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RESEARCH ARTICLE

PROVENANCE, TECTONIC SETTING AND MATURITY OF THE ISHARA SANDSTONE, SOUTH WESTERN, NIGERIA: INSIGHT FROM MAJOR ELEMENT GEOCHEMISTRY

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ABSTRACT

Major elements geochemical study of the Ishara sandstone of the Ise Formation in the Dahomey Basin, southwest Nigeria, was carried out to infer their provenance, maturity and tectonic setting. This study is based on the analysis of outcrop samples located between latitudes $6^0 57^1$ and $6^0 59^1$N; and longitudes $3^0 39^1$ and $3^0 41^1$E. On the basis of whole rock geochemistry (i.e. major elements), the sandstones are considered as continental sands which can be classified as lithic arenites. The ternary plot of Na_2O-K_2O-(Fe_2O_3+MgO) depicts ferromagnesian potassic sandstones suggesting acid igneous rocks and gneisses as probable source rock which are common components of the south western Precambrian Basement Complex. The negative correlation of SiO_2 with the other major oxides is ascribed to the relative abundance of quartz. The positive correlation of TiO_2 and Fe_2O_3 with Al_2O_3 implied their association with clay minerals. The relative depletion of Na_2O, K_2O, TiO_2, Fe_2O_3 and MgO were noticed but SiO_2 and CaO were relatively enriched. The bivariate plot of SiO_2 versus Al_2O_3+ K_2O+ Na_2O depicted that the sandstones were formed under semi-humid/humid conditions and mineralogically immature. The index of compositional variability (ICV) and log (K_2O/Na_2O) ratios also showed that the studied sandstones are mineralogically immature. Weathering indices such as chemical index of alteration (CIA), chemical index of weathering (CIW) and plagioclase index of alteration (PIA) suggest that the source materials underwent moderate weathering. The weathering trend suggests that the sandstones were once rich in plagioclase before alteration to smectite. The ternary plot of SiO_2/Al_2O_3, MgO and Fe_2O_3 indicated that the studied samples were deposited in the non marine and deltaic settings. This observed trend is supported by the binary plot of Fe_2O_3 versus MgO. The high Al_2O_3/TiO_2 ratio and low MgO values indicate these rocks are derived from felsic igneous source. The observed trend is further corroborated by the discriminant function plot which shows studied sandstones in the field of felsic igneous source. The plot of K_2O/Na_2O versus SiO_2 shows most of the studied clastic sediments in the field of active continental margin (ACM) and few samples in the field passive continental margin (PCM) which suggests syn-rift faulting.

INTRODUCTION

Clastic sediments are loose, solid particles that originate from the weathering and erosion of pre-existing rocks. Siliciclastic sedimentary facies are very important parts of sedimentary basin analysis. The textural features of these siliciclastic facies are due to natural processes like of weathering, erosion, transportation and deposition. The compositions of clastic sediments are affected by several factors, such as hydraulic sizing, tectonic environment, diagenesis, weathering and transportation processes (Taylor and Mclennan, 1985; Wronkiewicz and Condie, 1987; Wronkiewicz and Condie, 1989).

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Their composition consecutively depends on the primary chemical composition of the source rock area and the tectonic setting of the depositional basins (Bhatia and Crook, 1986; Das and Haake, 2003; Jin *et al*., 2006). Therefore, composition of sandstones has been used as sensitive indicator for provenance and weathering conditions at the source of sediments (Roser and Korsch, 1986, 1988; Huntsman-Mapilaa *et al*., 2005). The major assumption proposed for sandstone provenance studies is that each tectonic setting consist its own rock type (Dickson and Suczek, 1979; Dickson, 1985). Even though some geochemical ratios can be altered during weathering during oxidation (Taylor and McLennan, 1985) or diagenesis (Nesbitt and Young, 1989; Milodowski and Zalasiewicz, 1991), as long as the bulk chemical composition is not totally altered, the geochemical composition of sediments is an important tool in the study of provenance (Bhatia, 1983; Taylor and McLennan, 1985; Bakkiaraj *et al.,* 2010).

The major element discrimination diagrams of Bhatia (1983) have been usually used to classify the tectonic settings of sedimentary basins and was applied in recent study (e.g., Armstrong-Altrin *et al.,* 2004; Akinyemi *et al*., 2014), even though caution is required in their arbitrary use (Armstrong-Altrin and Verma, 2005). The most essential clues for the tectonic setting of basins come from the relative depletion of the oxides like CaO and Na_2O (the most mobile elements), among others. The oxides are understood to show enrichment or depletion of quartz, K-feldspars, micas and plagioclase. The ratio of the most immobile elements to the mobile ones increases towards the passive margin to the relative tectonic stability (Armstrong-Altrin *et al.,* 2004) and therefore suggests prolonged weathering.

The Dahomey basin is an extensive sedimentary basin extending almost from south-Ghana to Nigeria (precisely the Benin hinge-line). The Dahomey basin (Fig.1) is a marginal pull-apart basin (Klemme, 1975) or Margin sag basin (Kingston *et al*., 1983), which was initiated in the Late Jurassic to early Cretaceous (Whiteman, 1982) separation of African and South American lithospheric plates.

A number of authors have identified and described the eight lithostratigraphic units in the Dahomey basin (Jones and Hockey, 1964; Omatsola and Adegoke, 1980; Omatsola and Adegoke, 1981; Agagu, 1985; Akinmosin, 2005). In most parts of the basin, the stratigraphy is dominated by sand and shale alternations with minor proportion of limestone (Agagu, 1985). This investigative study was carried out in Ishara, Ogun State in the south-western Nigeria. It is a transition zone between sedimentary and basement complex lying between latitudes $6^{0}57^{1}$ and $6^{0}59^{1}$N; and longitudes $3^{0}39^{1}$ and $3^{0}41^{1}$E (Fig. 2). This present study intends to make precise deductions on the maturity, sediment source area weathering, provenance and tectonic settings of the Ishara sandstone based on major oxides geochemical data.

Stratigraphy of Dahomey Basin

Previous work on the Cretaceous stratigraphy of the Dahomey basin has recognized three formations belonging to the Abeokuta group (Omatsola and Adegoke, 1981) as follows; (1) The Ise Formation which is Neocomian to Albian in age consist essentially of continental sands, grits and siltstones. This is directly overlying the south western Precambrian Basement Complex. (2) The Afowo Formation which overlay Ise Formation consists of coarse to medium-grained sandstones with variable interbeds of shales, siltstones and clay.

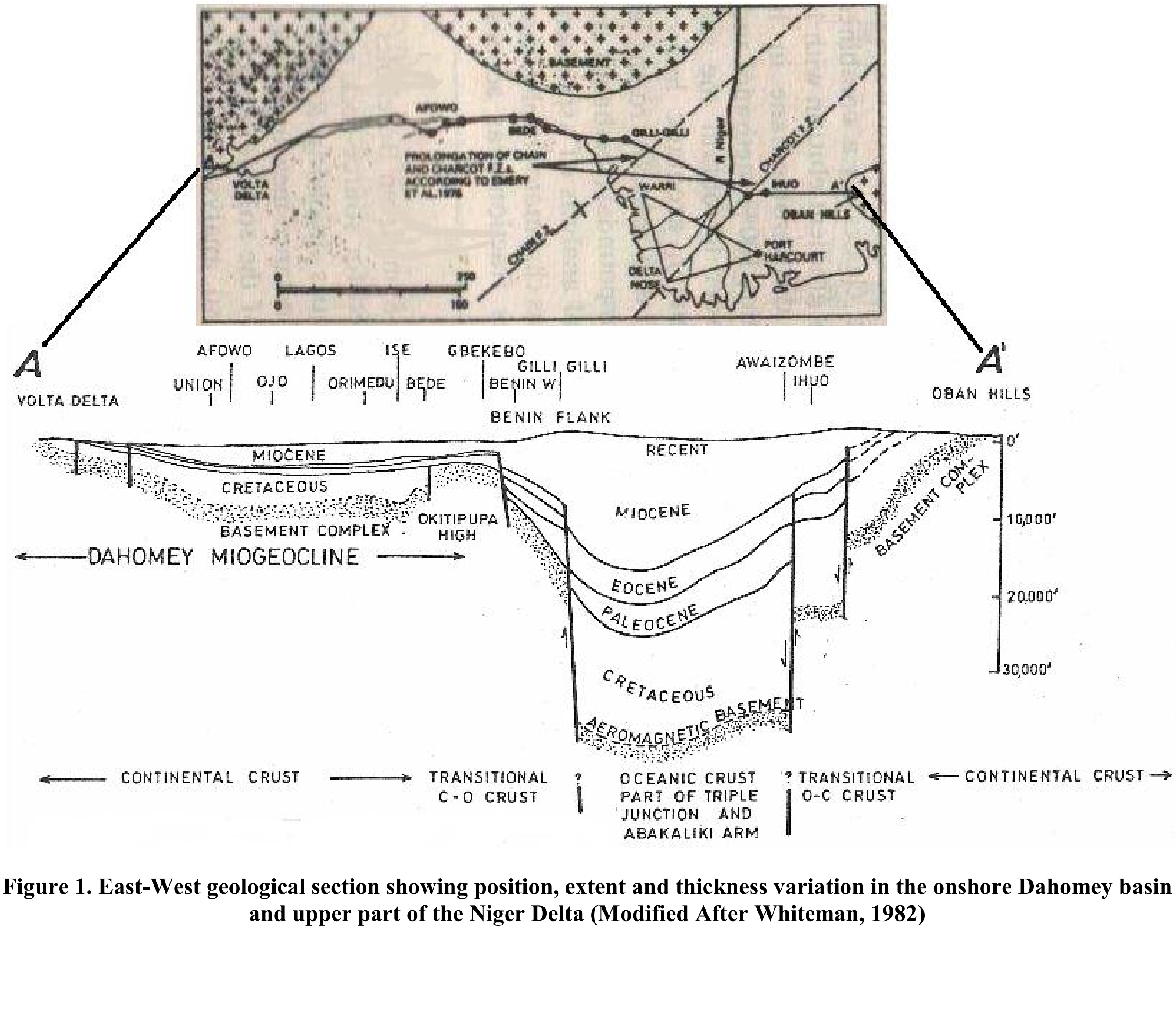

Figure 1. East-West geological section showing position, extent and thickness variation in the onshore Dahomey basin and upper part of the Niger Delta (Modified After Whiteman, 1982)

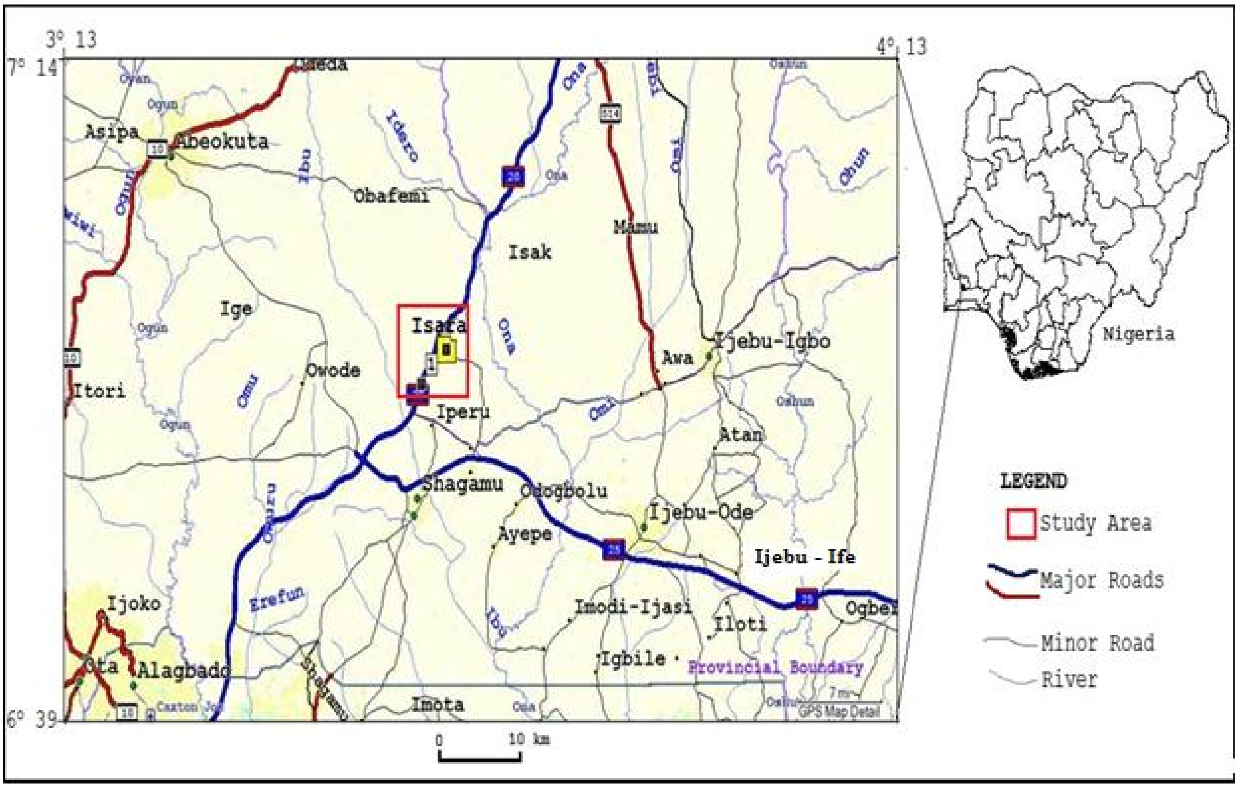

Figure 2. Map showing the location of the study area

Table 1. Major oxides component (Wt %) of Ishara sandstones and their weathering indexes

OXIDES	SAMPLES									AVER.
	1	2	3	4	5	6	7	8	9	
SiO_2	72.89	82.65	81.72	81.75	81.72	83.09	85.52	83.25	73.19	80.64
Al_2O_3	23.09	9.90	10.62	10.40	4.54	7.80	4.50	7.85	22.30	11.22
TiO_2	0.04	0.04	0.03	0.04	0.05	0.03	0.05	0.05	0.06	0.04
CaO	3.54	2.75	2.90	2.85	2.90	2.79	2.74	2.76	3.61	2.98
Fe_2O_3	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
Na_2O	0.06	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.06	0.05
K_2O	0.10	0.08	0.08	0.08	0.08	0.07	0.08	0.06	0.10	0.08
FeO	0.07	0.00	0.01	0.01	0.00	0.02	0.02	0.01	0.08	0.02
MgO	0.00	0.19	0.14	0.15	0.21	0.20	0.21	0.18	0.00	0.14
SO_3	0.00	0.03	0.01	0.01	0.00	0.02	0.04	0.03	0.00	0.02
SiO_2/Al_2O_3	3.16	8.35	7.69	7.86	18.00	10.65	19.00	10.61	3.28	9.84
K_2O/Na_2O	1.67	1.60	1.60	1.60	1.60	1.17	1.60	1.20	1.67	1.52
% CIA	86.19	77.46	77.80	77.73	59.97	72.76	61.06	73.23	85.54	74.64
% CIW	86.51	77.95	78.26	78.20	60.06	73.24	61.73	73.64	85.87	75.05

CIA: Chemical Index of Alteration

CIW: Chemical Index of Weathering

The sediments of this formation were deposited in a transitional to marginal marine environment during turonian to Maastritchtian age. (3) The Araromi Formation consists basically of sand, overlain by dark-grey shales and interbedded limestone and marls occasional lignite bands. The formation conformably overlies the Afowo Formation and Maastrichtian to Paleocene age has been assigned (Omatsola and Adegoke, 1981). The Abeokuta was conformably overlaid by Imo group which comprises of shale limestone and marls. The two-lithosratigraphic units under this group are: Ewekoro formation which consists of thick fossiliferous limestone. Adegoke (1977) described the formation as consisting of shaly limestone 12.5m thick which tends to be sandy and divided it into three microfacies. Ogbe (1972) further modified this and proposed a fourth unit. It is Paleocene in age and associated with shallow marine environment due to abundance of coralline algae, gastropods, pelecypods, echinoid fragments and other skeletal debris. The Akinbo Formation overlies Ewekoro Formation and it consists of shale, glauconitic rock bank, and gritty sand to pure grey and with little clay.

Limestone lenses from Ewekoro formation grades literally into the Akinbo shale towards the base. The base is characterized by the presence of a glauconitic rock. The age of the formation is Paleocene to Eocene. The Oshoshun Formation overlies the Imo group which is a sequence of mostly pale greenish-grey laminated phosphatic marls, light grey white-purple clay with interbeds of sandstones. It also consists of claystone underlain by argillaceous limestone of phosphatic and glauconitic materials in the lower part of the formation and were deposited during Eocene (Agagu, 1985). The sedimentation of the Oshoshun Formation was followed by a regression phase which deposited the sandstone unit of Ilaro Formation (Kogbe, 1976). The sequence represents mainly coarse sandy estuarine deltaic and continental beds which show rapid lateral facies change. The coastal plain sands are the youngest sedimentary unit in the eastern Dahomey basin. It conceivably unconformably overlay the Ilaro Formation but lack convincing evidence (Jones and Hockey, 1964). It consists of soft, poorly sorted clayey sand and pebbly sands deposited during Oligocene to Recent.

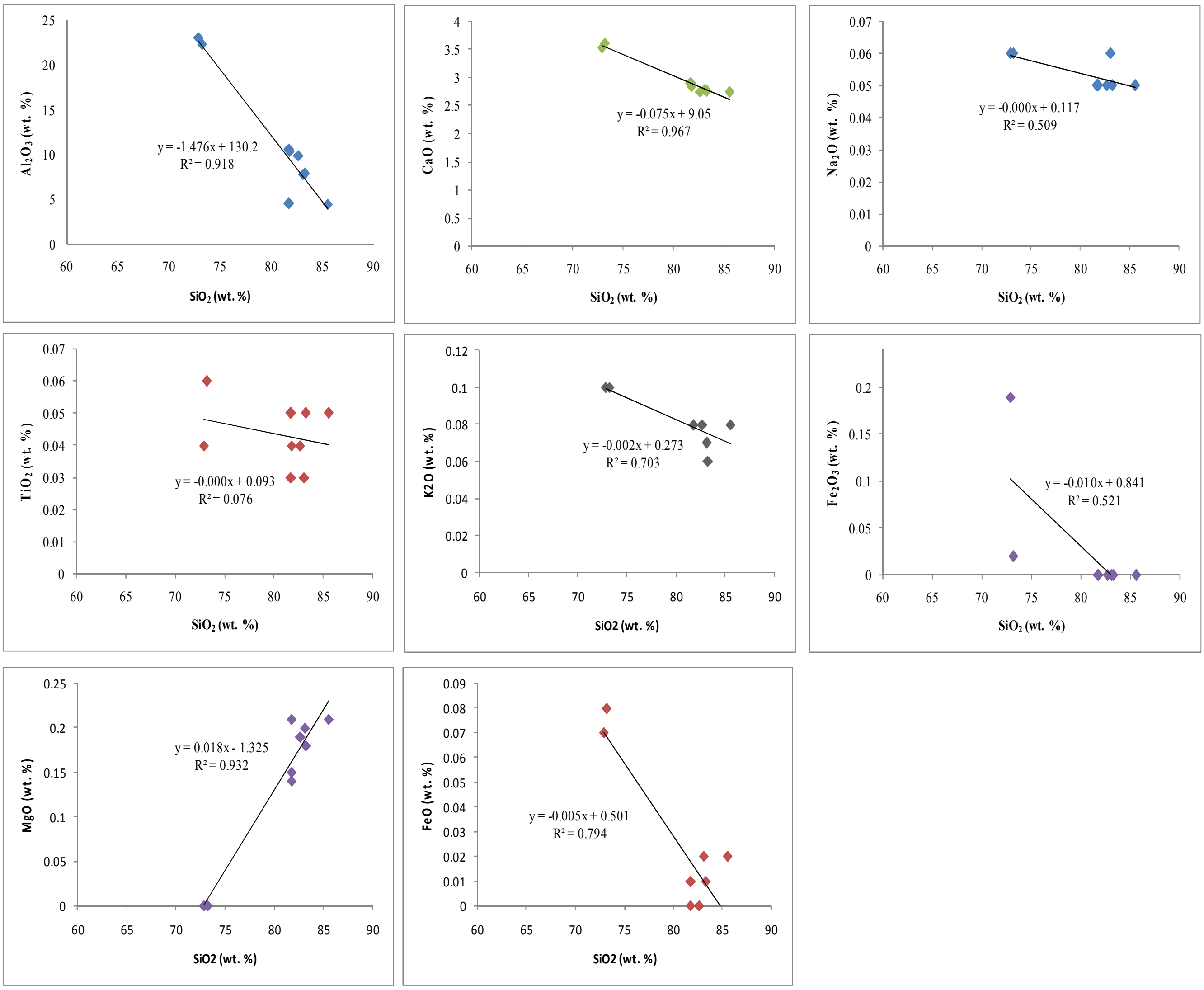

Figure 3. Cross-plots of major oxides against SiO_2 showing negative correlation except with MgO

MATERIALS AND METHODS

Eleven sandstone samples were collected at different locations from exposed Ishara sandstone deposits. Out of these samples, nine were systematically selected for laboratory analyses. They were first disaggregated cautiously to preserve the grain shapes and later subjected to X-ray fluorescence [XRF] analysis (Fairchild *et al.*, 1999). Samples for XRF analysis were oven-dried at 100ºC for 12 hr to remove the adsorbed water and then crushed with a mortal and pestle to a fine powder. A PW1480 X-ray fluorescence spectrometer using a Rhodium tube as the X-ray source was used. The technique reports concentration as % oxides for major elements and ppm for minor elements.

RESULTS AND DISCUSSION

Geochemical composition

Table 1 depicts the major oxides component of Ishara sandstones. The analyzed samples are dominated by silica SiO_2, which ranges from 72.89-85.52% (Average = 80.64%), Al_2O_3 ranges from 4.50-23.09% (Average = 11.22%). The variation of SiO_2 content may be due to variation in grain size and diagenesis. The high Al_2O_3 value may be attributed to composition of lithic fragments while the low concentrations of Fe_2O_3 (Average = 0.02%) MgO (Average = 0.14%); Na_2O (Average = 0.05%); K_2O (Average = 0.08%), TiO_2 (Average = 0.04%) and FeO (Average = 0.02%) may be ascribed to chemical destruction under oxidizing conditions during weathering and diagenesis or source-area composition. Chemical alteration of rocks during weathering led to the depletion of alkalis and alkaline earth elements and preferential enrichment of Al_2O_3 (Cingolani *et al.*, 2003). The CaO content ranges from 2.74-3.61% (Average = 2.98%); this could be attributed to dissolved diagenetic calcite cement. Obvious lack of MnO is probably due to dissimilatory manganese reduction by microbes or source-area composition. The negative correlation of SiO_2 with the other major oxides (Fig. 3) except MgO is due to most of the silica being appropriated in quartz, as indicated by Osman (1996). The TiO_2 and Fe_2O_3 correlates positively with Al_2O_3 (Fig. 4) suggesting their association with clay minerals. The observed K_2O/Na_2O ratio ranged from 1.17-1.67 (Average = 1.52) shows that K-bearing minerals are slightly more than Na-plagioclases. The high Al_2O_3/TiO_2 ratio of 90 - 577 (Average = 268) and low MgO values indicates felsic source rock.

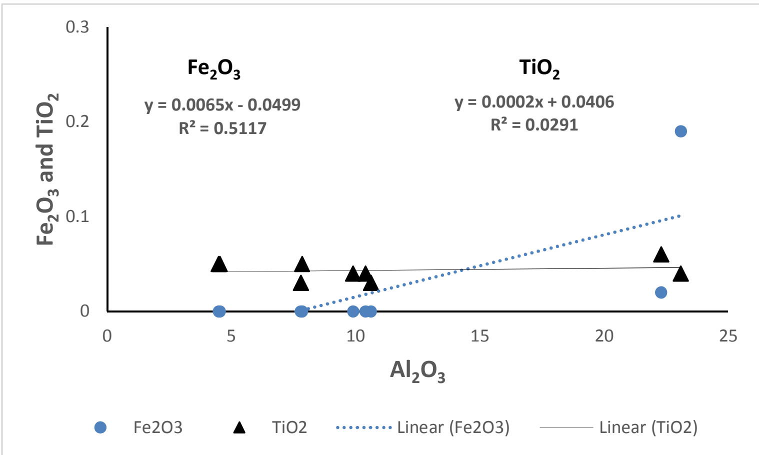

Figure 4. Cross-plot of major Fe and Ti oxides against Al_2O_3 showing positive correlation

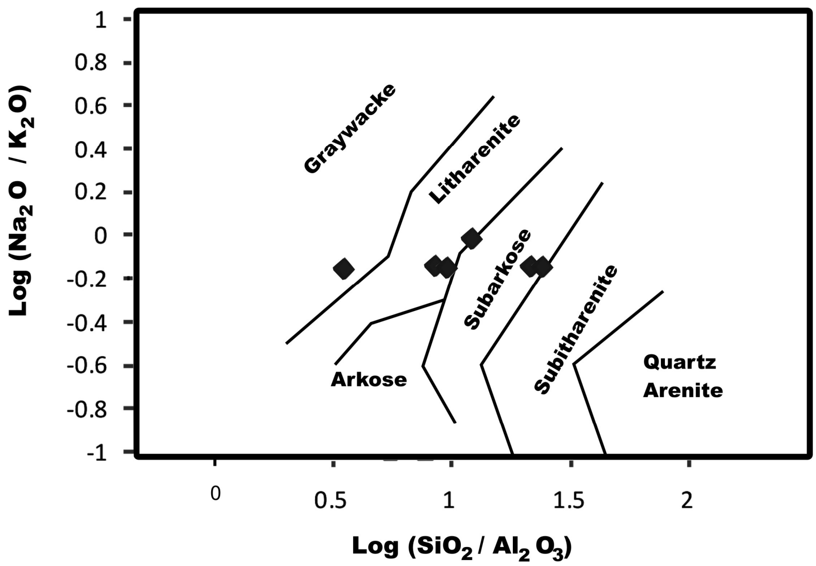

Figure 5. Chemical classification of Ishara sandstones based on Pettijohn scheme (1972)

Geochemical classification

The classification schemes used in this study was adopted from the geochemical classification diagrams of several authors (Pettijohn *et al.* 1972); Blatt *et al*. (1972); Folk (1974); Herron (1988); Lindsey (1999). Figure 5 was constructed based on the Pettijohn (1972) scheme which shows that majority of the sandstones were plotted in the litharenite zone and few on the subarkose and geywacke zones. The ternary diagram proposed by Blatt *et al*. (1972) shows the studied samples are mainly ferromagnesian potassic sandstones with little potassic sandstone (Figure 6). The ternary diagram by Blatt *et al*. (1972) omitted sandstones with less than 5% of Al_2O_3, consequently, quartz arenites is missing.

Based on the work by Lindsey (1999) using data from Pettijohn (1963 and 1975), the average lithic arenites are plotted in the ferromagnesian potassic sandstones field, but the average greywacke are plotted in the sodic sandstone field and average arkoses appeared in the potassic sandstones field. According to Pettijohn (1963), the lithic arenites are a diverse and poorly defined class. In addition to abundant rock fragments of widely varying composition, many lithic arenites contain clay matrix with different compositions which can contain higher levels of Fe and Mg. Also, many rock fragments of lithic sandstones are composed of materials that vary greatly in composition. Based on compositional fields for major classes of sandstones (Lindsey, 1999), the studied sandstones were plotted in the arkose field (Figure 7).

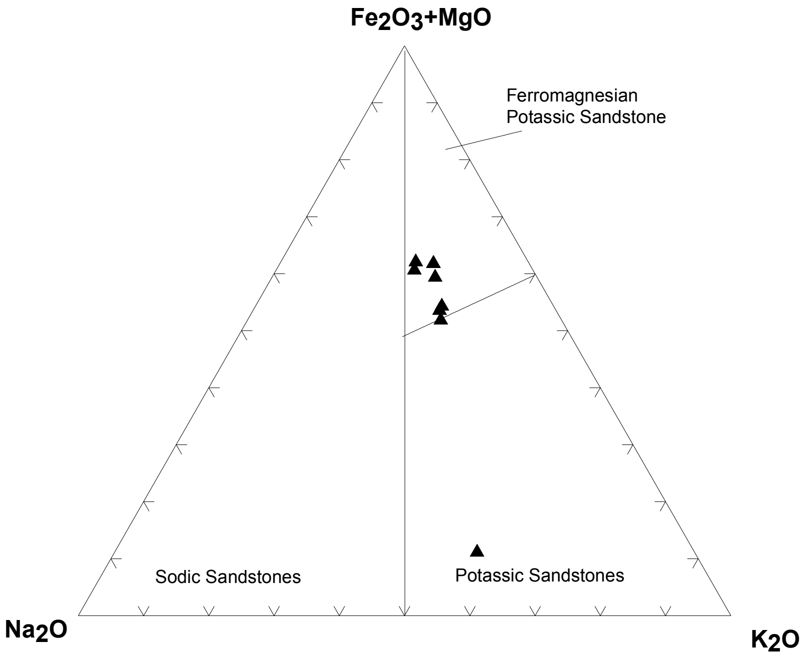

Figure 6. Ternary diagram of Na_2O-K_2O-(Fe_2O_3+MgO) of the Ishara sandstone from Blatt *et al.* (1972)

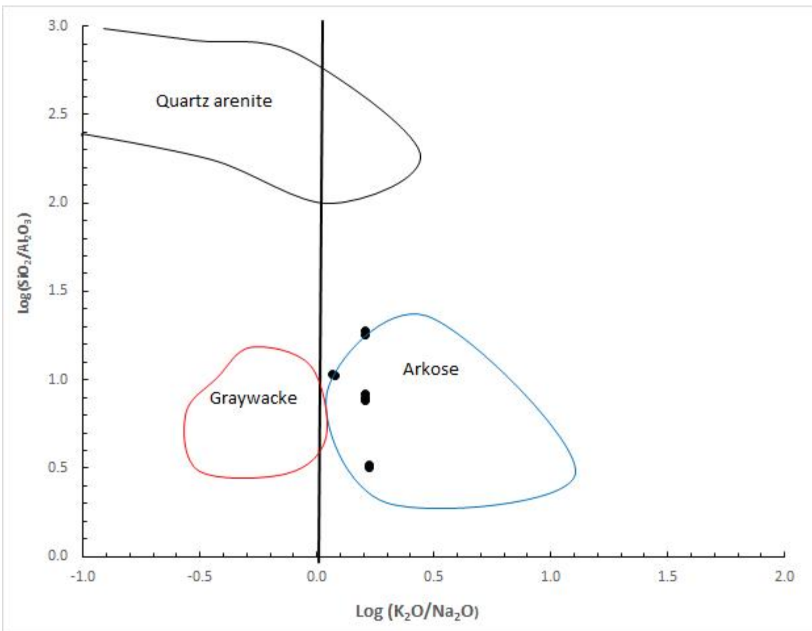

Figure 7. Compositional fields for major classes of sandstones (data from Pettijohn, 1963; 1975): log (SiO_2/Al_2O_3) versus log (K_2O/Na_2O). Ishara sandstone plotted in the arkose field (Adapted from Lindsey, 1999)

Based on the study of a reference set, Lindsey (1999) proposed the four guidelines for chemical classification of sandstones; Ishara sandstone falls within the requirements of the fourth condition and thus classifies as a lithic arenite.

Maturity and climatic conditions during sedimentation

SiO_2/Al_2O_3 ratios of clastic rocks are sensitive to sediment recycling and weathering process and can be used as an indicator of sediment maturity. With increasing sediment maturity, quartz survives preferentially to feldspars, mafic minerals and lithics (Roser and Korsch, 1986; Roser et al., 1996). Average SiO_2/Al_2O_3 ratios in unaltered igneous rocks range from ~ 3.0 (basic rocks) to ~ 5.0 (acidic rocks). Values of SiO_2/Al_2O_3 ratio > 5.0 in sandstones are an indication of progressive maturity (Roser et al., 1996). The SiO_2/Al_2O_3 ratios of the sandstones vary from 3.16 to 19.00 (average = 9.84). Values of K_2O/Na_2O ratio range from 1.17 to 1.67 (average = 1.52). Low values of SiO_2/Al_2O_3 ratios and low values of K_2O/Na_2O together indicate mineralogically immature sediment. The immatured nature of the sandstones suggests active uplift of the source region, rapid erosion of the variously weathered source material, short distance fluvial transport and poor sorting. Figure 8 indicates that majority of the sandstones tends towards increasing chemical mature because they formed under semi-humid/humid conditions. Sandstones usually contain clay minerals growing on the surface of the grains or lining and sometimes filling the pore space (Prothero, 2004). The high values given from the ratio of SiO_2/Al_2O_3 indicate that all the samples have low degree of clayness. The higher the SiO_2 content the lower the degree of clayness. Colours are caused by presence of varying mixtures of mobile oxides such as haematite and limonite. Depletion of these oxides is mostly caused by weathering processes (Muhs *et al*., 1987). The $Al_2O_3/(CaO+MgO+Na_2O+K_2O)$ ratio can be used in determining the stability of mobile oxides as proposed by Gill and Yemane (1996). From the positive values obtained (0.40 to 6.24), it shows that there are stable mobile oxides in the Ishara sandstones. The presence of calcite is the most common cement in sandstone, although when present it does not fill all pore spaces completely but occurs as patchy cement.

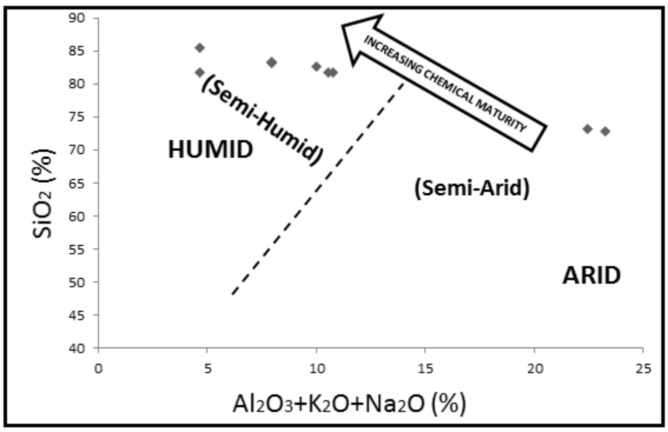

Figure 8. Chemical maturity of the Ishara sandstones expressed by bivariate plot of SiO_2 versus Al_2O_3+ K_2O+ Na_2O (After Suttner and Dutta, 1986)

Calcite cemented sandstone often have their cement partially dissolved. It occurs as a result of chemical weathering of rocks (Hendry and Trewin, 1993). The $CaO+MgO/Al_2O_3$ molecular weight ratio was used to determine calcification in the studied sandstones as proposed by Gills and Yemane (1996). All the samples have low values which indicate that the sandstones are less calcified. An approach towards assessing detrital mineralogy is to use the Index of Compositional Variability (ICV) and ratio of K_2O/Al_2O_3 (Cox *et al.,* 1995). The Index of Compositional Variability is defined as: $(Fe_2O_3+Na_2O+CaO+MgO+TiO_2)/Al_2O_3$. More matured sandstone with mostly clay minerals displays lower ICV values that are less than 1.0 and such sandstones are derived from cratonic environment (Cox *et al*., 1995). According to the results of the Index of Compositional Variability, all of the sandstones have values less than 1, this indicate that the sandstones are mineralogically mature.

Source-area weathering

Previous work on clastic sedimentary rocks shows that their chemical composition is mainly dependent on the composition and the weathering conditions at the source rock area (Nesbitt and Young, 1989; Nesbitt *et al*., 1996). Nesbitt and Young (1982) was of the opinion that evaluation of the degree of chemical weathering/alteration of the sediments' source rocks can be determined by calculating the Chemical Index of Alteration (CIA), where CIA = molar ($Al_2O_3/[Al_2O_3$+ $CaO+Na_2O+K_2O]$).This index works correctly when Ca, Na, and K decrease as the intensity of weathering increases (Duzgoren-Aydin *et al*., 2002). The Chemical Index of Weathering (CIW) proposed by Harnois, (1988) is similar to the CIA except for the exclusion of K_2O in the equation: CIW = molar ($Al_2O_3/(Al_2O_3$+ CaO + Na_2O)). The CIA and CIW are interpreted in similar way with values of 50 for unweathered upper continental crust and roughly 100 for highly weathered materials, with complete removal of alkali and alkaline-earth elements (McLennan *et al*., 1983; McLennan, 1993; Mongelli *et al*., 1996). Low CIA values (i.e. 50 or less) also might reflect cool and / or arid conditions (Fedo *et al*., 1995). The CIA and CIW values for the Ishara sandstones yielded almost the same values: the CIA ranged between 60 and 86% (Average = 74.64%), while CIW ranged from 60-87% (Average = 75.05%) indicating a moderate degree of weathering of the source materials. The results of the major elements geochemistry of the Ishara sandstone, however, displayed of SiO_2 values above 80% and relatively low quantity of K-feldspar and Na-feldspars suggest that the source rock was exposed to weathering.

Figure 9 shows the Ishara sandstones plotting in the smectite line, insoluble residues are close to the area where illite and smectite lies (Kovács, 2007). The weathering trend suggests that the sandstones were once rich in plagioclase feldspars before alteration to smectite silicates. The plot of CIA versus Al_2O_3 depicts moderate degree of weathering of source materials (Figure 10). The chemical composition of weathering products in a river basin is expected to exhibit entrenched concepts on mobility of various elements during weathering (Nesbitt *et al*., 1980; Singh *et al*., 2005), and therefore to assess the state of chemical and physical weathering (Vital and Stattegger, 2000; Singh *et al*., 2005; Liu *et al*., 2007). Elemental ratios calculated with respect to Al are used to identify and evaluate the major element mobility. According to Singh *et al*. (2005), the ratio of the content of element X and Al_2O_3 in rivers divided by the ratio of the same element content of upper continental crust (UCC) gives the following elemental ratio:

$$\text{Elemental ratio (X)} = \frac{X/Al_2O_3\ (\text{rivers})}{X/\ Al_2O_3\ (\text{UCC})}$$

However, this ratio was modified for this work using the following elemental ratio:

$$\text{Elemental ratio (X)} = \frac{X/Al_2O_3\ (\text{sediments})}{X/\ Al_2O_3\ (\text{UCC})}$$

In a plot of Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 introduced by Garrels and Mackenzie (1971), depletion of Na and K is evident in the samples, compared to UCC (Fig. 11). During the formation of sedimentary particles from the crust, the very mobile Na will be removed into marine environment while more K is retained in the sediments.

The degree of the chemical weathering can also be estimated using the Plagioclase Index of Alteration (Fedo *et al*., 1995); in molecular proportions: PIA = $[(Al_2O_3-K_2O)/\ (Al_2O_3 + CaO^* + Na_2O-K_2O)] \times 100$ where CaO* is the CaO residing only in the silicate fraction. Unweathered plagioclase has PIA value of 50 while Phanerozoic shales have PIA value of 79. The Ishara sandstone has PIA values of between 60 and 86 with an average of 75 indicating moderate weathering at the source

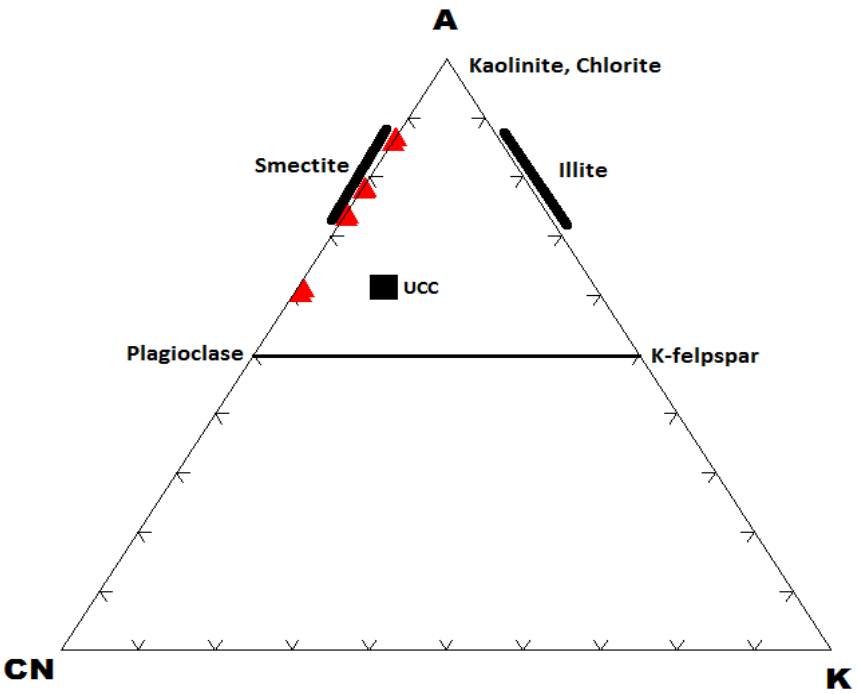

Fig. 9. Ternary diagram showing the weathering trend of Ishara sandstone (all in molar proportions); Al_2O_3–CaO +Na_2O−K_2O (A–CN–K). Average UCC value from Rudnick and Gao (2003)

The elemental ratio refers to the relative enrichment or depletion of the element, i.e., >1 indicates enrichment, <1 indicates depletion, and =1 indicates no change in the relative abundance of the element. For the Ishara sandstones, Na_2O, K_2O, TiO_2, Fe_2O_3, MgO have values less than 1, while SiO_2, and CaO have values greater than 1. The depletion of highly mobile K and Na elements is due to leaching during the formation of clay minerals during increased chemical weathering. Ca is a highly mobile element that is enriched, this may be attributable to dissolved diagenetic calcite cement or secondary enrichment sourced from overlying carbonate rocks. Si is a less mobile element and its enrichment suggests moderate chemical weathering; the immobile Fe and Ti and the less mobile Mg elements were depleted, this suggest that they may be from a common source with a preponderance of felsic minerals and paucity of ferromagnesian minerals under moderate chemical weathering condition.

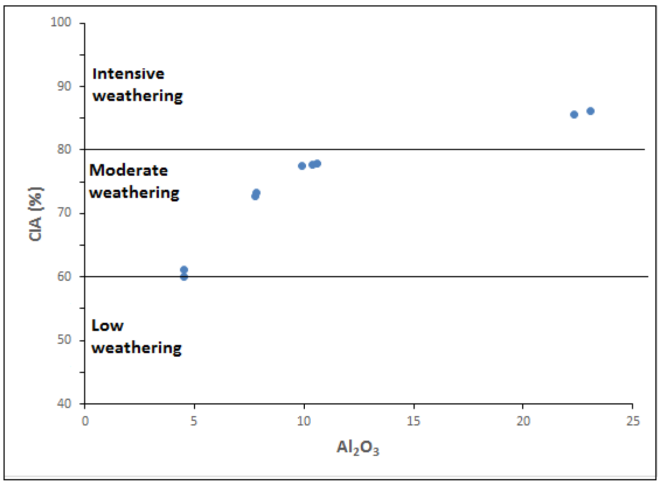

Fig. 10. Chemical index of alteration (CIA) of the Ishara sandstone and its correlation with Al_2O_3

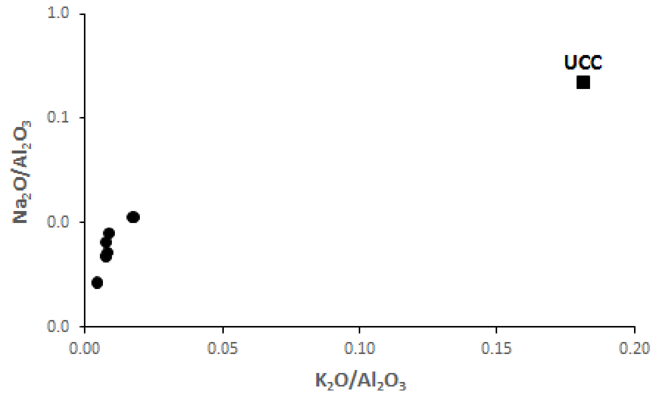

Fig. 11. Diagram showing variations in Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 (all molar ratios) for all of the samples and UCC (After Garrels and Mackenzie, 1971)

Provenance and tectonic settings

Several authors (Blatt *et al*., 1980; Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986 & 1988) have related sandstone geochemistry to specific tectonic environment. The discriminant function plot of Roser and Korsch (1988) defined four (4) main provenances: mafic igneous provenance; intermediate igneous provenance; felsic igneous provenance; and quartzose sedimentary provenance (Figure 12). The Ishara sandstone plots converged in the felsic igneous provenance field demonstrating that they are derived from a silicic crystalline (plutonic-metamorphic) terrain with a lesser intermediate-acid volcanic component. This also may indicate a substantial contribution of clastic materials from rifted continental margins.

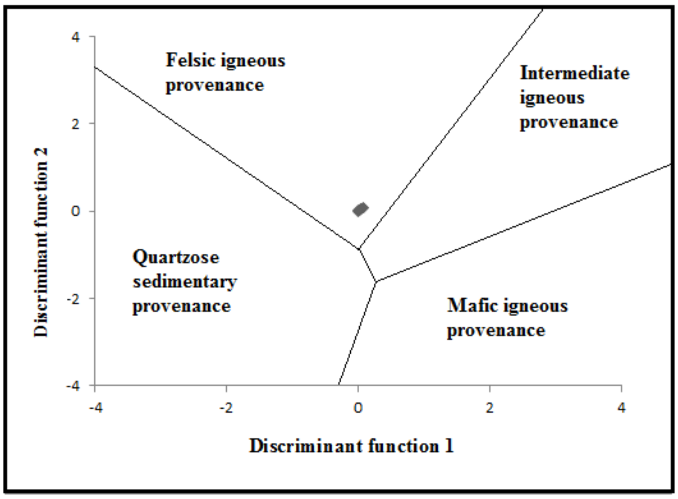

Fig. 12. Discriminant function diagram using major elements for the provenance signatures of the Ishara sandstones (After Roser and Korsch, 1988)

Roser and Korsch (1986) created a tectonic discrimination diagram using K_2O/Na_2O ratio versus SiO_2 (Fig.13) to determine the tectonic setting of clastic terrigenous sedimentary rocks. The cross plot is used to discriminate between sediments deposited in the Passive Continental Margin, Active Continental Margin and the Oceanic Island Arc. Most of the studied samples plotted in the active continental margin (ACM) tectonic settings suggesting a syn-rift faulting setting of a transform margin. Figure 14 also confirms that the Ishara sandstones are continental sands.

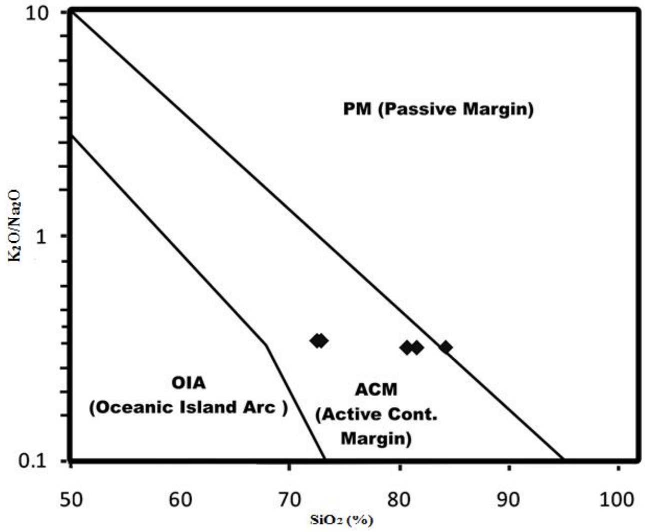

Fig. 13. Tectonic discrimination plot for the Ishara sandstones (After Roser and Korsch, 1986)

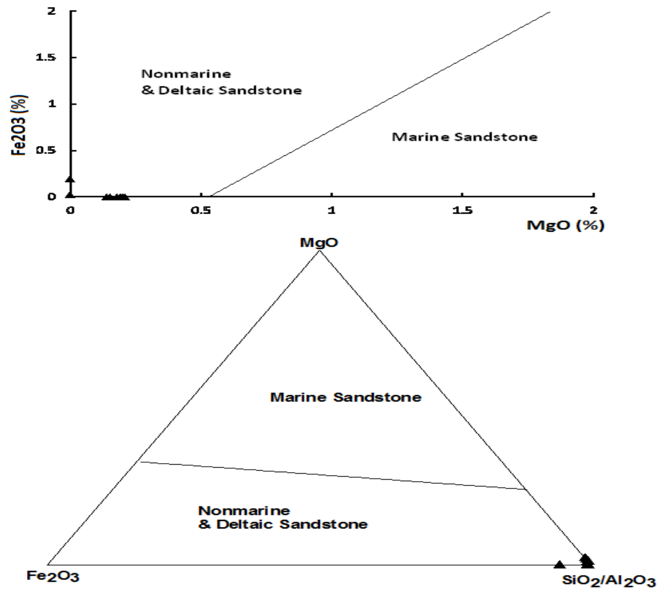

Fig. 14. Binary and ternary diagrams showing characterization and differentiation of marine from nonmarine sandstones. Ishara sandstones plotted in the non-marine and deltaic field (After Ratcliffe *et al*., 2007)

Conclusion

The Ishara sandstones are continental sands that can be classified as lithic arenites that are ferromagnesian potassic sandstones signifying acid igneous rocks and gneisses as probable sources because they are common constituents of the basement complex in the surrounding area. The sandstones were formed under semi-humid/humid conditions and are immature. All the weathering indices indicate that the source area experienced moderate weathering condition. The high Al_2O_3/TiO_2 ratio and low MgO values indicate these rocks come from a felsic igneous source. This is also supported by the provenance discrimination plot. The tectonic setting is the Active Continental Margin, which suggests syn-rift faulting.

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