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Hydrothermal alteration and mineral potential zones of Bauchi area Northeastern Nigeria using interpretation of aeroradiometric data

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Abstract

This research focuses on hydrothermal alteration and mineral potential zones of the Bauchi area in northeastern Nigeria using the interpretation of aeroradiometric data. The high resolution aeroradiometric data were acquired and analyzed for possible areas of mineral potentials, lithologic units, and hydrothermal alteration. The radiometric data were interpreted by minimum curvature gridding techniques, arranged in three different grids as radioelement of percentage potassium (%K), equivalent thorium (eTh), and equivalent uranium (eU), and were displayed as pseudo-coloured images to reveal the surface concentration of each of the radioelements. The radioelement maps, K/eTh ratio map, and ternary image were used to recognize and interpret the radiometric signatures for mineral potential zones, lithological units, and identification of hydrothermal alteration zones in the study area. The relatively high eTh concentration (32.1274-54.8017 ppm) could be attributed to granitic rocks and high K/eTh ratio (0.285718-0.422418 wt%/ppm) indicates hydrothermally altered areas. The regions with high %K, high eTh and high eU coincide with the granitic rocks and this indicates that hydrothermal alteration and mineral potential zones are predominance in older granites and younger granites. The hydrothermal alteration zones are favorable areas for mineralization as observed from the K/eTh ratio map. The hydrothermally altered areas are underlain by granitic rocks and this attests that the hydrothermal alteration process is accompanied by granitic intrusions and emplacement of late intrusive rocks which provide the heat sources for hydrothermal solutions along fractures for the formation of minerals or react with the enclosing rock for hydrothermal alteration and subsequent mineralization.

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1. Introduction

A radiometric survey is a geophysical tool that is useful for rock and mineral identification using radioelements [1, 2]. This involves the measurement of naturally occurring radioactive elements, uranium (U), thorium (Th), and potassium (K) for the outermost part of the Earth's surface, where the rock-forming minerals and the soil profiles exist [3–5]. The radiometric method characterizes the changes in lithological units due to the variations in the concentration of the radioelements between different rock units [6–8].

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A mineral indicator is any physical or chemical phenomenon that occurs with an ore mineral and indicates its presence [9]. Indicators such as faults, fractures, porphyry intrusives, and oxidized and hydrothermally altered areas have been found useful in the exploration of minerals [10–13]. For example, faults/ fractures provide a conduit or serve as traps for mineralizing fluids while intrusions provide heat sources that cause chemical reactions with intruded rocks that may bring about mineral transporting, concentration, and deposition at or near the intrusive contacts [14]. Several authors have used an indirect tool for mapping zones of mineralization by identifying mineral indicators favourable to mineralization [15–17].

Nigeria is endowed with minerals such as energy fuels, industrial, metallic, and non-metallic minerals [18] and the minerals can be found along fractures controlled by hydrothermal fluid that carries large amounts of dissolved minerals of magmatic origin [19]. Minerals such as gold, zinc, lead, iron ore, magnesite, wolframite, barite, manganese, copper, and tantalite have been reported in northern Nigeria and possibly occur in the study area [20]. The hydrothermal alteration process has been reported to be associated with the process of soil and rock formation within the Basement complex of northcentral and southwestern Nigeria [21–23]. The hydrothermal process may be accompanied by mineralization in the Basement terrain of central Nigeria using the mineralogical and geochemical signatures [24, 25].

The previous geophysical research in the study area includes groundwater potentials using the electrical resistivity method [26, 27], groundwater quality using geophysical and hydrogeochemical methods [28], and geotechnical investigation of aquifer using electrical resistivity and geotechnical tests [29]. The aeromagnetic data in the study area were interpreted and analyzed for gold exploration [30]; geological transition zones [31]; depth to magnetic source determination using Source Parameter Imaging [32] and Geothermal Potential [33].

The geological field investigation of the Basement rocks in the study area was carried out by Oshilike *et al.* [34] on the petrographic and structural characters of lithological units in the Kura area while Yahuza *et al.* [35] reported on the geology and petrography of Schlieren cum Nebulites from Bauchi area, Northeastern Nigeria. The ground radiometric survey of Hong Hills, Hawal Basement Complex, northeastern Nigeria was reported by Bassey and Unachukwu [36] and the research aimed to delineate lithological units. The possible pegmatite occurrences were suggested based on high radiometry and ground truthing results in the northern sector of the area.

The radiometric investigations for hydrothermal and mineral potential zones have not been reported in the study area. The present research focuses on the identification of hydrothermal alteration and mineral potential zones of the Bauchi area in northeastern Nigeria using the interpretation of aeroradiometric data.

1.1. Location and Geology of the Study Area

The study area predominantly lies in Bauchi State and also partly lies in Plateau State (Figure 1). The Bauchi area is located at latitudes 9°30′ to 11°00′ n and longitudes 9°30′ to 10°30′E. The area comprises six topographical sheets, namely: Mandaki sheet 128, Ganjuwa sheet 129, Bauchi sheet 149, Alkaleri sheet 150, Tafawa-Balewa sheet 170, and Yuli sheet 171. The study area covers a total area of 18,150 km^2 and is accessible through Jos-Yobe Road and Jos-Gombe Road (Figure 1). There are also major roads, minor roads, and footpaths throughout the area.

The Geology of the Bauchi State is broadly divided into areas underlined by crystalline basement complex rocks and sedimentary rocks. The southwestern part of the Bauchi State is covered by Precambrian-Paleozoic basement rocks, while the southeastern part of the state is covered by the Paleocene Kerri-Kerri formation [37]. The migmatites, migmatites-gneiss, and the granite-gneiss complex form the oldest rock group of presumably late Precambrian to early Palaeozoic age [38–41]. During the Pan-African Orogeny, a suite of intrusive granites, older granites, and the charnockite rocks were employed in a magmatic phase within the country rock migmatite-gneiss complex [42].

The older granite suites are predominantly of porphyritic biotite granite or Biotite-Hornblende granites. They are usually foliated due to the mafic minerals present in them [27, 43]. A petrographic study of the rocks reveals pelitic mineral assemblages suggesting high grade metamorphism and characteristic structures such as gneissosity and granoblastic textures were observed in the area [34].

The geological map of the study area is shown in Figure 2 and is underlain by crystalline rocks such as migmatite, porphroblastic gnesis, granite gneiss, biotite and biotite hornblende granodiorites and meta-conglomerate in eastern part and other rock units are quartz prophyry, biotite granite, ignimbrite, coarse biotite and biotite muscovite granite, fine grained biotite granite and charnockitic rocks while alluvium occurs in the southeastern part of the study area (Figure 2).

The deformation and migmatization of the rocks produced orientations in different directions, with an abundance of geologic structures such as foliation, ptygmatic folds, veins, fractures, and dykes. Most of these structures found on the rocks tend to trend towards the NE-SW and E-W directions [34]. The migmatite-gneiss complex was intruded by low grade schist during the Kibaran orogeny, they range between quartz schist, mica schist, quartzites, and concordant amphibolites [44]. They are generally trending NE-SW with some trending N-S, they are responsible for most gold mineralization in Nigeria, with quartz veins serving as carriers of the gold in most places [45]. Schist belts were intruded by Pan-African granitoids during the Pan-African orogeny (600Ma±150), they range between migmatites, older granites, and gneisses [46].

From the aeromagnetic survey, the migmatites have higher magnetic susceptibility and high intensity of interconnected fractures that are trending NW-SE, NE-SW, and minor E-W that are interconnected. These fractures are regional and may serve as conduits for hydrothermal mineralization [30]. The result of the analytic signal in Bauchi State highlighted areas of high magnetization contents which could be sites for possible mineralization [47]. The Aeromagnetic data of the Rimin Zyam area in Bauchi was assessed and areas with high and low magnetic

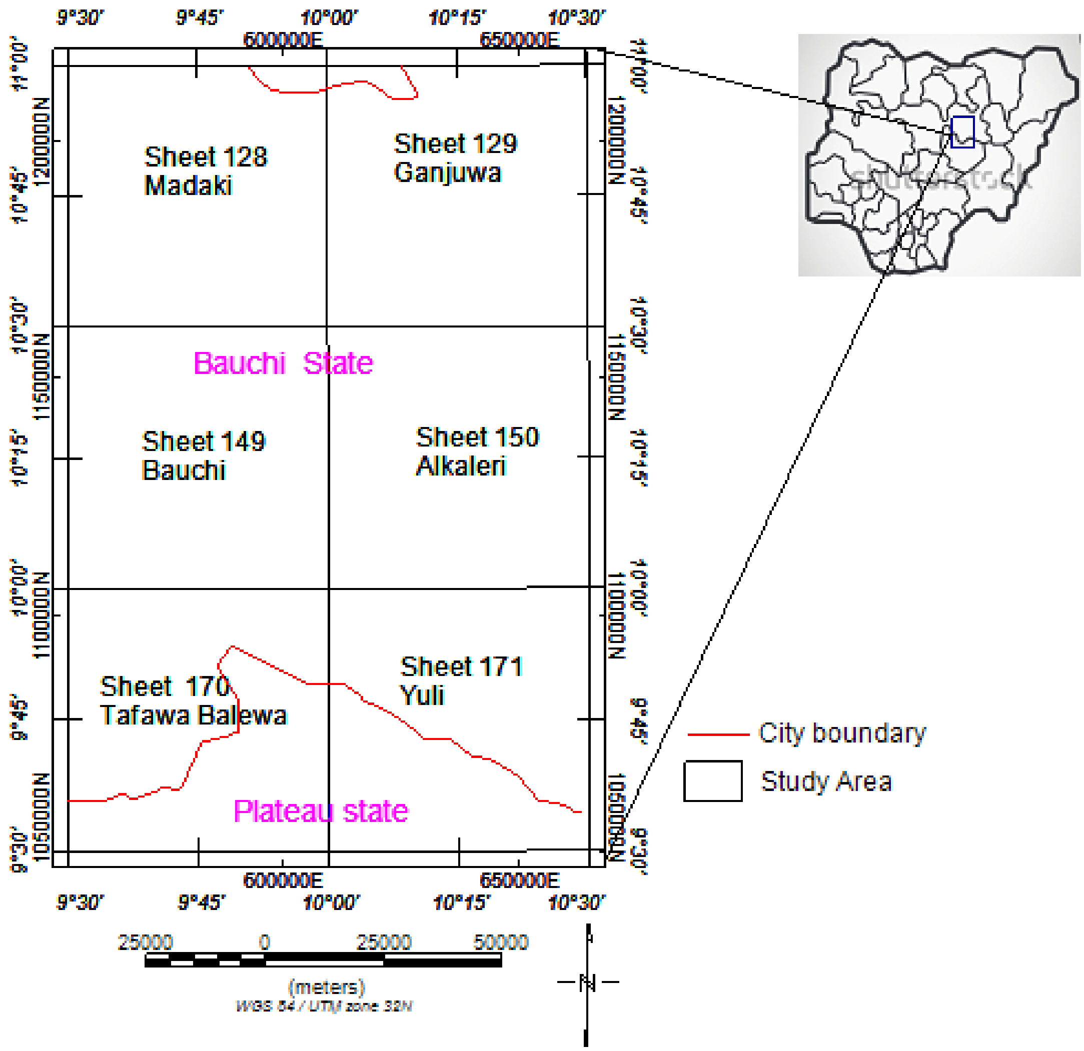

Figure 1. Location map of Bauchi area.

anomalies were identified with NNW-SSE and NNE-SSW as the dominant structural trends. These structures may serve as conduits for the mineralization of magnetic minerals [30].

Bassey and Unachukwu [36] mapped radio-lineaments using a ground radiometric survey with the majority aligned in Pan African deformational direction (N-S, NE-SW) while others aligned in the N-W and E-W directions, and suggested that the area could be designated as a pegmatite zone and targets for mineralization.

2. Materials and Methods

The data used consist of six (6) topographic maps of high resolution aeroradiometric data acquired from the Nigerian Geological Survey Agency (NGSA) on a scale of 1:100,000 which include Mandaki Sheet 128, Ganjuwa Sheet 129, Bauchi Sheet 149, Alkaleri Sheet 150, Tafawa-Balewa Sheet 170 and Yuli sheet 171. Each of the sheets has an area of 55 km by 55 km giving a total area of 18,150 km^2. The topographical sheets acquired were processed and merged into a common dataset.

The acquired airborne radiometric data with a resolution of 0.01nT contains Potassium (K), equivalent Thorium (eTh) and equivalent Uranium (eU) grid map. The aeroradiometric data were corrected for background radiation ensuing from cosmic rays and variation rooted by changes in the aircraft altitude relative to the ground and Compton-scattering gamma rays in K and U energy windows. The radiometric data were interpreted by minimum curvature gridding techniques, arranged in three different grids as radioelement (K, eTh and eU) and were displayed as pseudo-coloured images to reveal the surface concentration of each of the radioelements.

2.1. *Software used in the study*

The software used for the interpretation of this research is ArcGIS and Oasis Montaj.

2.2. *The total count map of the study area*

The measurement of the concentration level of each of the radioelements was carried out by estimating the degrees of

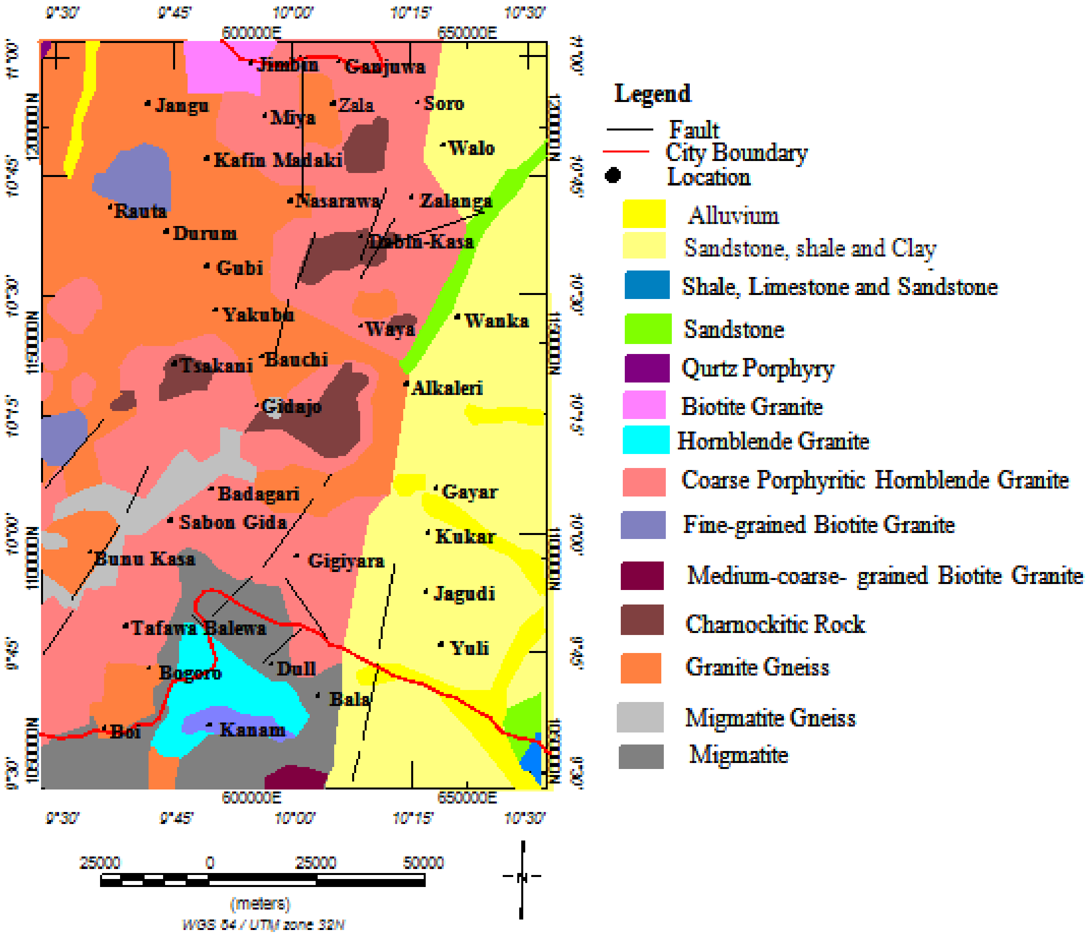

Figure 2. Geological map of Bauchi area.

emitting gamma-ray radiation which was used to produce maps showing the three (3) radioelements with their ratios.

2.3. The Three Primary Variables Radioelements, %K, eTh and eU Map

The three primary variables were produced from the total count using K_Th_U separation techniques. The grid and Image were applied to the total count and filtered out with a trend of one (1) to produce one (1) of the variables. The remaining two variables were produced using Grid Maths in Oasis Montaj software. The grids of the three (3) variables were displayed and ready for analysis and qualitative interpretation. The potassium image was developed to identify regions of strong potassium percentage while thorium is usually immobile [48]. The reduction in thorium and increase in potassium show signs of ore alteration that was used to produce the Th image map. These maps were displayed with their concentrations showing in Red, Blue and Green (R-G-B) colours indicating different lithology. The uranium, thorium, and potassium maps indicate areas where the specific radioelement occurs in greater amounts [48, 49].

2.4. Potassium _Thorium Ratio (K/Th) Map of the Study Area

The potassium _Thorium (K/Th) ratio map was produced by inserting the grid variables into the grid Maths in Grid and Image of Oasis Montaj software. Lithological variations are shown in different colours. The K/Th ratios were created to identify areas where a relative amount of potassium occurs in greater percentages (i.e. where potassium concentration is strong). A K/eTh ratio map was developed to map the hydrothermally altered areas since an increase in K and a decrease in eTh is a pointer for altered zones in various ore deposits [50].

2.5. Ternary map of the study area

The ternary image is the combination of the three primary grids (K, Th and U). The ternary image was produced using Grid and Image techniques that were then displayed as a ternary image in red-green-blue (RGB) colour on Oasis Montaj software. A ternary map in the RGB colour model for which potassium, thorium and uranium were assigned to red, green and blue, respectively, was generated. This ternary map represented the typical radiometric response in the ratios of the three radioelements.

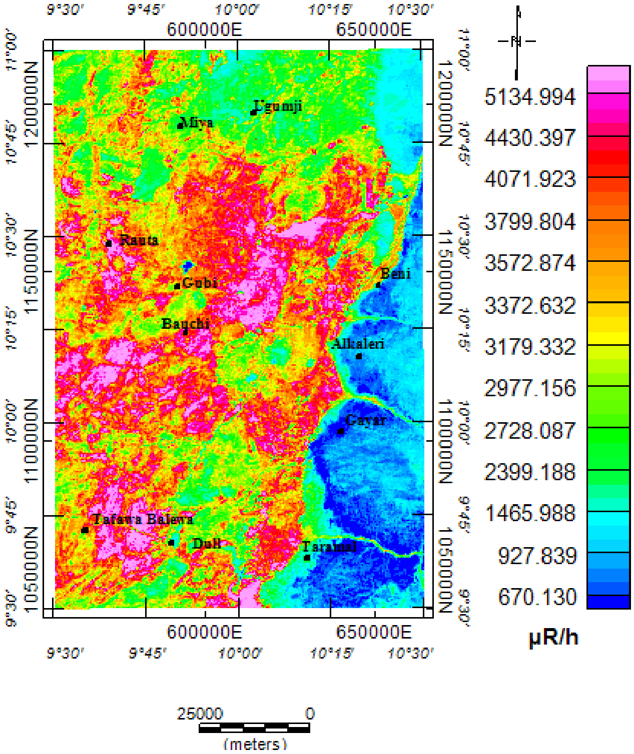

Figure 3. Total count map of Bauchi area.

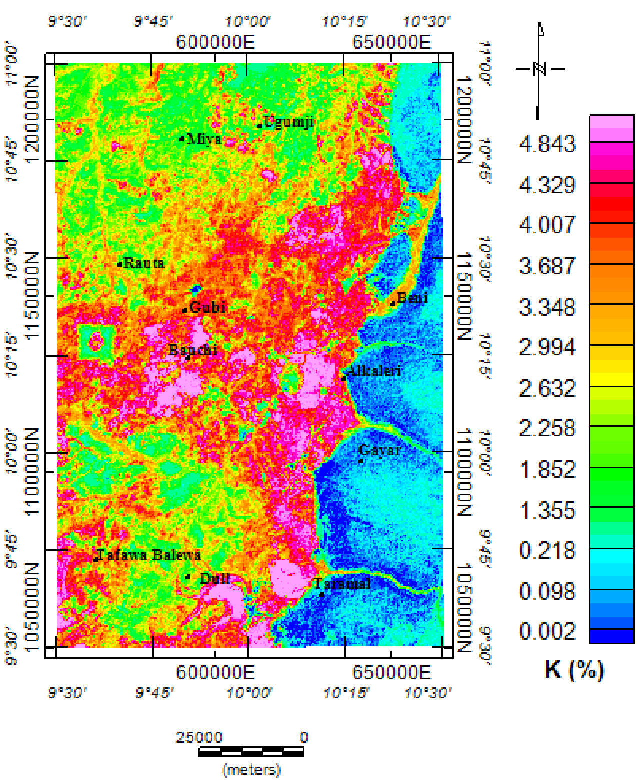

Figure 4. Potassium (K) map of the study area.

2.6. Hydrothermal alteration map of the study area

The hydrothermal alteration zones were mapped out on the Potassium/Thorium ratio map and superimposed on the geological map using Oasis Montaj software. This helps to delineate the region of hydrothermal alteration which is an area of potential mineral interest. It was also used to map the lithological units. The radioelement maps, K/eTh ratio map and ternary image were used to recognize and interpret the radiometric signatures associated with the rocks essential to mineral potential zones, lithological units, and identification of hydrothermal alteration zones within the study area.

3. Results and discussion

3.1. Total count map of the study area

The total count map in Figure 3 shows a high radioactive count with pink and red colours ranging from 3974.21 to 5694.95μR/h at western part on the study area. Moderate radioactive count ranging from 2243.6 to 3974.21μR/h with yellow and green colours was observed at northern and southern part of the study area while relatively low radioactive count ranging from 670.13 to 2243.6μR/h with blue colour was observed at eastern part of the study area (Figure 3). Variation in radioactive count may result from the presence of rock types, mobility of the radioelement, weathering and hydrothermal alteration activities in the study area.

3.2. Potassium percentage (%K) map of the study area

The percentage potassium (%K) map of the Bauchi area (Figure 4) shows %K ranging from 0.002033 to 5.24882 % which indicates the responses of %K from different lithologic units and the dominance of K among the radioactive elements within the intrusive rocks near the surface. Figure 5 shows %K map with an outline of the geology that describes the boundary of the %K anomaly and the associated lithologic units. The potassium (K) radiation is mainly due to K-feldspar, especially microcline and orthoclase or micas such as muscovite and biotite, which are common in granites and are relatively low in basalts and andesites [51]. According to Manu [52], high K anomaly areas can be interpreted as alteration zones and implying that it might be a useful pathfinder for detecting the mineral potential zones

Older granites, younger granites and porphyroblastic gneiss were identified in high %K areas (Figure 5) and a high %K value suggests the presence of granitic intrusions because granitic rocks have high K-feldspar rich minerals [53]. A moderately high %K with a yellow colour coincide with migmatite, charnockite, quartzite, and meta-conglomerate while a low %K coincide with the presence of sediments synonymous with sediments rich in quartz and clay materials which could have been obtained through weathering of pre-existing rocks (Figure 5). This is similar to the research of Tawey *et al.* [53] on the assessment of hydrothermal alteration regions in northcentral Nigeria using aeroradiometric data where different lithologic units were identified when %K map was superimposed on geological map.

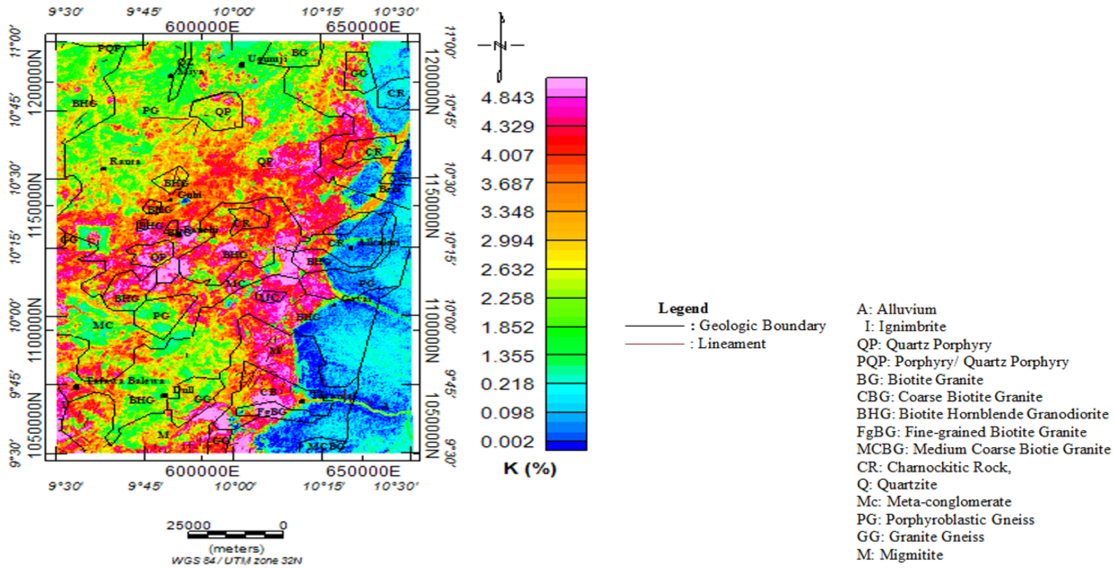

Figure 5. Outline of geology map on the Potassium map of the study area.

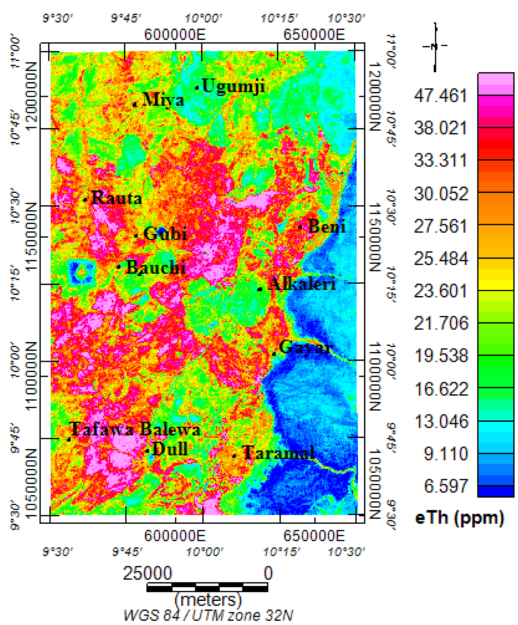

Figure 6. Equivalent Thorium (eTh) map of Bauchi area.

3.3. *Equivalent Thorium (eTh) concentration (ppm) map*

The eTh distribution map of the Bauchi area is shown in Figure 6 while Figure 7 shows the eTh distribution map of the Bauchi area with an outline of the geology map. The eTh concentration ranges from 6.59647 to 54.8017 ppm and the relatively high eTh concentration of 32.1274 to 54.8017 ppm with pink colour could be attributed to granitic rocks and coincide with older granite and younger granites in the study area (Figure 7). According to Manu [52], low eTh concentrations are associated with mafic minerals and high eTh concentrations are associated with felsic minerals

The regions with a shade of green and yellow colours show moderate Thorium concentrations of 15.5471 to 32.1274 ppm (Figure 6) and could be attributed to migmatite, granite gneiss and meta-sedimentary rocks (Figure 7) while a shade of blue shows relatively low concentrations of eTh could be associated with a sedimentary sequence which lacks granitic intrusion and hydrothermal activities in the area. Thorium is typically immobile during weathering but K-feldspar can be altered through weathering and hydrothermal alteration processes to kaolinite [19].

3.4. *Equivalent Uranium (eU) (ppm) map of the study area*

The eU distribution map is shown in Figure 8 while Figure 9 shows the outline of the geology of the Bauchi area on the eU concentration map. The eU concentrations vary from 2.56568 to 11.9959 ppm. The relatively high eU concentration with red and pink colours ranges from 9.79176 to 11.9959 ppm coincide with the granitic rocks such as Porphyry/quartz porphyry, Quartz porphyry, Ignimbrite, Biotite granite, Coarse Biotite Granite, Fine-grained and Biotite Granite (Figure 9).

The moderate eU concentration ranges from 6.45272 to 9.79176 ppm with yellow and green colours which coincide with migmatite, granite gneiss, porphyroblastic gneiss, meta-conglomerate and charnockitic rocks while relatively low eU concentration ranges from 2.56568 to 6.45272 ppm and is associated with sedimentary sequence (Figure 9). Thorium, which is not usually equally affected by the weathering and the alteration processes generally presents a much larger increase in comparison to eU [52].

3.5. *Potassium percentage-equivalent Thorium ratio (%K/eTh) map*

The K/eTh (%/ppm) ratio map (Figure 10) shows relatively high K/eTh values of 0.285718 to 0.422418 %/ppm in pink colour and characteristic high K/eTh ratio can be interpreted as alteration which is more intensive in mineral potential zones. The high K/eTh ratio indicates hydrothermally altered areas

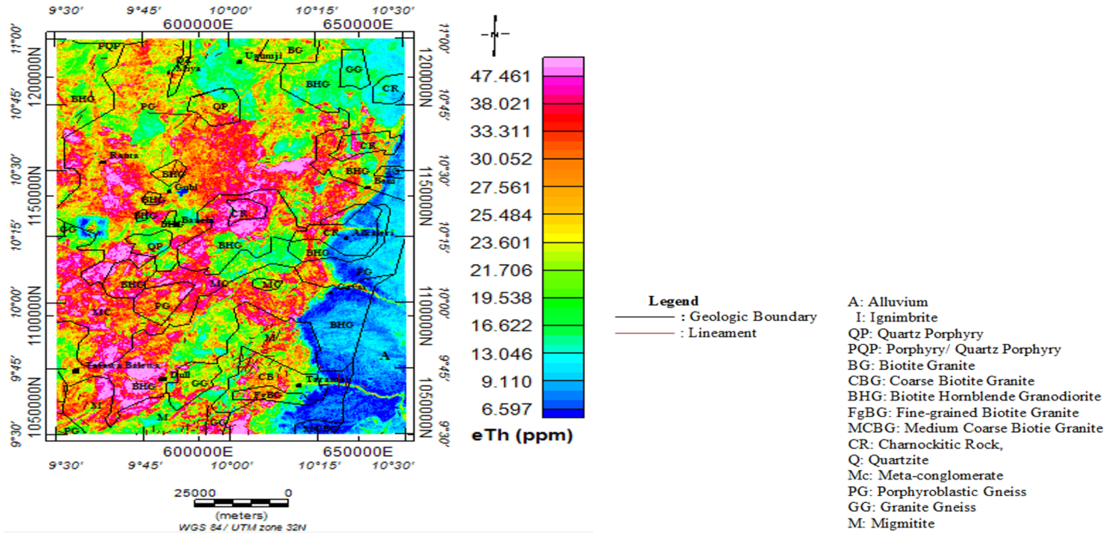

Figure 7. Outline of geology map on the equivalent Thorium (eTh) map of the study area.

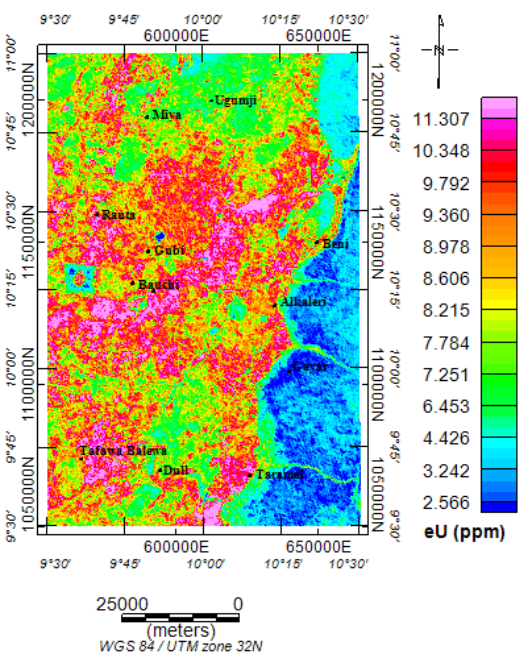

Figure 8. Equivalent Uranium (eU) map of Bauchi area.

and high potassium concentrations are associated with alteration zones related to mineralization in the study area.

The K/eTh ratio anomalies can distinguish areas of hydrothermal alteration characterized by K enrichment and areas affected by the hydrothermal processes have a high ratio of K/eTh [7]. Ostrovskiy [50] refers to an increase in K and a decrease in eTh for the alteration environment in various ore (mineral) deposits. The K/eTh ratio map can be used to identify zones having high concentrations of potassium while thorium is generally considered to be a major and immobile element [7]. The ratios of the K/eTh map can be used to indicate the degree of differentiation and mineralization areas [54–57].

This is similar to the report of Moxham *et al.* [58] on studies of hydrothermally altered rocks where a high K/eTh ratio showed hydrothermal alteration and the report of Bennett [59] on exploration of hydrothermal mineralization with airborne gamma-ray spectrometry where high K/eTh ratio suggested mineralized areas. Maden and Akaryali [51] reported on the potassium enrichment areas related to epithermal gold mineralization which showed anomalously high K/eTh ratios in NE Türkiye and indicated that the gold mineralization occurs where the potassic alteration is the most pervasive and the most extensive. This area of high K/eTh ratio in NE Türkiye clearly shows the highest potassium concentrations associated with alteration zones related to mineralization [51].

Arogundade *et al.* [60] adopted airborne radiometric data for mapping potential areas of mineralisation deposits in Zamfara, northwest Nigeria and the K/eTh ratio map showed more structural relationships that aided the migration of hydrothermal fluids for subsequent alteration. The present findings agree with the report of Appiah [61] on airborne radiometric data interpretation in the Chirano area for gold mineralization and the work of Abdellatif and Elkhateeb [6] in delineation of potential gold mineralization zones in Egypt using airborne radiometric data where high K/eTh ratio indicates hydrothermal alteration and mineralized zones.

The hydrothermally altered map of the area was superimposed on the geology map of the study area (Figure 11). It was observed that the hydrothermally altered area with a tick blue line coincides with the granitic rocks (Porphyry /Quartz porphyry, Quartz porphyry, ignimbrite, Coarse Biotite Granite, Fine-grained and Biotite Granite). The regions with hydrothermally altered areas (Figure 11) show the occurrence of granitic rocks and indicate that the hydrothermal alteration process is accompanied by granitic intrusions which provide the heat needed for alteration and subsequent mineralization. This is similar to reports on hydrothermal alteration processes which were associated with the formation of hydrothermal clays overlying granitic rocks in northcentral Nigeria where the granitic

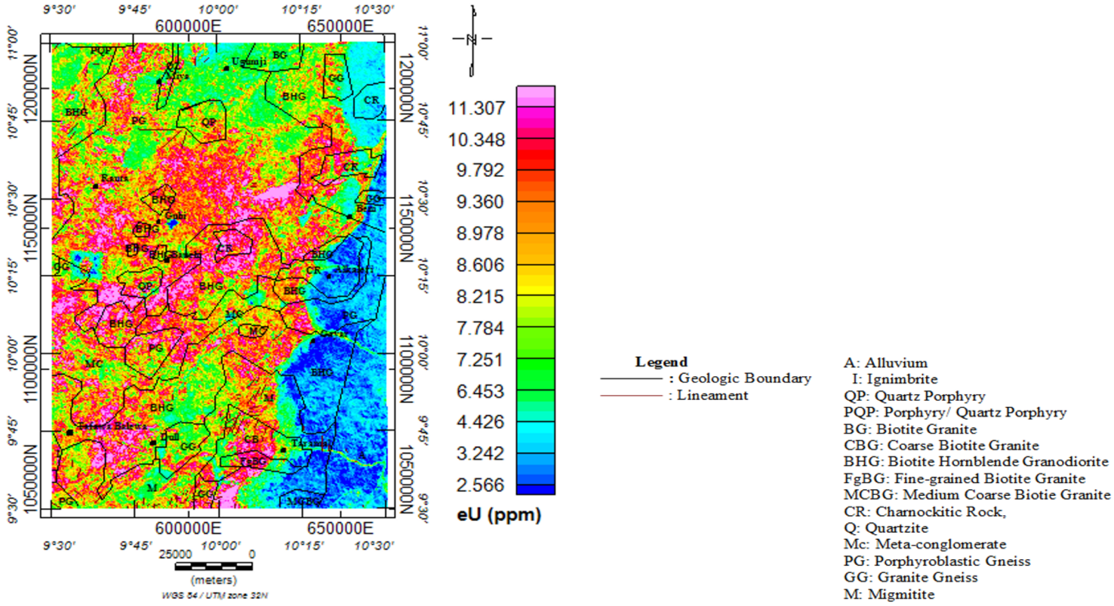

Figure 9. Outline of geology map on the equivalent Uranium (eU) map of Bauchi area.

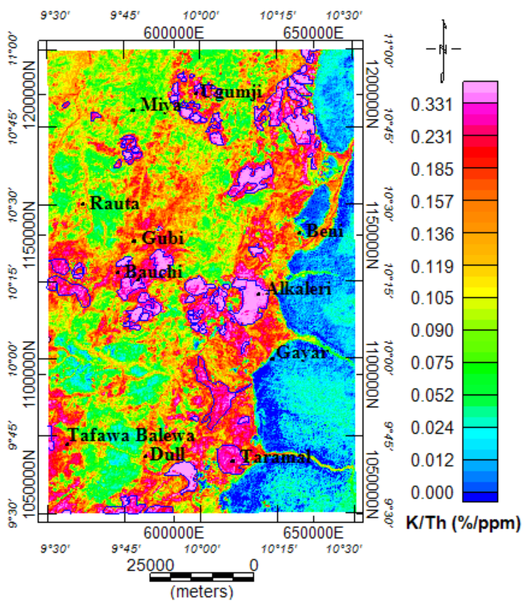

Figure 10. K/eTh map showing Hydrothermal altered zone within Bauchi area.

intrusions provided the energy sources for the alteration of granitic protoliths to kaolinitic clay minerals [62–64].

3.6. *Ternary map*

The ternary map (Figure 12) was generated from the composite of gamma-ray spectrometric data of the radioelements (%K, eU and eTh). The radiometric response, to some extent, shows a fairly close spatial correlation with the rock units. These responses are a result of different rock types having different characteristic concentrations of radioelements. The colour of the legend shows K in red, eTh in green and eU in blue which indicates a 100% concentration of each radioelement. Colours other than the three primary colours (red, Blue and green) indicate areas with various, well-defined proportions of K, eU, and eTh (Figure 12). According to Shives *et al.* [57], a ternary map shows radioelement abundances which reflect lithological variations.

The moderate potassium and thorium with relatively low Uranium concentrations are associated with quartz porphyry, ignimbrite, biotite granite, coarse biotite and biotite muscovite granite and fine-grained biotite granite (Figure 12). The region of relatively high thorium and uranium with low potassium concentration is associated with meta-conglomerate and porphyroblastic gneiss. Most of the rock units/geological formations do not provide colour discrimination between them, which might be due to the redistribution of radioelement concentration because of weathering processes [65].

The hydrothermally altered areas are underlain by granitic rocks and this attests that the hydrothermal alteration process is accompanied by granitic intrusions and emplacement of late intrusive rocks which provide the heat energy for hydrothermal solutions to deposit minerals along fractures or react with the enclosing rock for hydrothermal alteration and mineralization. The late intrusive rocks such as pegmatites, aplites and quartz veins were emplaced along lineaments or fractures during Pan-African Orogeny and can accompanied by granitization, chloritization, sericitization, K-metasomatism, folding, faulting, etc. [40, 42]. This is in agreement with the report of Arogundade *et al.* [60] that areas with high structural complexity have a high occurrence of porphyry features indicating a strong probability for ore deposition. The porphyry features and hydrothermally altered zones from the K/eTh ratio map showed more structural relationships that aided the migration of hydrothermal fluids that react with rock formation for subsequent alteration [60].

The present study shows that the hydrothermally altered ar-

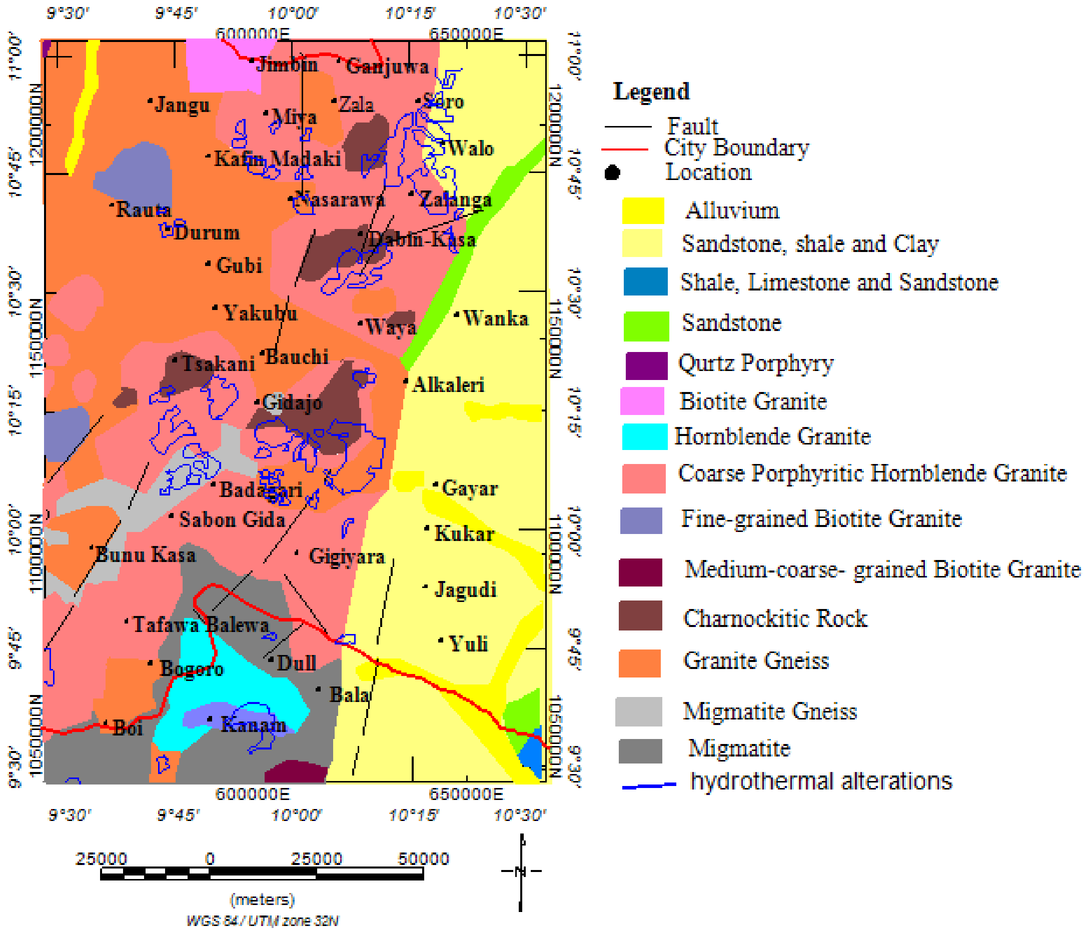

Figure 11. Updated geology map of Bauchi area.

eas occur within the granitic rocks as shown in Figures 5 to 11 using %K, eTh, eU and K/eTh ratio maps. The heat sources for the hydrothermal alteration in the study area are suggested to be magmatic and were associated with granitic intrusions and emplacement of late intrusive rocks. This is in contrast to reports of Ogunsanwo *et al.* [66] in southwestern Nigeria that the radioelements depositions were found in sediment formation and were attributed to geomorphic activity such as weathering, leaching, and intrusion. The three radioelements were as well found to have their major deposit in sediment formation compared to basement and weathered basement formations [66]. Catherine *et al.* [67] reported on the assessment of radionuclide distribution and associated radiological hazards of soils in Mayo-Belwa, Adamawa State and the aim was to monitor their potential impact on human health. This is in contrast to the present study where hydrothermal alteration and mineral potential zones were of interest in the Bauchi area.

The areas with high %K concentrations coincide with granitic rocks (Figure 5) and high %K anomaly areas were interpreted as alteration zones according to Manu [52]. The high K values in the study area indicate granitic rocks and this is in agreement with the report of Mam *et al.* [68] that attributed very high K values to older granitoids (undifferentiated Older granite and porphyritic rock) in the Gitata area, northcentral Nigeria. The area with relatively high eTh concentration is underlain by granitic and gneissic rocks (Figure 7) and the present study is in agreement with the report of Mam *et al.* [68] where high eTh concentration was attributed to migmatite around the north and porphyritic granite around the northwest of Gitata Sheet 187, northcentral Nigeria.

The regions with high eU values were underlain by granitic rocks (Figure 9). This shows that high eU values were recorded in granitic rocks compared to gneissic, metasedimentary and sedimentary units. The hydrothermally altered area with a tick blue line coincides with the granitic rocks (Figure 11). The high K/eTh ratio indicates hydrothermally altered areas since an increase in K and a decrease in eTh is a pointer for altered zones in various ore deposits [50] and signs of ore alteration [48]. Mam *et al.* [68] delineated mineralized and hydrothermal alteration zones in the Gitata area using radiometric data and suggested that the hydrothermal alteration zones are predominance in undifferentiated older granites.

The regions with high %K (Figure 5), high eTh (Figure 7), high eU (Figure 9) and high K/eTh ratio (Figure 11) coincide with the granitic rocks indicating that hydrothermal alteration and mineral potential zones are predominance in older granites

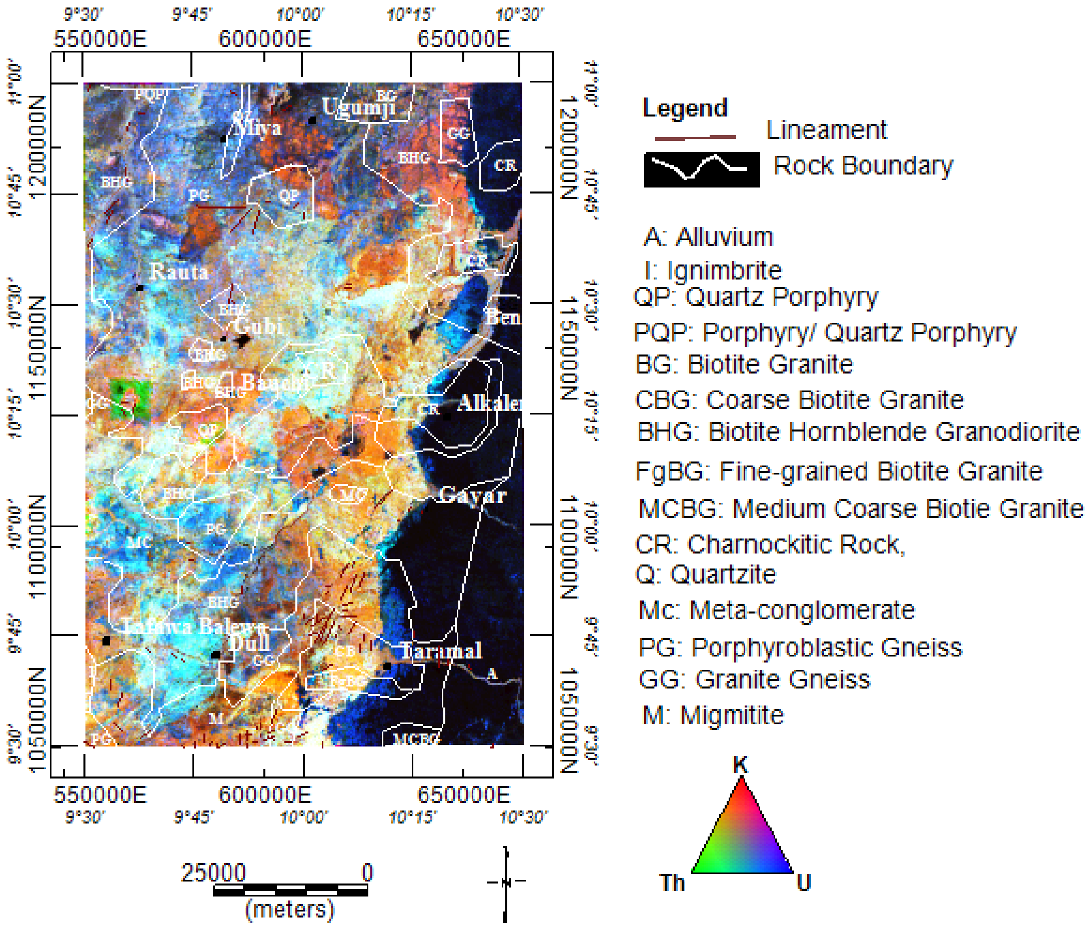

Figure 12. Ternary map of Bauchi area.

and younger granites in the study area and granitic intrusions provide the heat sources for hydrothermal fluids.

4. Conclusion

The regions with high %K, high eTh and high eU coincide with the granitic rocks and this indicates that hydrothermal alteration and mineral potential zones are predominance in older granites and younger granites.

The high K/eTh ratio indicates hydrothermally altered areas and high potassium concentrations are associated with alteration zones related to mineralization. This suggests that the hydrothermal alteration zones are favourable areas for mineralization in the study area.

The hydrothermally altered areas are underlain by granitic rocks and this attests that the hydrothermal alteration process is accompanied by granitic intrusions and emplacement of late intrusive rocks which provide the heat sources for hydrothermal solutions along fractures for the formation of minerals or react with the enclosing rock for hydrothermal alteration and subsequent mineralization.

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