\text{--}0.81$, an average of 0.54), samples ALA 33 and ALA 15B have small or negligible Eu anomalies ($Eu/Eu^* = 0.81$ and 1.14, respectively), except for samples ALA 15, ALA 30, ALA 28B and ALA 29B, which have positive Eu anomalies ($Eu/Eu^* = 1.3, 1.53, 3.14$ and 3.31, respectively). A negative Eu anomaly in almost all the analyzed samples, indicate that the migmatite-gneisses are highly fractionated, except for four samples that show positive Eu anomaly and no anomaly observed in two. This contrasting Eu behaviour can be attributed to the difference in the geodynamic setting (tectono-metamorphic and tectono-magmatic) of the emplacement of these rocks. The rocks are characterised by subduction related Sr/Y content (< 100), which are characteristic of the samples except sample ALA15 and ALA15B that showing high concentration of Sr/Y (142.16 and 116.35 respectively). Taking into account these data, the involvement of a crustal - derived or subduction – modified component in mantle sources is apparent.

The results of the abundance and distribution of the rare earth elements (REE) in the migmatite-gneisses of the study area are presented in Table 1. The results show that the migmatite-gneisses are highly enriched in the lighter rare earth elements (LREE) Sm, Pr, Nd, La and Ce, in that order of increasing abundance, with average values of 4.81 ppm, 7.90 ppm, 27.50 ppm, 38.44 ppm, 68.22ppm, respectively; and relatively depleted in the heavy rare earth elements (HREE) Lu, Tm, Tb, Ho, Yb and Er, with average values ranging 0.28 ppm, 0.30 ppm, 0.58 ppm, 0.65ppm, 1.91 ppm and 1.88 ppm respectively (Table 1).

The total rare earth elements abundance $\{TREE = \Sigma(La + Ce + \dots + Lu)\}$ varies from 508.88ppm in the migmatite, to 1586.21 ppm in the granite gneiss, through 1114.05 ppm in the augen gneiss.

The REE patterns (Figure 7b) are highly fractionated (chondrite-normalized, after Sun and McDonough (1995), $La/Yb = 1.8\text{--}97.92$, average of 32.33), showing a relatively sharp decrease from La to Sm (chondrite-normalized $La/Sm = 2.64\text{--}6.95$, average of 4.83) and a flat heavy REE (HREE) profile (chondrite-normalized $Tb/Yb = 0.56\text{--}6.95$, average of 2.64).

5. Discussion

5.1 Classification

Based on normative Ab – An – Or scheme (after O'Connor, 1965), the migmatite-gneisses can be classified according to the presumed origin of the parent rocks. The rocks plot mainly in the field of granite which indicates a granitic protolith. On the classification scheme of Frost et al. (2001), the migmatite-gneisses display magnesian to ferroan characteristics, mainly alkali – calcic affinities and with few calc – alkali, they are peraluminous. They are I - type in nature. These characteristics together with the positions of the samples on the $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ versus $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ discrimination diagram (after Garrels and Mackenzie, 1971), and TiO_2 versus SiO_2 plot (after Tarney, 1977) further support I – type affinity for the migmatite-gneisses (Figure 8). On the classification plot of K_2O versus SiO_2 of Peccerillo and Taylor (1976) (Figure 9), the rocks plot mainly in the field of high – K series field. All these characteristics give an indication of varying source of the migmatite-gneiss rocks.

5.2 Petrogenesis

The major and trace elements compositions have been used to evaluate the origin of the migmatite-gneisses of the study area. The major element compositions of the samples reveal an evolutionary trend for the rocks.

The Al_2O_3 , Na_2O , CaO , MgO , TiO_2 , Fe_2O_3 , MgO , TiO_2 and P_2O_5 decrease, with relatively little scatter, with increasing SiO_2 and, although with great scatter, negative correlations are also seen between SiO_2 and Al_2O_3 , and Na_2O , Zr and Y. These observations suggest, on one side, closed system behaviour during metamorphism, and, on the other side, a comagmatic origin of the igneous protolith (with the possible exception of the two most silica-rich samples).

The apparent negative correlation between SiO_2 and Fe_2O_3 , MgO , CaO , Y, Ni, and Nb contents in the rocks indicate fractional crystallization involving the assemblage plagioclase and biotite which is in good agreement with the field and petrographic evidence of the abundance of plagioclase phenocrysts and biotite.

The abundance of hydrated minerals (e.g. biotite) in the plutonic rocks suggests that the melting of the protolith took place under hydrous conditions. The mostly granitic features observed (Figure 6b), the high Na_2O and K_2O contents (Table 1) together with their affinity for alkalic – calcic with a few plotting in the calcic and calc – alkalic fields (Figure 4b) may be compared to the Achaean migmatite-gneisses which indicate the migmatite-gneisses to be the product of reworking of these suits during the Pan-African.

They have comparable Sr/Y (< 100) ratio with relatively low Y contents which are characteristics of transitional composition between Archean and an arc rocks (Dada, 1998), which allows us to suggest evolution of the composition of the primary melt as a result of assimilation of Archean crust material or mixing of the basic melt with acid melt formed during crust melting. It is noted that Archean migmatite-gneiss complexes are characterised by subduction signatures coupled with steep rare earth profiles (LILE enrichment), thus may originate by fusion of basalt in a subduction setting (Rapp et al., 1991).

The geochemical differences between the samples may also support the idea of crystal fractionation of the protolith probably, during the ascent of the melts from the lower crust where they were generated up to the upper crust where they finally solidified. Frost et al. (2001) observed from MALI diagram that most granitoids follow sub – parallel alkali – lime trends during differentiation. Hence, any observed crossing of trend divides or lines by a granitoid suite may indicate mixed magma sources or extreme differentiation of the parent magma for the rocks. On the Frost et al. (2001) diagrams, the migmatite-gneisses show magnesian to ferroan, calcic to alkali calcic (Figure 4a and 4b), peraluminous to weakly metaluminous (Figure 3) with I – type imprints (Figure 8a and 8b). Iron enriched melts derived from reduced basaltic sources (either tholeiitic or mildly alkalis) make important contribution to ferroan granitoids and reflects a close affinity to relatively anhydrous, reduced magmas and source regions (Frost and Frost, 1997). According to the latter authors, because these magmas are

hotter, they are likely to undergo extensive fractionation towards iron rich alkali compositions; magnesian rocks in contrast are probably related magmas which follow relatively oxidizing differentiation trends.

A secondary effect on Fe^* which seem particularly at high silica contents is the composition of the crustal melt with wide range of Fe^* may be explanation for the population of ferroan granitoids and magnesian nature may be source inheritance. However, according to Chappell and White (1974), I – type granitoids, peraluminous to weak metaluminous, relatively sodic, with wide range of silica contents are formed from mafic to felsic meta – igneous source, possibly by partial melting of continental crust. The studied rocks show elevated concentration of K with $K_2O > 1$ and plot in the High – K fields. Their High – K to medium – K and peraluminous to weakly metaluminous character requires a peraluminous and high – medium – K source material or protoliths. The geochemical features of high – K migmatite-gneisses are supportive of origin in relation to a convergent margin setting, pointing to an important petrogenetic role of remelting and differentiation of arc – accretionary complex crust. Although there are some controversies, it is generally accepted that water plays a major role in producing high – K, I – type, alkali-calcic magmas Murphy (2007).

5.3 Tectonic Setting

Several schemes exist for assigning granitoids to various tectonic environments by means of their geochemical characteristics (e.g., Pearce et al., 1984; Maniar and Piccoli, 1989; Pearce, 1996a). Trace elements have been paramount in such schemes. However, few of the major-element schemes have been useful in discriminating between the granitoids that belong to different tectonic environments.

The nearly linear negative slope pattern with enrichment in LREEs and LILE (Rb, K, Pb, Sr) and depleted in HFSE with negative Ta, Nb, Ti are typical arc roots together with the ferroan to magnesian, and calcic to alkali calcic characteristics may also testify magmatic activity involving mixing sources. Ferroan granitoids reflect a close affinity to relatively anhydrous, reduced magmas and source regions. Such are conditions are common in extensional environment (Frost and Lindsley, 1991; Frost et al., 2001). Magnesian series reflect close affinity to relatively hydrous, oxidizing magmas and sources region which is consistent with origins that are broadly subduction related (Frost and Lindsley, 1991; Frost et al., 2001). These give indication of mixing tectonic setting but, as already discussed, a secondary effect on Fe^* which seem particularly at high silica contents is the composition of the crustal melt with wide range of Fe^* may be explanation for the population of ferroan granitoids at high silica content (Frost et al., 2001). The primitive mantle – normalized multi-element plots (Fig. 6) of these rocks show elevated concentration of LILE with typical arc like signatures (deep Nb, Ta and Ti troughs together with large positive Pb anomalies) Orejana et al. (2009). The enhanced level of LILE relative to HFSE in the migmatite-gneisses points to the subduction – zone enrichment and/or crustal contamination of the source region (Arvin and Rotstamizadeh, 2000). Such crustal influence is also reflected in the incompatible trace element ratios and major element as explained above. According to Kumar and Sreejith (2011), the LREE – enriched patterns with negative Eu anomalies together with high – K signatures are also typical of many subduction related magmas from island arcs or active continental margins.

Accordingly, in order to infer the geotectonic environment of emplacement of the migmatite-gneisses, we have used various tectonic discrimination diagrams. The rocks show subduction related signatures with $Sr/Y < 100$ (Huang et al., 2010). except sample ALA15 and ALA15B that showing high concentration of Sr/Y (142.16 and 116.35 respectively), the plot of Sr/Y vs Y is consistent with subduction components (Figure 10a).

On the R1-R2 diagram Batchelor and Bowden, (1985), all the samples plot in the syn – collisional field with only two samples plotting in the field of Pre – collision and Late-orogenic granites field. Syn-collisional is synonymous to the volcanic arc granite (VAG) in the scheme of Pearce et al. (1984) and Pearce (1996a) (Figure 10b). Syn – collision settings are linked to the process of crustal thickening, usually by the underthrusting of one crustal 'slice' beneath another (Batchelor and Bowden 1985), which was founded in the chemical classification scheme of De La Roche et al. (1980). Syn-collision granites linked to continent – arc collision are the last intrusions in the life – cycle of a volcanic arc where they form peraluminous, I – type granites with biotite as one of most common ferromagnesian minerals.

The trace elements tectonic discriminant plots of $Y+Nb$ versus Rb, Y versus Nb, $Ta+Yb$ versus Rb and Yb versus Ta (Figure 11) also suggest volcanic arc roots for the granitoids and are plotted in the volcanic arc granitoids (VAG) field Pearce et al. (1984). Volcanic arc granites (VAG) form discrete, often zoned plutons in

island arc terranes and linear, composite batholiths at active continental margins. They commonly form I-type granite, granodiorite and tonalite intrusions which are peraluminous, calc – alkaline, with biotite as common ferromagnesian minerals have standard subduction signatures with enrichment in LIL elements relative to HFS (high field strength) elements (Pearce, 1996a).

However, the high K₂O contents of the migmatite-gneiss rocks reveal their high – K nature. As well as having enhanced K contents as a result of high K₂O contents of the migmatite-gneisses, their enrichment in other incompatible elements reflects the importance of crustal rocks in the magma source (s) (Roberts et al., 1993; Arvin and Rotstamizadeh, 2000). Such an enrichment event accounts for the arc – like signatures of this mantle – derived rocks and explains the addition of volatiles to the mantle source. This geochemical signature is likely to be related to metasomatism of the sub – continental lithospheric mantle via crustal recycling. Taking into account these data, the involvement of a crustal – derived or subduction – modified component in the mantle sources is apparent. The crustal component may have derived from partial melting of these rocks as they form part of the Pan African belt. The migmatite-gneisses in conclusion are believed to have formed in continental subduction during the Pan African collision.

All the analysed samples are characteristically enriched in the LREE and depleted in the HREE, the samples of whole rock REE of migmatites has a total REE abundance of 508.88 ppm, TLREE of 441.17 ppm and THREE of 67.71 ppm, yielding a TLREE/THREE ratio of 6.52 which is consistent with the general trend. The depletion maxima is recorded in the granite gneiss, which shows TREE abundance of 1586.21 ppm, TLREE (1483.64 ppm), THREE (102.57 ppm), giving a TLREE/THRE ratio of 14.47. The augen gneiss has TREE of 1114.05 ppm, TLREE (1029.81 ppm) and THREE (84.24 ppm), thus giving a TLREE/THREE ratio of 12.22.

The very high enrichment trend possibly indicates high abundance of cerium earths which favours the concentration of LREE relative the HREE (Taylor, 1985), the behaviour and range of the REE are within rocks of igneous origin.

Interpretation of the elemental abundance shows that the large ion lithophile element Rb vary from 116.72 ppm in the migmatite, through 152.65 ppm in the granite gneiss to 205.03 ppm in the augen gneiss, the rocks have an average Rb content of 157.58 ppm. The Rb content is very close to the concentration of 150 ppm for average granite, and 112 ppm for average continental crustal rock (Taylor and McLennan (1985), thus confirming a granitic protolith for the migmatite-gneisses.

Thus, corroborating a crustal source for the protoliths of the rocks which have been affected during the Pan – African tectonothermal events. The trend of distribution also shows the migmatite gneisses are highly differentiated and fractionated, and generally conform to the characteristics of similar rocks from other tectonic settings.

6. Conclusion

Precambrian migmatite-gneisses of the study area constitute more than 70 % of the basement rocks. They are peraluminous, calc-alkaline, granitic in composition, and of igneous protolith, emplaced in a within plate granite – syn-collision granite tectonic setting. The LREE-enriched patterns with negative Eu anomalies observed together with high – K characteristics are typical of many subduction related magmas from island arcs or active continental margins, thus the origin of the protolith. The rocks show LREEs and LILE enrichment consistent with source with strong affinity to VAG and appear to be characterized by mingling of mantle derived magma and crustally derived melts. The chemical discrimination diagrams shows that the protoliths of the migmatite-gneisses were derived from partial melting and differentiation of granitic magma of hybrid origin.

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TABLE 1: MAJOR AND TRACE ELEMENTS COMPOSITION OF MIGMATITE, GRANITE GNEISS, AND AUGEN GNEISS

Rock name	Migmatite	Migmatite	Migmatite	Migmatite	Migmatite	Migmatite	Granite gneiss	Granite gneiss	Granite gneiss	Granite gneiss	Granite gneiss	Granite gneiss	Granite gneiss	Granite gneiss	Augen gneiss	Augen gneiss	Augen gneiss	Augen gneiss	Augen gneiss	
Sample	ALA 28	ALA 28 B	ALA 29	ALA 29 B	ALA 30	ALA 31	ALA 14	ALA 15	ALA 15 b	ALA 17	ALA 26	ALA 27	ALA 32	ALA 33	ALA 1	ALA 2	ALA 4	ALA 6	ALA 18	ALA 21
MAJOR OXIDES wt%																				
SiO ₂	74.01	74.09	73.64	73.95	73.71	73.9	66.27	71.78	73.72	73.37	74.09	73.68	71.34	72.46	64.68	69.94	67.74	70.51	74.15	69.94
Al ₂ O ₃	13.45	14.52	13.69	14.73	14.73	14.01	14.6	15.26	14.5	13.63	13.87	13.74	16.02	14.82	16.41	14.73	15.23	14.67	13.76	14.6
Fe ₂ O ₃	1.45	0.87	1.55	1.17	1.15	0.95	2.54	0.82	0.46	2	1.2	1.7	1.15	1.03	3.57	3.04	3.74	2.9	1.44	3.51
CeO	0.75	1.36	1.16	1.6	1.88	0.9	5.74	1.27	0.66	0.9	0.66	1.01	1.4	0.84	2.63	1.72	1.83	1.18	0.58	1.58
MgO	0.09	0.11	0.26	0.17	0.26	0.14	1.1	0.13	0.01	0.28	0.18	0.11	0.17	0.13	1.47	0.95	1.16	0.66	0.14	0.94
Na ₂ O	2.79	4.18	3.36	4.62	4.6	3.5	3.52	3.94	3	2.98	3.17	3.34	4.24	3.16	4.36	3.77	3.42	3.54	2.92	3.52
K ₂ O	6.44	3.75	5.02	2.83	2.36	5.26	4.31	5.43	6.55	5.56	6.34	5.44	4.1	5.84	4.4	4.4	4.19	4.65	5.03	4.76
MnO	0.06	0.01	0.02	0.02	0.02	0.01	0.12	0.02	<0.01	0.04	0.02	0.05	0.02	0.02	0.05	0.04	0.05	0.04	<0.01	0.06
TiO ₂	0.08	0.09	0.17	0.12	0.12	0.09	0.3	0.07	0.02	0.17	0.12	0.1	0.1	0.07	0.61	0.47	0.66	0.38	0.09	0.49
P ₂ O ₅	0.03	<0.01	0.05	0.02	0.04	0.02	1.11	0.02	0.02	0.05	0.02	0.02	0.04	0.01	0.29	0.14	0.17	0.1	0.01	0.14
Cr ₂ O ₃	0.052	0.05	0.052	0.055	0.043	0.037	0.04	0.068	0.052	0.027	0.033	0.066	0.047	0.061	0.043	0.057	0.039	0.069	0.038	0.052
TRACE ELEMENT (ppm,Au in ppb)																				
Ba	382	719	576	533	295	684	808	1477	1201	607	541	331	406	580	1786	535	637	549	267	660
Be	3	2	1	<1	<1	<1	3	<1	<1	<1	<1	3	6	4	6	4	4	8	3	2
Co	2.9	3.3	3.2	3.5	3.7	2.7	4.5	3.6	2.6	2.7	2	3.1	3.5	3.4	8.2	8.6	8.9	7.1	3	8.3
Cs	1.9	4.4	3.1	5.4	4.8	2.3	1.7	2.1	4	2	1.3	3	3.5	3.5	4.2	10	19.1	26.8	3.4	12.5
Ga	20	13.1	12.7	15.1	15	14.4	21.9	13.2	12.7	16.1	19.3	20.5	18.9	16.2	25	21.6	23.3	20.4	17.7	19.5
Hf	3	1.8	4.3	0.9	3.1	2.6	7.8	0.3	1.1	5.8	3.6	3.1	3.3	3.4	5.9	5.9	7.1	4.3	4.1	5.8
Nb	17.3	2.8	8.2	6.5	6.7	5.7	11.5	1.5	0.5	18.9	6.4	19	7.2	5.4	14.1	14	15.8	15.3	31.2	14.5
Rb	202.5	88.5	130.1	77.6	76.7	124.9	121.8	103.1	136.7	148.6	196.7	178	145.3	191	132.4	199.7	209.7	224.9	246	217.5

Sn	2	2	2	2	3	1	7	1	1	1	1	1	1	1	1	2	2	2	3	4	6	3	4
Sr	67.1	188.2	138.9	200.3	201.9	172.7	471.3	440.7	337.4	154.8	130.4	63.3	94.7	97.3	874.9	237.1	257.3	193.6	56.3	223			
Ta	0.3	0.6	0.6	1.7	0.7	0.3	0.7	<0.1	<0.1	0.6	0.2	0.5	0.4	0.4	1.1	1.1	1.7	2.6	1.4	2.1			
Th	26.5	1.9	18.6	6.2	4.6	19.1	42.6	8.3	11.2	59.7	18.5	23.6	12.5	7.3	12.3	27.5	24.8	29.7	39.7	27.8			
U	10.4	0.8	1.5	2.3	1.3	1.6	6.8	0.7	1	5.2	4.3	9.9	1.3	0.9	2.4	7.7	8.2	8.9	8.3	12.6			
V	<8	<8	<8	<8	<8	<8	19	<8	<8	<8	<8	<8	<8	<8	66	48	57	33	<8	33			
Zr	91	65.9	133.4	27.6	109.6	71.8	293.4	12.3	31.9	173.4	105.8	91.2	102.3	96.8	237.1	221.4	275.1	161.7	116.2	207.2			
Y	77.4	3.7	14.6	11.1	6.9	3.9	17.5	3.1	2.9	19.9	4.9	77.3	13.3	6.1	11.5	14.9	14.8	22.4	41.5	19			
La	33.7	5	37.5	3.6	8.7	30.3	101	23.5	13.5	106.7	27.3	29.9	67.9	26.5	39.8	53.2	20.7	44.3	44.6	51			
Ce	59.9	8.3	65.7	2.5	17.3	56.2	205.1	41.2	27.8	187.1	48	53.6	68.3	33.8	86.4	85	82.4	73.2	67.1	95.4			
Pr	5.9	1.02	6.99	0.48	1.72	5.65	23.79	4.21	2.73	20.35	5.1	5.22	15.41	6.05	9.44	9.88	6.01	9.31	8.65	10.01			
Nd	17.7	3.5	23.3	1.9	6.6	18.5	86	15.3	9.6	69.7	17.9	17.7	49.5	20.5	36.5	33.2	22.6	33.5	30.3	36.2			
Sm	3.97	0.69	4.99	0.55	1.43	3.4	11.1	2.08	1.65	12.1	3.25	3.8	8.65	3.51	6.6	5.34	4.83	6.17	6.15	5.96			
Eu	0.52	0.7	0.7	0.77	0.71	0.78	2.15	0.75	0.51	0.87	0.59	0.48	1.1	0.79	1.48	0.94	0.81	1.05	0.72	1.06			
Gd	5.17	0.68	4.1	0.93	1.43	2.84	6.83	1.51	1.14	9.95	2.26	4.95	6.08	2.57	4.77	4.42	3.66	5.19	5.9	4.87			
Tb	1.22	0.12	0.53	0.2	0.24	0.31	0.68	0.17	0.14	1.18	0.29	1.22	0.84	0.35	0.54	0.58	0.52	0.7	1.06	0.62			
Dy	9.04	0.75	2.77	1.56	1.2	1.19	3.1	0.79	0.58	5.26	1.21	9.39	3.44	1.54	2.4	2.69	2.83	4.03	6.46	3.29			
Ho	2.53	0.11	0.43	0.38	0.27	0.16	0.6	0.11	0.08	0.73	0.22	2.48	0.56	0.24	0.39	0.5	0.5	0.71	1.28	0.61			
Er	8.67	0.34	1.18	1.11	0.66	0.24	1.48	0.17	0.23	1.6	0.48	8.42	1.15	0.6	0.97	1.23	1.41	1.79	4.19	1.76			
Tm	1.47	0.05	0.15	0.17	0.1	0.03	0.22	0.03	0.04	0.23	0.06	1.41	0.15	0.07	0.13	0.21	0.2	0.3	0.62	0.27			
Yb	9.85	0.43	0.92	1.33	0.75	0.21	1.45	0.16	0.29	1.17	0.33	9.09	0.78	0.46	0.87	1.29	1.44	1.85	4.1	1.49			
Lu	1.34	0.06	0.16	0.19	0.11	0.03	0.18	0.01	0.03	0.18	0.05	1.37	0.11	0.08	0.12	0.17	0.22	0.28	0.59	0.22			
SumREE	160.98	21.75	149.42	15.67	41.22	119.84	443.68	89.99	58.32	417.12	107.04	149.03	223.97	97.06	190.41	198.65	148.13	182.38	181.72	212.76			
Mo	4.5	2.3	2.4	2.8	2.4	2.7	2.3	3.1	2.8	1.7	1.9	4.8	3.7	3.6	2.2	3.9	1.2	3.5	2.7	4.4			
Cu	25.1	7.4	7.1	8.1	7.8	5.9	6.2	10.8	8.5	4.7	6.7	12.2	10.7	12.6	31.1	15.6	19.7	14.6	7.3	21.5			
Pb	12.7	6.2	4.3	8.4	8	7.6	11	11.9	8.9	6.4	6.9	12	9.8	9.8	5.9	7.7	8.5	13.7	14.6	9.2			

Zn	22	12	27	17	21	14	14	13	4	31	22	23	14	15	70	56	61	40	18	57
Ni	104.5	86.6	68.9	96.3	91.8	77	70.5	110.1	102.7	60.2	50.2	117.3	108.4	103.8	77	98.9	59.8	125.2	78.4	99.3
Tl	0.2	0.1	0.3	0.2	0.2	0.1	<0.1	<0.1	<0.1	0.4	0.3	0.3	0.2	0.2	0.5	0.8	0.9	0.6	0.3	0.7
LaN	102.12	15.15	113.64	10.91	26.36	91.82	306.06	71.21	40.91	323.33	82.73	90.61	205.76	80.3	120.61	161.21	62.73	134.24	135.15	154.55
CeN	69.25	9.6	75.95	2.89	20	64.97	237.11	47.63	32.14	216.3	55.49	61.97	78.96	39.08	99.88	98.27	95.26	84.62	77.57	110.29
PrN	52.68	9.11	62.41	4.29	15.36	50.45	212.41	37.59	24.38	181.7	45.54	46.61	137.59	54.02	84.29	88.21	53.66	83.12	77.23	89.38
NdN	28.1	5.56	36.98	3.02	10.48	29.37	136.51	24.29	15.24	110.63	28.41	28.1	78.57	32.54	57.94	52.7	35.87	53.17	48.1	57.46
SmN	19.56	3.4	24.58	2.71	7.04	16.75	54.68	10.25	8.13	59.61	16.01	18.72	42.61	17.29	32.51	26.31	23.79	30.39	30.3	29.36
EuN	6.75	9.09	9.09	10	9.22	10.13	27.92	9.74	6.62	11.3	7.66	6.23	14.29	10.26	19.22	12.21	10.52	13.64	9.35	13.77
GdN	18.73	2.46	14.86	3.37	5.18	10.29	24.75	5.47	4.13	36.05	8.19	17.93	22.03	9.31	17.28	16.01	13.26	18.8	21.38	17.64
TbN	25.96	2.55	11.28	4.26	5.11	6.6	14.47	3.62	2.98	25.11	6.17	25.96	17.87	7.45	11.49	12.34	11.06	14.89	22.55	13.19
DyN	26.36	2.19	8.08	4.55	3.5	3.47	9.04	2.3	1.69	15.34	3.53	27.38	10.03	4.49	7	7.84	8.25	11.75	18.83	9.59
HoN	36.14	1.57	6.14	5.43	3.86	2.29	8.57	1.57	1.14	10.43	3.14	35.43	8	3.43	5.57	7.14	7.14	10.14	18.29	8.71
ErN	38.53	1.51	5.24	4.93	2.93	1.07	6.58	0.76	1.02	7.11	2.13	37.42	5.11	2.67	4.31	5.47	6.27	7.96	18.62	7.82
TmN	49	1.67	5	5.67	3.33	1	7.33	1	1.33	7.67	2	47	5	2.33	4.33	7	6.67	10	20.67	9
YbN	44.77	1.95	4.18	6.05	3.41	0.95	6.59	0.73	1.32	5.32	1.5	41.32	3.55	2.09	3.95	5.86	6.55	8.41	18.64	6.77
LuN	39.41	1.76	4.71	5.59	3.24	0.88	5.29	0.29	0.88	5.29	1.47	40.29	3.24	2.35	3.53	5	6.47	8.24	17.35	6.47
Eu/Eu*	0.35	3.14	0.48	3.31	1.53	0.77	0.76	1.3	1.14	0.24	0.67	0.34	0.47	0.81	0.81	0.59	0.59	0.57	0.37	0.6
LaN/YbN	2.28	7.75	27.17	1.8	7.73	96.19	46.44	97.92	31.03	60.8	55.15	2.19	58.03	38.41	30.5	27.49	9.58	15.96	7.25	22.82
LaN/SmN	5.22	4.46	4.62	4.03	3.74	5.48	5.6	6.95	5.03	5.42	5.17	4.84	4.83	4.64	3.71	6.13	2.64	4.42	4.46	5.26
CeN/YbN	1.55	4.91	18.16	0.48	5.87	68.06	35.98	65.49	24.38	40.67	36.99	1.5	22.27	18.69	25.26	16.76	14.55	10.06	4.16	16.28
CeN/SmN	3.54	2.82	3.09	1.07	2.84	3.88	4.34	4.65	3.95	3.63	3.47	3.31	1.85	2.26	3.07	3.74	4	2.78	2.56	3.76
EuN/YbN	0.15	4.65	2.17	1.65	2.7	10.61	4.24	13.39	5.02	2.12	5.11	0.15	4.03	4.91	4.86	2.08	1.61	1.62	0.5	2.03
Rb/Sr	3.02	0.47	0.94	0.39	0.38	0.72	0.26	0.23	0.4	0.96	1.51	2.81	1.53	1.96	0.15	0.84	0.81	1.16	4.37	0.97
U/Pb	0.11	0.01	0.04	0.02	0.01	0.004	0.016	0.0008	0.003	0.028	0.007	0.11	0.011	0.0081	0.02	0.02	0.026	0.02	0.04	0.024
Lu/Hf	0.45	0.03	0.04	0.21	0.03	0.01	0.02	0.03	0.03	0.03	0.01	0.44	0.03	0.02	0.02	0.03	0.03	0.06	0.14	0.04

Sm/Nd	0.22	0.2	0.21	0.29	0.22	0.18	0.13	0.14	0.17	0.17	0.18	0.21	0.17	0.17	0.18	0.16	0.21	0.18	0.2	0.16
Th/U	2.55	2.37	12.4	2.7	3.54	11.94	6.27	11.86	11.2	11.48	4.3	2.38	9.62	8.11	5.13	3.57	3.02	3.34	4.78	2.21
Th/Yb	2.69	4.42	20.22	4.66	6.13	90.95	29.38	51.87	38.62	51.03	56.06	2.6	16.03	15.87	14.14	21.32	17.22	16.05	9.68	18.66
Ta/Yb	0.03	1.39	0.65	1.28	0.93	1.43	0.48	0.62	0.35	0.51	0.61	0.06	0.51	0.87	1.26	0.85	1.18	1.41	0.34	1.41
Ce/Pb	4.72	1.34	15.28	0.3	2.16	7.4	18.64	3.46	3.12	29.23	6.96	4.47	6.97	3.45	14.64	11.04	9.69	5.34	4.6	10.37
Ba/Nb	22.08	256.79	70.24	82	44.03	120	70.26	984.67	2402	32.12	84.53	17.42	56.39	107.41	126.67	38.21	40.32	35.88	8.56	45.52
Sr/Y	0.87	50.87	9.51	18.04	29.26	44.28	26.93	142.16	116.35	7.78	26.61	0.82	7.12	15.95	76.08	15.91	17.38	8.64	1.36	11.74

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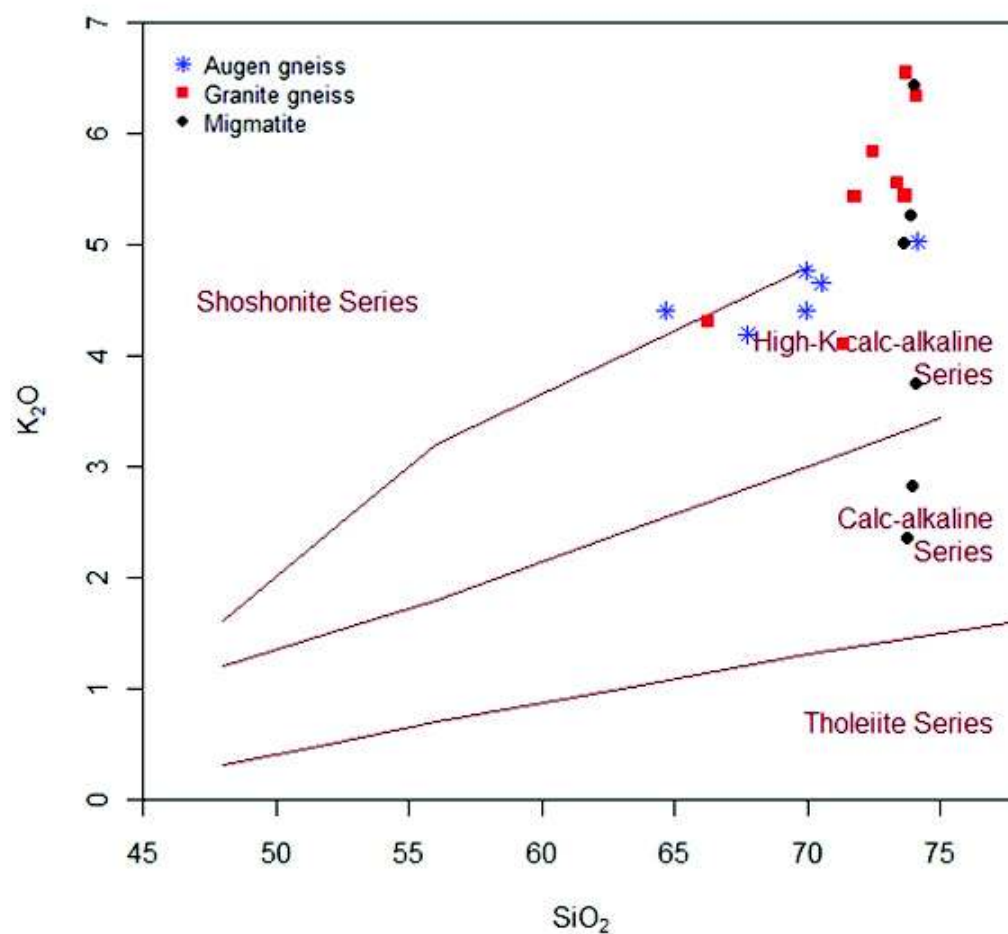


Figure 2: Classification plot of SiO_2 versus K_2O of migmatite-gneisses (after Peccerillo and Taylor, 1974; Rickwood, 1989)

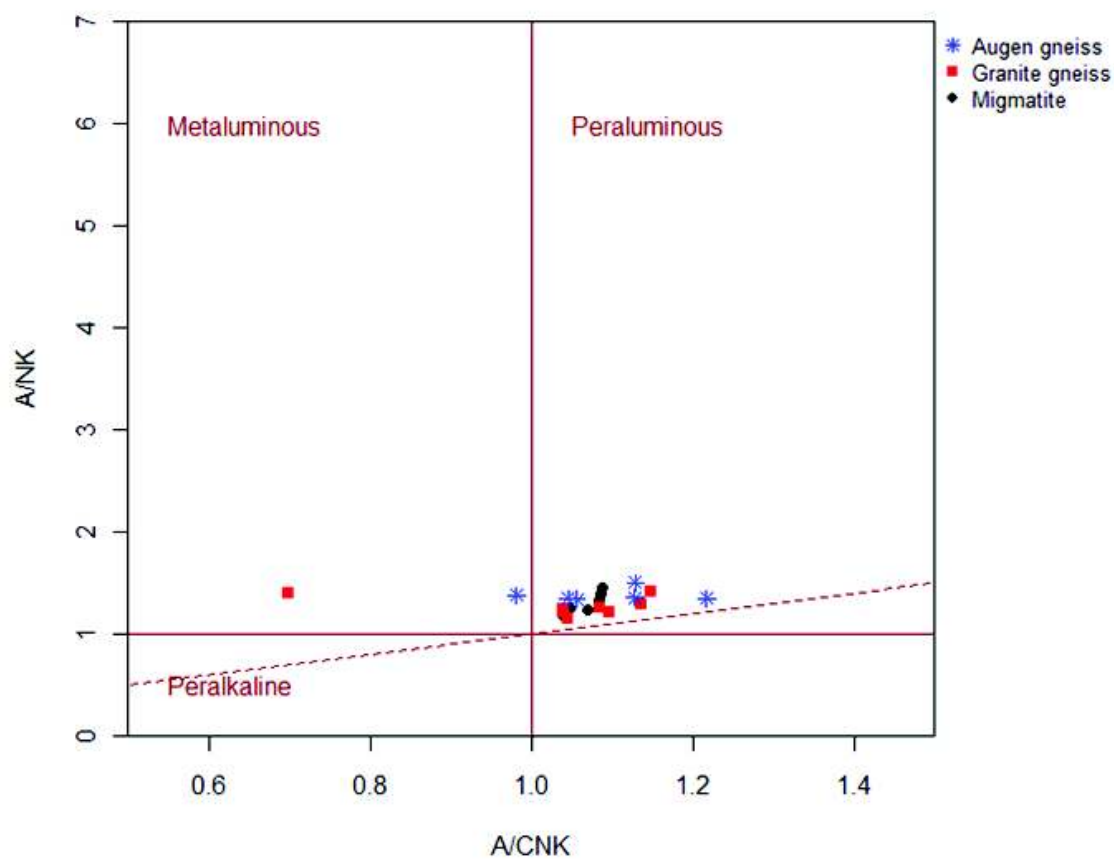


Figure 3: Geochemical plot of A/CNK versus A/NK of migmatite-gneisses (after Shand, 1943 Maniar and Picolli 1989)

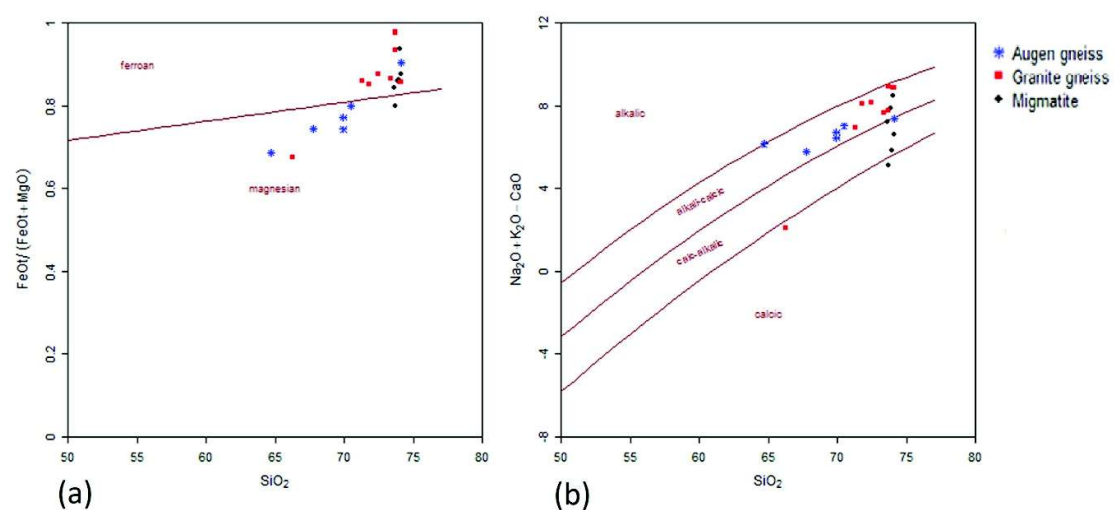


Figure 4: Binary plot for classification of the migmatite-gneisses (after Frost et al. 2001) (a) SiO_2 versus $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3+\text{MgO})$ (b) SiO_2 versus $(\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO})$

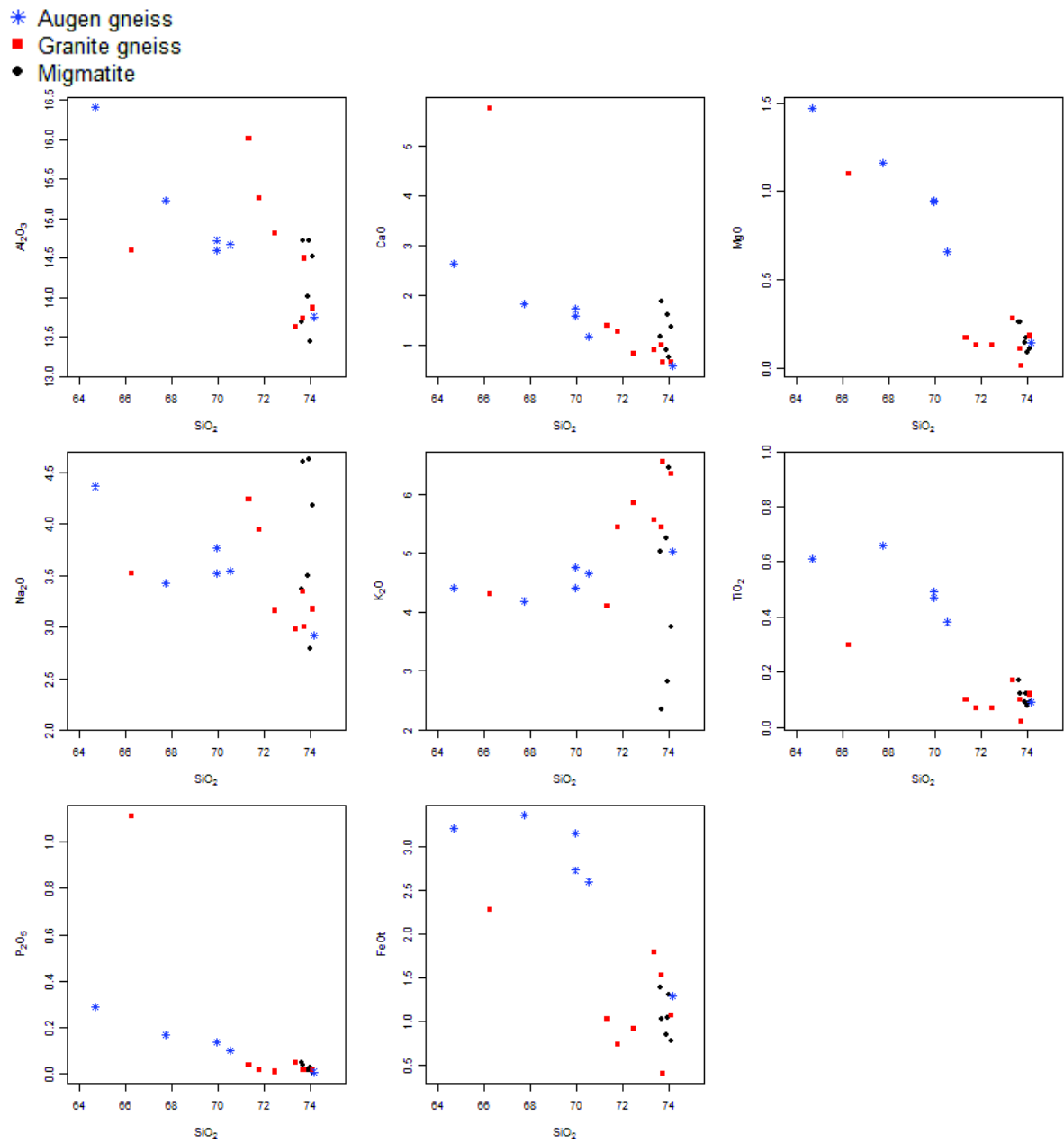
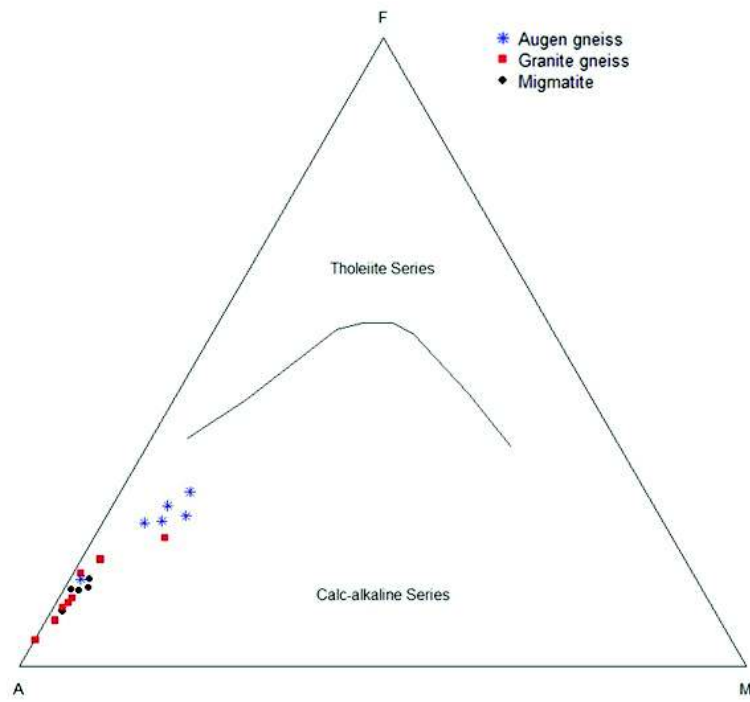
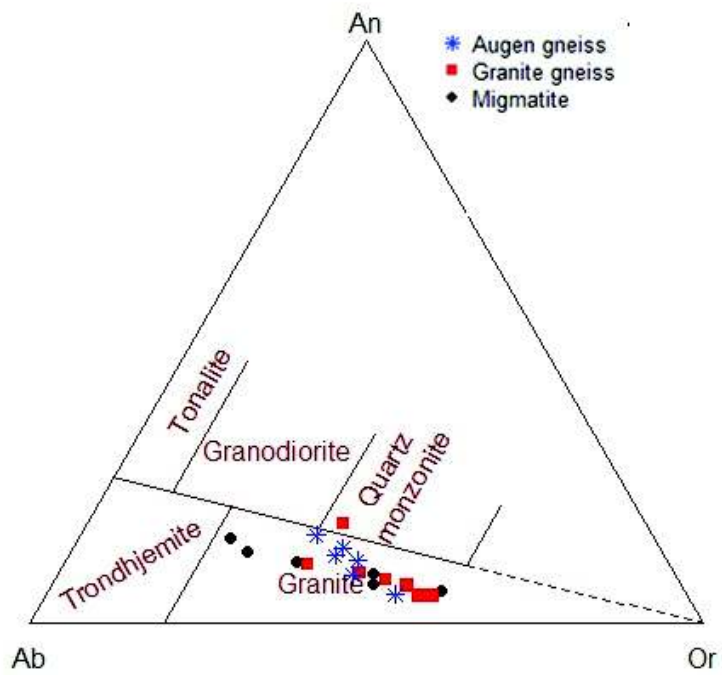


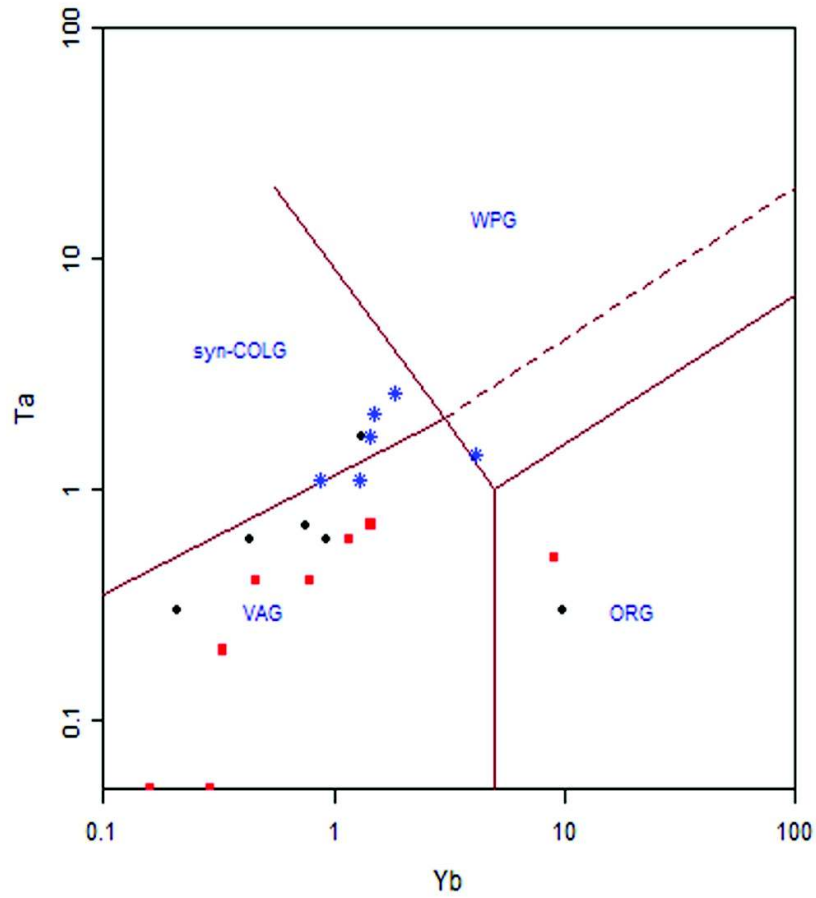
Figure 5: Harker diagrams of major elements for the migmatite-gneisses



(a)



(b)



(c)

Figure 6: Geochemical characteristics of migmatite-gneisses (a) Normative An–Ab–Or diagram with fields of granites from Barker (1979) (b) AFM diagram (Irvine and Baragar, 1971), where $A = Na_2O + K_2O$, $F = Fe_2O_3$, $M = MgO$. (c) Ta vs. Yb discrimination diagram (Pearce et al., 1984). Syn-COLG, syncollision granite; VAG, volcanic arc granite; WPG, within-plate granite; ORG, ocean ridge granite

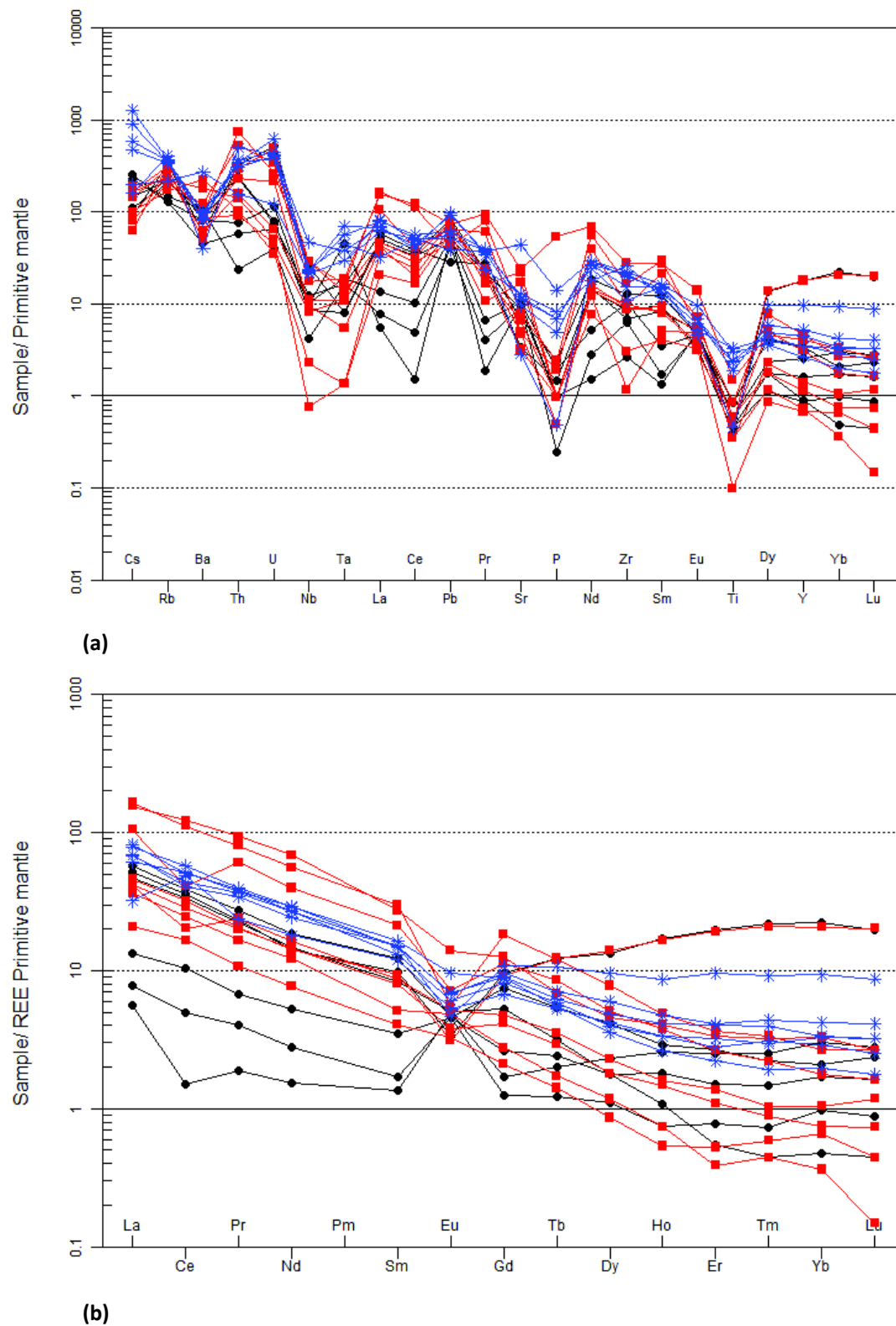
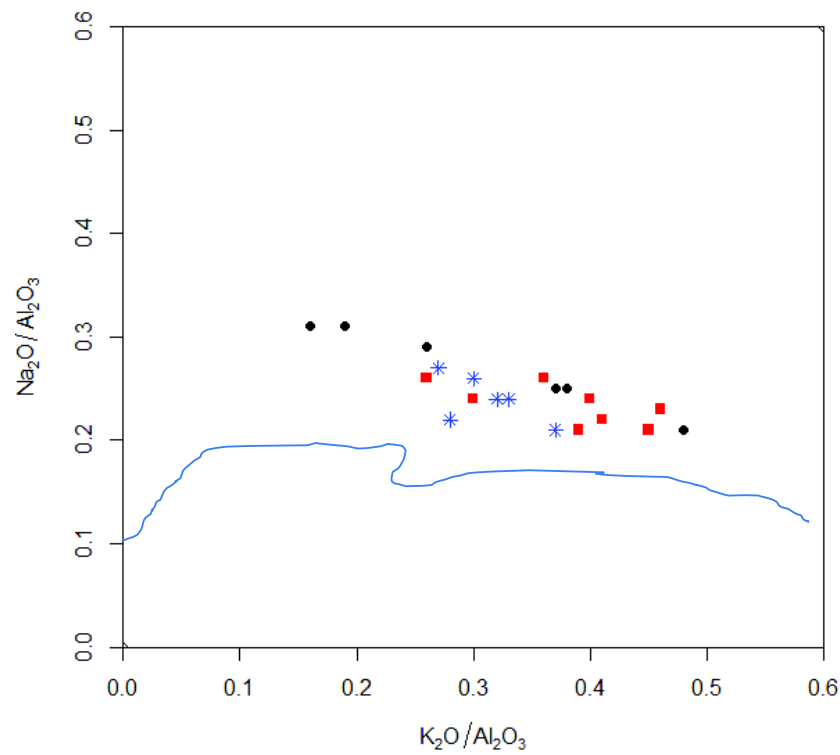
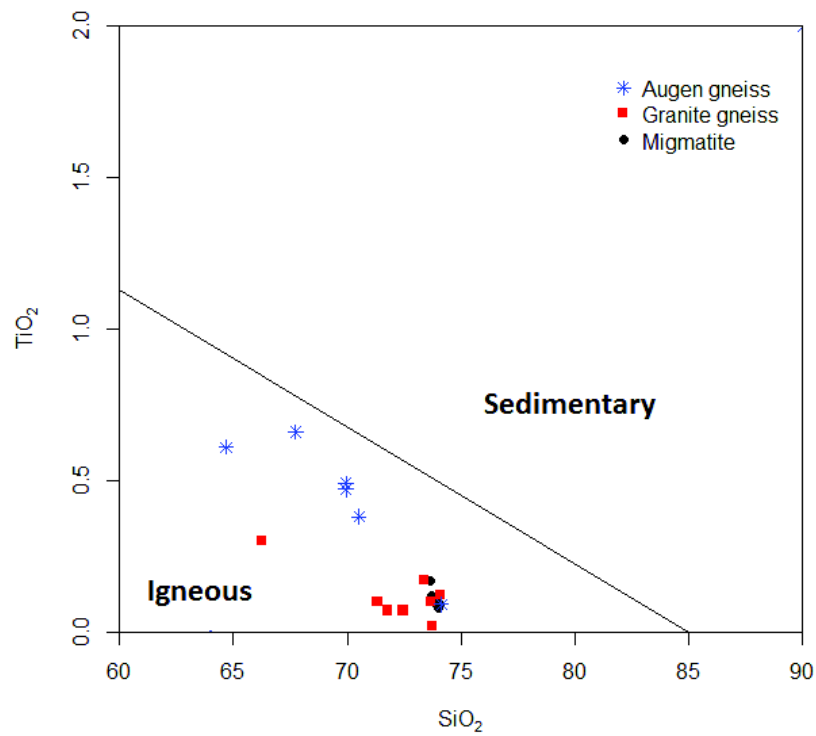


Figure 7: (a) Primitive mantle-normalized incompatible element patterns and (b) Chondrite-normalized patterns for migmatite-gneisses. Normalization values from Sun and McDonough (1995)



(a)



(b)

Figure 8: $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ versus $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ plot (after Garrells and Mackenzie, 1971) and TiO_2 versus SiO_2 discrimination diagram (after Tarney, 1977) showing plot of different migmatite-gneisses in the study area

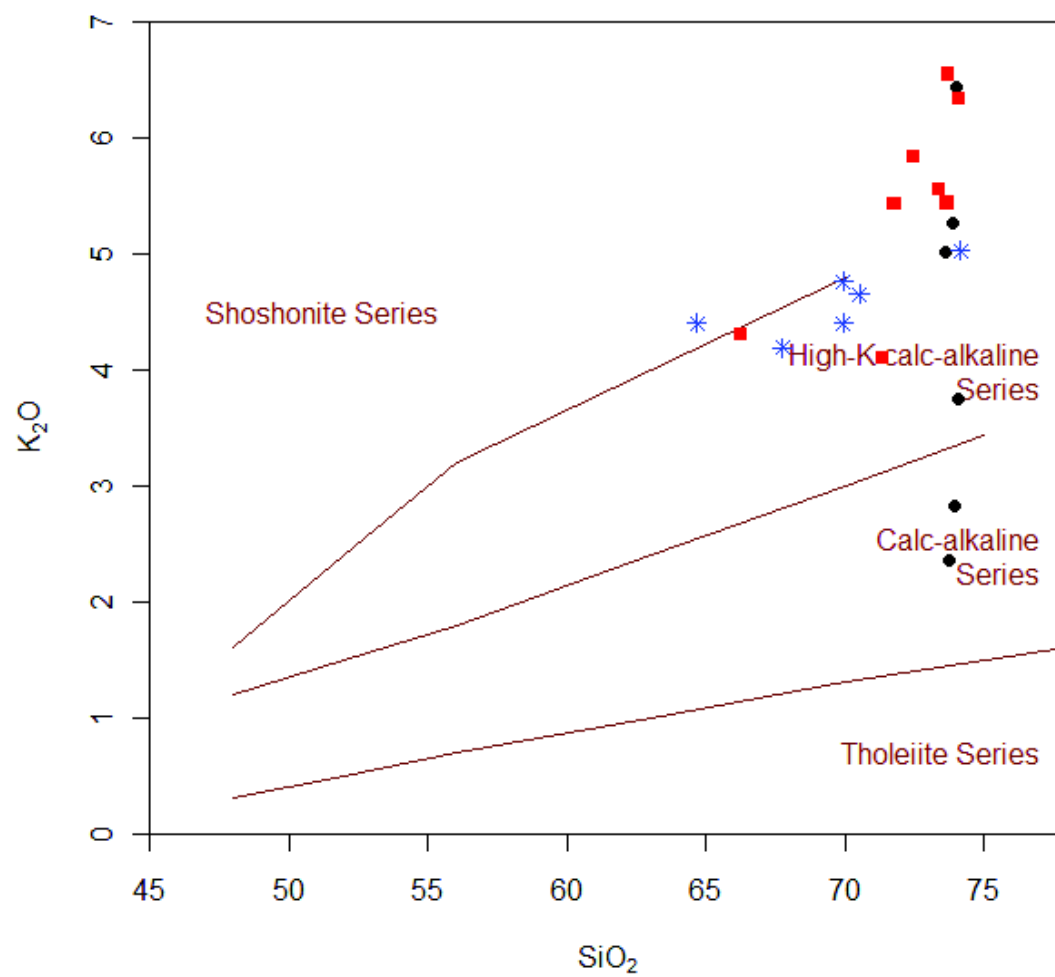
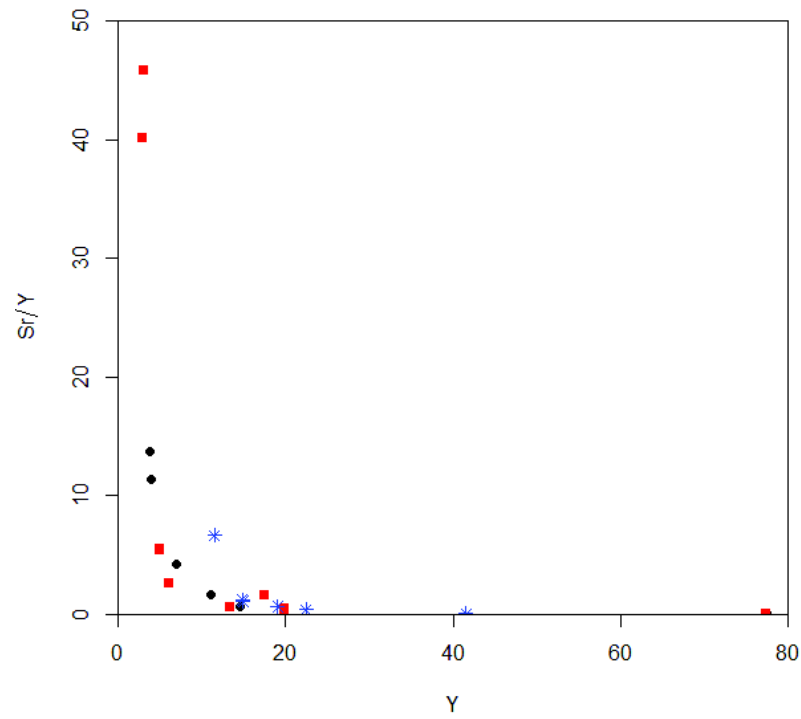
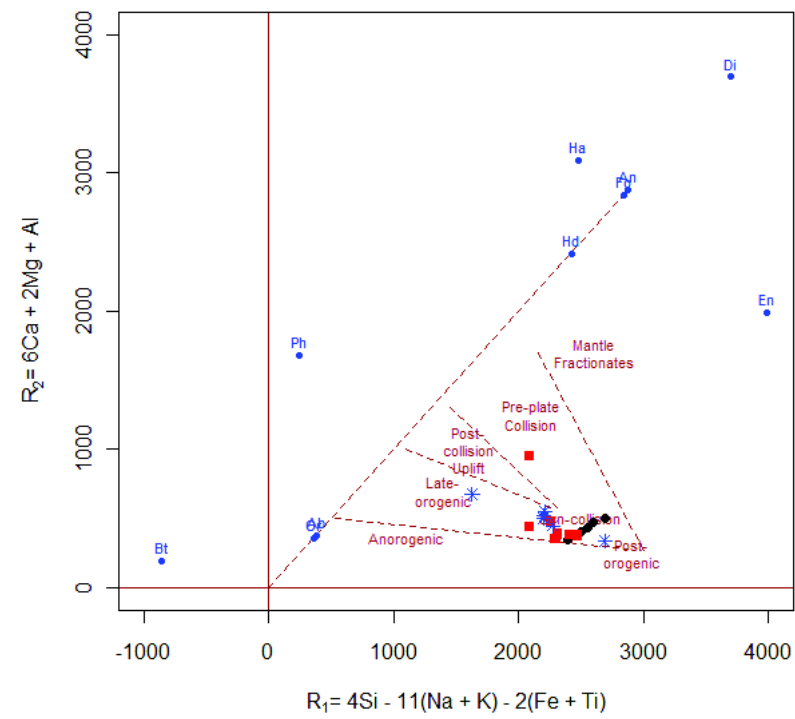


Figure 9: Classification plot of SiO_2 versus K_2O (after Peccerillo and Taylor, 1974; Rickwood, 1989)



(a)



(b)

Figure 10: Plot of (a) Y versus Sr/Y (b) R_1 versus R_2 (after, Batchelor and Bowden, 1985)

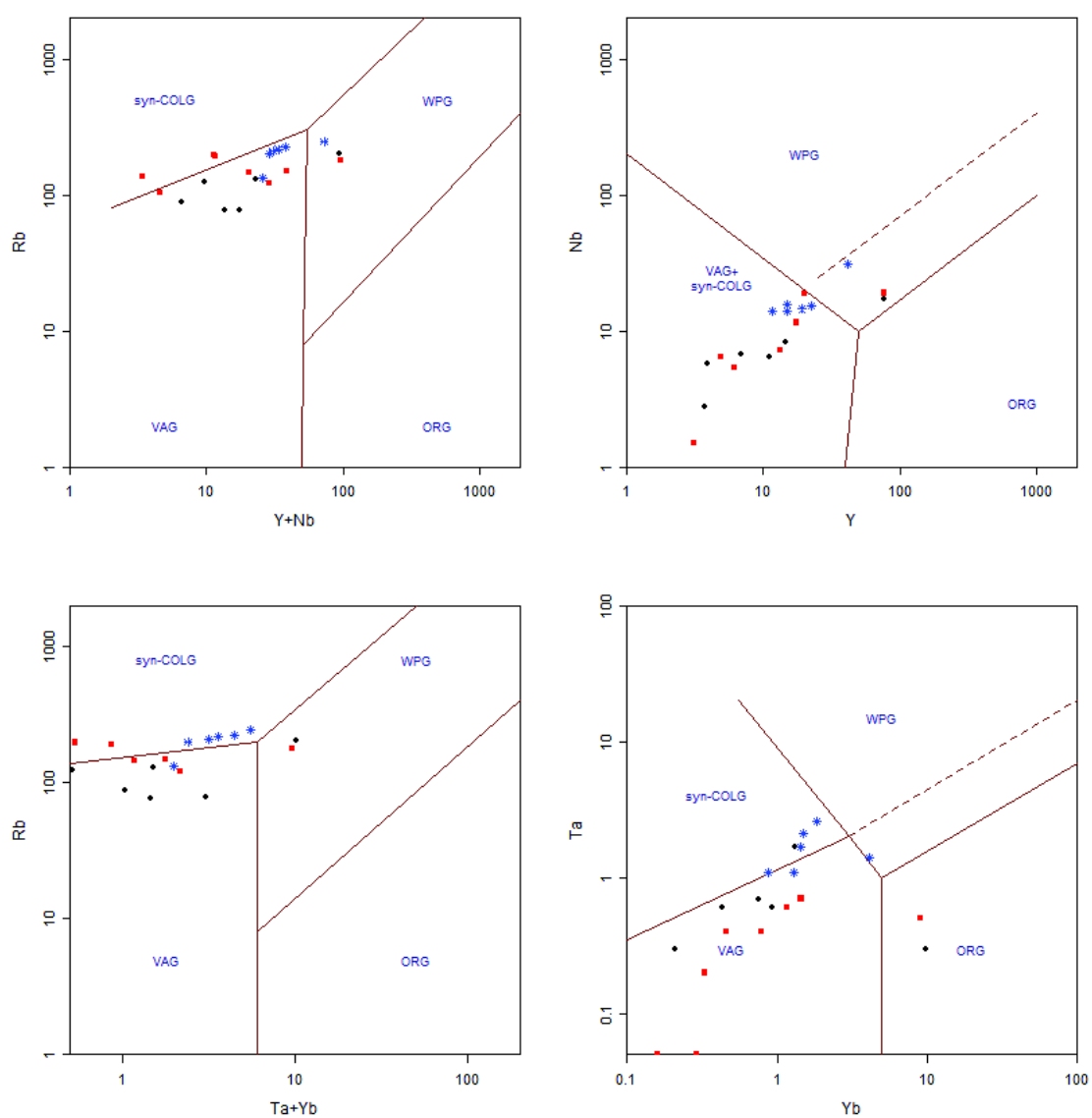


Figure 11: Trace elements ratio plots for tectonic classification of the granitoids from Dahomeyide orogenic belt (i) Y + Nb versus Rb (ii) Y versus Nb (iii) Ta + Yb versus Rb (iv) Yb versus Ta (After Pearce, 1996a)