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# Sedimentological and geochemical evaluation of sandstones of the Ilaro formation, Dahomey Basin, Southwestern Nigeria: Insights into paleoenvironments, provenance, and tectonic settings

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**Abstract**

Grain size analysis, geochemistry, and petrography of sandstones of the Ilaro Formation exposed at the Ajegunle area were investigated to infer provenance, transportation history, tectonic setting, paleoenvironment, and degree of palaeoweathering of the sediments. Selected sandstones were analyzed, and the major, trace, and rare earth elements were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Results from the granulometric analysis showed that sandstones were deposited in fluvial conditions. The sandstones exhibit a coarse-grained texture, displaying poor sorting and being texturally immature. The petrographic analysis indicated that quartz was predominant, whereas opaque minerals, muscovite, and ferruginous ground mass were present in smaller quantities. The sandstones can be geochemically classified as arkose and subarenite. The sandstones have an average composition of $SiO_2$ (82.87%) and $Al_2O_3$ (9.49%), while $K_2O$, $Na_2O$, MgO, CaO, and $P_2O_5$ have <1% each. The elevated $Al_2O_3$ content is associated with the lithic fragment composition, whereas the low concentrations of MgO (mean 0.03%), $Na_2O$ (mean 0.008%), and $K_2O$ (mean 0.04%) suggest chemical destruction in an oxidizing environment. The angularity of the grains indicated a short transportation history very close to the provenance. Bivariate and discriminant plots from major elements and trace elements suggest the sandstones were non-marine and sourced from intermediate rocks. The sandstones were deposited in an oxic-dyoxic condition under a humid climate and passive or active continental margins. The average values of the weathering indices indicate an intense degree of chemical weathering.

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## 1. Introduction

The formation of clastic sediments is an interplay of weathering, transportation, deposition, and diagenetic changes after deposition. The characteristics of sedimentary rocks play a crucial role in the interpretation of stratigraphy, resource po-

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tential, tectonic activity of the origin, and paleoenvironments [1, 2]. Geochemical imprints are significant in the determination of prehistoric and depositional events in rocks. The provenance, weathering, transportation, and paleoclimatic conditions of siliciclastic sediments can be determined by investigating the composition of the sediment [3, 4]. The objective of evaluating the sedimentary provenance is to characterize source areas by determining the texture and sediments composition [5]. Interpreting the stratigraphy and paleoenvironments of a basin requires a study of the distribution of particle size, composition of the heavy mineral assemblages, geochemistry, and properties of sedimentary rocks. The heavy mineral assemblages and particle size distribution of sedimentary rocks are invaluable in unraveling the provenance and paleodeposition of sediment in the earth's crust [6].

The Dahomey Embayment, also called the Dahomey Basin (Figure 1), is a collection of interior, coastal, and offshore basins that covers southern Ghana, Togo, the Republic of Benin, and southwestern Nigeria [7, 8]. The Okitipupa Ridge, a subsurface basement high, divides the basin from the Niger Delta. The Cretaceous Gulf of Guinea opened out in West Africa, forming the Dahomey Basin, which is a portion of Nigeria's interior basin. Block faulting and basement subsidence caused a succession of thick clastic deposits to emerge during the Early Cretaceous [9, 10]. The separation of the African and South American plates marked the beginning of the Dahomey Basin [9]. Before Africa and South America separated, sediment deposition started in the Early Cretaceous because of the tectonic subsidence of the Precambrian Basement Complex rocks. Brazilian basins and West African fringe basins' sedimentary histories indicated that the two landmasses were formerly one [8]. According to the work Whiteman and Billman [10, 11], Offshore sediments are 3000 m thick, whereas onshore sediments are just 100 m thick . The basement of the Dahomey Basin is non-conformably covered by Cretaceous to Recent layers [10]. The basement complex is overlain unconformably by the basal Ise Formation (Figure 2), which is a component of the Abeokuta Group. It is made up of coarse micaceous conglomeratic sediments that are weakly sorted, imbricated, and include ironstones in certain places. The sandstones are interbedded with shales that were deposited in continental and deltaic settings and are coarse to medium grained, soft, cross-bedded, friable, and interbedded with shales [10, 12]. Based on paleontological assemblages, this deposit was given a Neocomian-Albian age [13].

The transitional to marine Afowo Formation (Figure 2) overlies the Abeokuta group. The sandstone of the Afowo Formation is medium-coarse grained with varied thicknesses of interbedded shale, siltstone, and claystone [14]. The Ise Formation underlies this formation. The palynological assemblage dates the lowest portion of this deposit to Turonian, whereas the higher section is Maastrichtian [14].

The Araromi Formation underlies the Afowo Formation. The uppermost stratum of the Afowo Formation consists of shales and siltstone with interbeds of limestone and sand. This formation is made up of a fine- to medium-grained base sand that is coated in shale and siltstones with thin intercalations of marl and limestone [8]. The shale is gray to black in color and has a high organic content. This formation and the Nkporo Shale are quite similar in composition but are in separate basins and have different geologic histories. The Paleocene Ewekoro, which is fossiliferous limestone and conformably overlies the Araromi Formation, makes up the post-rift (tertiary deposits). The Late Paleocene-Early Eocene Akinbo Formation and Oshosun Formation are composed of clay and shale with interbedded sandstones [7, 15] that underlie the Ewekoro Formation. Kogbe [16] stated that the coarse estuary and continental sand strata that make up the Ilaro and Benin Formations (coastal plain sand) were prevalent. The Oshosun Formation, composed of yellowish, poorly consolidated cross-bedded sandstone, conformably overlies the Ilaro Formation (the investigated formation) [17].

There have been several reports on stratigraphy, sedimentology, paleodepositional environments, biostratigraphy, and petroleum potential in most of the geological formations in the Dahomey Basin. The existing literature pertaining to the assessment of paleoenvironments, source area weathering, and tectonic setting of the Ilaro sandstones in the eastern Dahomey Basin is currently constrained in terms of its extent. Recent works in the Dahomey Basin include that of Adekeye *et al.* [18], Oluwajana *et al.* [19], Adamolekun *et al.* [20], Ogala *et al.* [21], Akaegbobi and Ogungbesan [22]. Sedimentological and geochemical studies on sandstones within the basin include the work of Madukwe [23] and Ikhane *et al.* [24], which focused on provenance, tectonic settings, and the paleoenvironment of deposition. This research utilizes granulometric analysis, along with major, trace, and rare earth element geochemistry, to ascertain the origin, tectonic setting, paleoweathering, paleoclimatic conditions, and paleoenvironmental reconstruction of the Ilaro sandstones located in the eastern Dahomey Basin.

This work will provide background information for geochemical studies and baseline information for the Dahomey Basin. The studied area is southwestern Nigeria, within the eastern portion of the Dahomey Basin. It covers Latitude N $6^0$ 45′12″ and Longitude E $003^0$ 07′44″. In this study, sandstone outcrops were observed and studied in the Ajegunle area. The area was accessed by major roads.

## 2. Methodology

The methodologies utilized in this study involve field studies and laboratory studies. Detailed observations were made in the field, and records of sedimentary features such as thickness, grain size, texture, color, and sedimentary structures of outcropping sediments within the locality of Ajegunle were documented.

### 2.1. Field investigation

The objective of the field investigation was to identify the various rock units and their local relationships. Twelve sandstone samples were collected from various lithological units based on their field relationships and characteristics. Stratigraphic outcrop sections mainly exposed by road cuts were

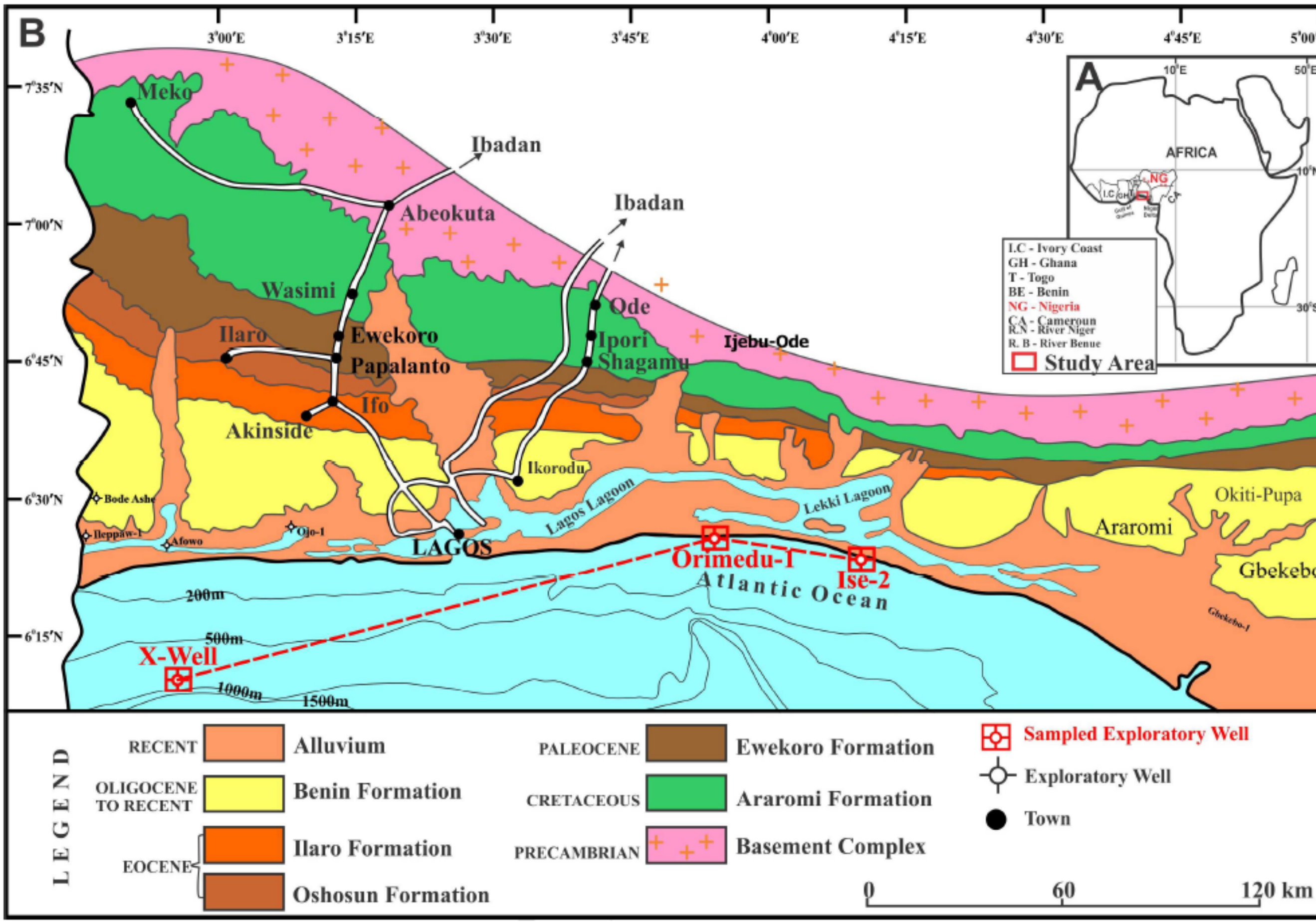


Figure 1. Geological map of Dahomey Basin, Southwestern Nigeria showing the formations and the study area [18].

studied, and fresh samples were carefully collected from the section. Measurements of each bed's thickness were taken along with the collection of fresh chipped samples of each lithological unit, packed in durable sample bags. These samples were labeled accordingly. Thereafter, a lithological section was drawn to show the lithofacies present in the study area (Figure 3).

### 2.2. Laboratory analysis

The laboratory analysis carried out includes grain size analysis, ICP-MS, and petrography. Twelve sandstone samples were analyzed for grain size distribution to determine the sorting, skewness, kurtosis, and graphic mean. Seven sandstone samples were analyzed petrographically to determine the texture and mineral/framework compositions. The present study employed ICP-MS analysis to ascertain the major, trace, and rare-earth elements in a set of five samples. Granulometric and petrographic analyses were conducted at the Sedimentological Laboratory, Department of Geology, Kwara State University, Malete, Nigeria, whereas ICP-MS analyses was carried out at MSA-LAB in Canada. Following the drying process, a sieve analysis was conducted to ascertain the weight retained in relation to the grain size, specifically in relation to the size of the sieve. A total mass of 100 grams was measured for each sample and subsequently distributed across a series of nine (9) interconnected sieves, each possessing distinct aperture sizes spanning from -2.20mm to 4.00mm, with an additional pan. They were arranged in order, with the finest at the bottom and the coarse at the top and set in a vibrator. The vibrator is then switched on to shake the samples in the sieve evenly and distribute them into different sieves based on the size of the grains for 10 minutes. Each sample retained in each sieve is poured into a bowl, weighed, and recorded, ensuring that no grain is stuck in the sieve. I used a brush to get my initial weight of 100 grams.

The grain size analysis findings were utilized to calculate the textural parameters such as mean, standard deviation (sorting), skewness, and kurtosis. The petrographic slides were prepared by the thin-section machine and studied under the microscope. Sandstone samples were dried at $60^oC$ and sieved by 80-mesh size for the ICP-MS analysis. In a steel and puck mill, a 200 g aliquot was divided and ground to 85% passing 200 meshes. ICP-MS equipment was utilized to evaluate the major, trace, and rare earth elements from 0.30 g of rock powder mixed with 1.5 g of $LiBO_2$ dissolved in 100 ml of 5% $HNO_3$.

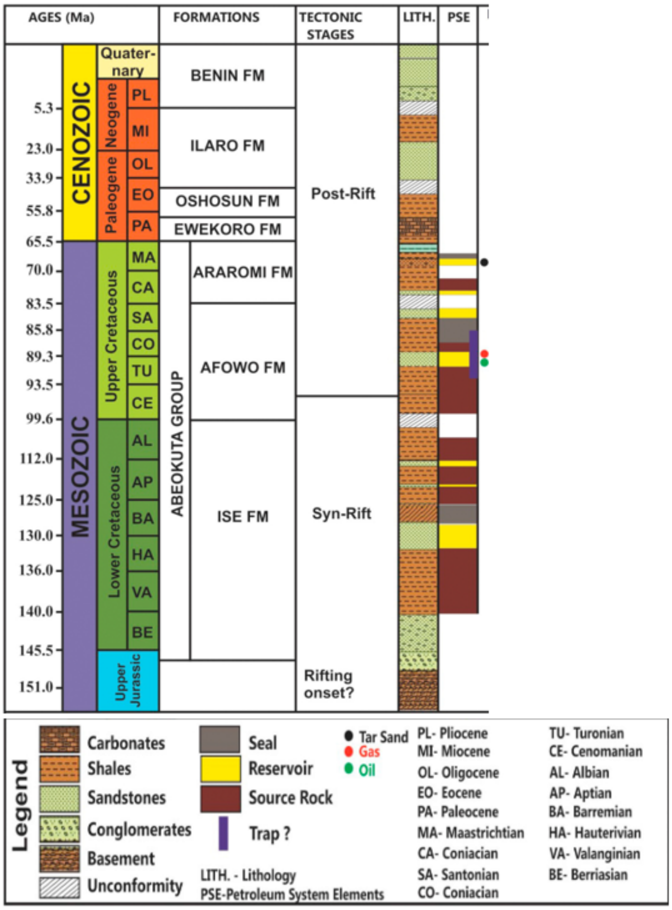


Figure 2. Chronostratigraphic chart of the Dahomey Basin showing the geologic Formations and lithologies [25].

## 3. Results and discussion

The grain size analysis results are presented in Table 1. The grain size distribution, individual weight, cumulative weight, and cumulative weight percentages were determined to construct a histogram and a cumulative frequency curve for each sample. The phi values 5, 16, 25, 50, 75, 84, and 95 were used for the calculation of statistical parameters (Table 1), which were obtained from the cumulative frequency curves. The mean, sorting, skewness, and kurtosis were calculated using the formula by Folk and Ward [26].

### *3.1. Grain size and sorting*

The mean parameter obtained from the grain size analysis of the sandstone of the Ilaro Formation ranges from -0.40 (very coarse sand) to 0.40 (coarse sand), with an average of 0.19 indicating coarse sands (Table 1). Calculated sorting showed that all the analyzed samples were poorly sorted (Table 1). The poorly sorted sandstones are indicative of high-energy environments [27].

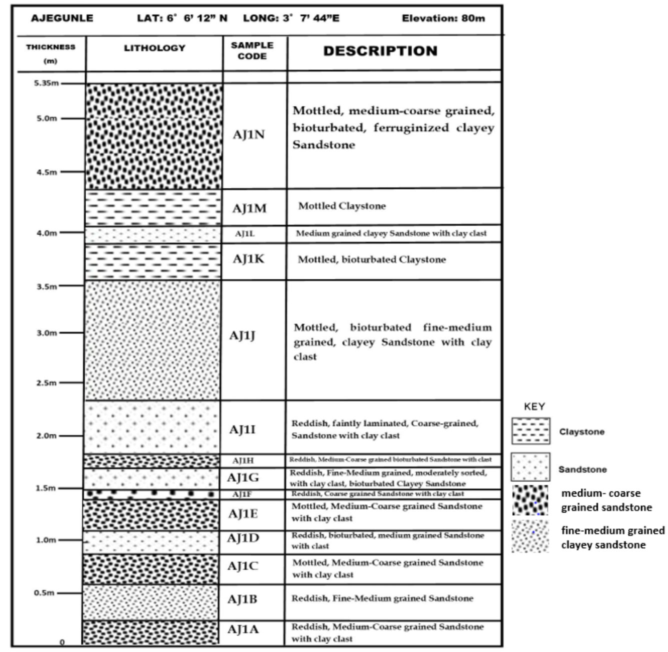


Figure 3. A lithological section of an outcrop exposed at Ajegunle, Ilaro, Ilaro Formation.

### *3.2. Transportation history, sorting, and depositional environment*

River sediment tends to be poorly sorted because the current velocities are very variable at different times. With an average of 1.28, the inclusive graphical standard derivation (ρ) ranges from 1.15 to 1.49, indicating poorly sorted sands (Table 1). Due to the poor sorting, it can be inferred that the sands are river-deposited (Figure 3 and 4). Beach sediments tend to be well sorted because of high current velocities and are said to be texturally immature. The sandstones within the Ilaro Formation exhibit a predominantly coarse skewness on average. According to Friedman [27], the skewness ($Sk_1$) value ranging from -0.87 to 0.29 suggests that the mode of transportation exhibits characteristics associated with high energy and is of fluvial origin. On average, the sandstones of the Ilaro Formation are coarsely skewed. The skewness ($Sk_1$) value of -0.87 to 0.29 indicated that the medium of transportation is suggestive of high energy and is of fluvial origin [27]. The kurtosis ($K_G$) value, as determined through calculations, varies between 0.73 and 1.51, indicating a range from platykurtic to leptokurtic distributions [28]. The average kurtosis value of 1.07 (Table 1) suggests that most of the samples exhibit mesokurtic characteristics. The skewness values obtained for all samples exhibit a near - symmetrical distribution, except for sample AJ1J, which displays a highly negative skew. The scatter plots of mean against sorting (Figure 4) and skewness against kurtosis (Figure 5) show that the sandstones are poorly sorted and are deposited in a fluvial setting.

### *3.3. Major elements geochemistry*

The analyzed samples are composed mainly of silica $SiO_2$, which ranges from 79.01–86.59% (average = 82.9%), and

Table 1. Summary of grain size analysis results for the sandstones of the Ilaro Formation.

| S/N | Sample No | Mean size (Mz) | Sorting (ρ) | Skewness ($Sk_1$) | Kurtosis ($K_G$) |
|---|---|---|---|---|---|
| 1. | AJ1A | 0.25 | 1.2 | 0.03 | 1.1 |
| 2. | AJ1B | 0.3 | 1.15 | 0.04 | 0.95 |
| 3. | AJ1C | -0.2 | 1.17 | -0.87 | 0.73 |
| 4. | AJ1D | 0.24 | 1.17 | 0.06 | 0.98 |
| 5. | AJ1E | 0.2 | 1.25 | 0.003 | 1.1 |
| 6. | AJ1F | -0.4 | 1.13 | 0.29 | 1.51 |
| 7. | AJ1G | 0.2 | 1.3 | 0.03 | 1.12 |
| 8. | AJ1H | 0.35 | 1.22 | 0.03 | 1.23 |
| 9 | AJ1I | 0.3 | 1.42 | 0.04 | 1.21 |
| 10 | AJ1J | 0.33 | 1.48 | -0.03 | 0.96 |
| 11 | AJ1L | 0.4 | 1.49 | 0.03 | 0.91 |
| 12 | AJ1N | 0.28 | 1.43 | 0.06 | 1.09 |
| | Average | 0.19 | 1.28 | -0.02 | 1.07 |

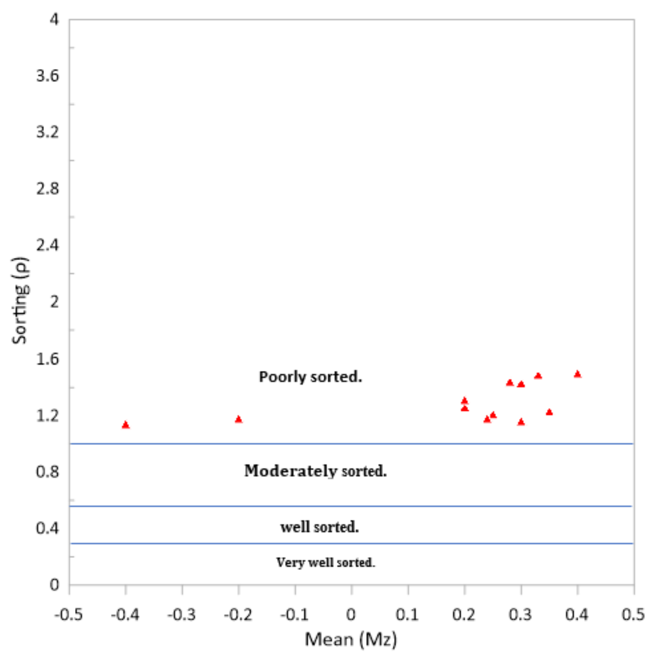


Figure 4. Bivariate plot of sorting vs mean indicating poorly sorted sand [26, 27].

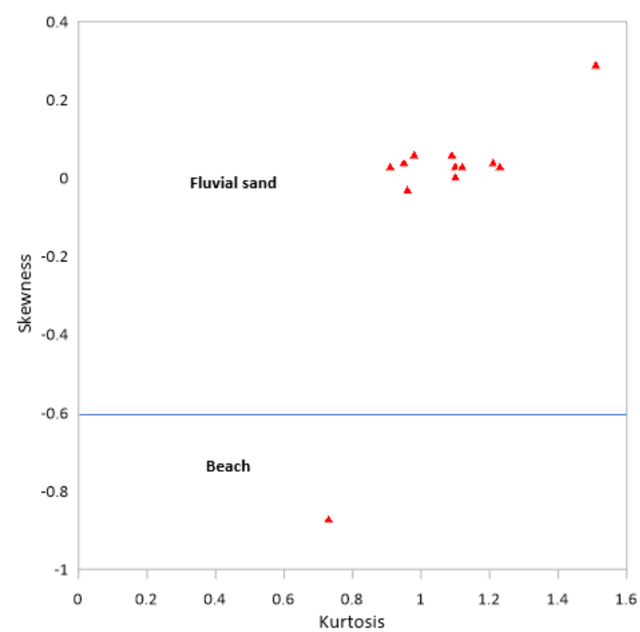


Figure 5. Bivariate plot of skewness vs kurtosis indicating river deposited sands [26, 27].

$Al_2O_3$, which ranges from 7.22-11.43% (average = 9.49%) (Table 2). The observed variation in $SiO_2$ concentration could potentially be attributed to the heterogeneity in grain size and the diagenetic processes affecting the sandstone. The elevated $Al_2O_3$ content can likely be attributed to the presence of lithic fragments within the sandstone. Conversely, the relatively low levels of MgO (mean = 0.03%), $Na_2O$ (mean = 0.03%), and $K_2O$ (mean = 0.04%) in the sandstone are due to chemical degradation occurring under oxidizing conditions during weathering and diagenesis, or potentially originating from the source area. The variation in $SiO_2$ content may be due to the grain size and diagenesis of the sands. The observed negative correlation between $SiO_2$ and $Al_2O_3$, $TiO_2$, MgO, and $Fe_2O_3$ (Figure 6), as well as the negative correlation with CaO, $Na_2O$, and $K_2O$, can be attributed to the significant presence of silica in the form of quartz. The positive correlation between $TiO_2$ and $Fe_2O_3$ with $Al_2O_3$ (Figure 6) indicates a potential association with clay minerals. The $K_2O/Na_2O$ ratio observed in this study exhibited a range of 0.6–6.0, with an average value of 2.78. These findings indicate that minerals containing potassium (K) are slightly more prevalent compared to sodium (Na)-rich plagioclase minerals.

The felsic source provenance is indicated by the $Al_2O_3/TiO_2$ ratio ranging from 12.1 to 22.0 (with an average of 17.2) and the presence of low MgO values. A high concentration of MgO indicates the presence of carbonate minerals, while a low value is attributed to the presence of clay miner-

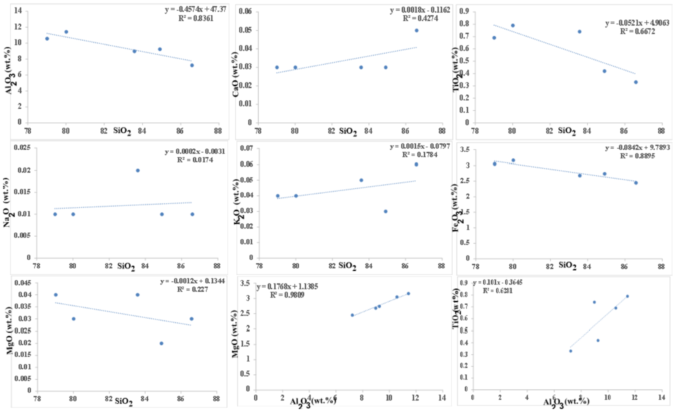

Figure 6. Cross-plots of major oxides against $SiO_2$ of Ilaro Sandstones.

als. The reduction of $Na_2O$ content in the sandstones can be attributed to significant weathering, the recycling of the parent rock, and subsequent removal during transportation [29–31]. The occurrence of moderate $K_2O/Na_2O$ ratios can be linked to the presence of minerals containing potassium, such as K-feldspar, mica, and illite [32–34].

### 3.4. *Trace elements geochemistry*

Table 3 shows the results of trace element geochemistry. The trace element suites had the greatest concentrations of Zr, ranging from 120-549 ppm, with sample AJ1C having the lowest concentration and sample AJ1E having the highest. Cr concentrations vary from 63 to 79 ppm, whereas Pb concentrations range from 6.4 to 325 ppm. Sr has a concentration range of 17-22.9 ppm, with sample AJ1J having the greatest concentration and sample AJ1N having the lowest (Table 3). The concentrations of Th, Zn, and Ni range from 5.34-11.95 ppm, 8-14 ppm, and 7.4-9.5 ppm, respectively. Mo, Cu, Ag, As, U, Au, and Cd are among the other trace elements discovered.

### 3.5. *Geochemical classification*

The geochemical schemes utilized in this study encompass the frameworks proposed by Blatt *et al.* [35], Pettijohn *et al.* [36], Herron [37] and Lindsey [38]. Blatt *et al.* [35] introduced a ternary diagram to illustrate the composition of the studied samples, revealing sodic sandstones (Figure 7). The scheme proposed by Pettijohn *et al.* [36] and Lindsey [38] indicated most of the sandstones are arkose, as depicted in Figure 8 and 9. According to Herron [37] classification, the sandstones were categorized as Fe-sands based on the plot of log ($SiO_2/Al_2O_3$) versus log ($Fe_2O_3/K_2O$) (Figure 10).

### 3.6. *Provenance and tectonic setting*

Hayashi *et al.* [39] employed Zr concentration to describe the type and composition of source rocks. The $TiO_2$-Zr diagrams (Figure 11) aid in differentiating three distinct source rock types: mafic, felsic, and intermediate. The Ilaro sandstones were most likely derived from intermediate rocks and acid source rocks, respectively, according to the plots of $TiO_2$ vs Zr and $TiO_2$ versus Ni (Figure 11 and 12). A plot of Th/Yb

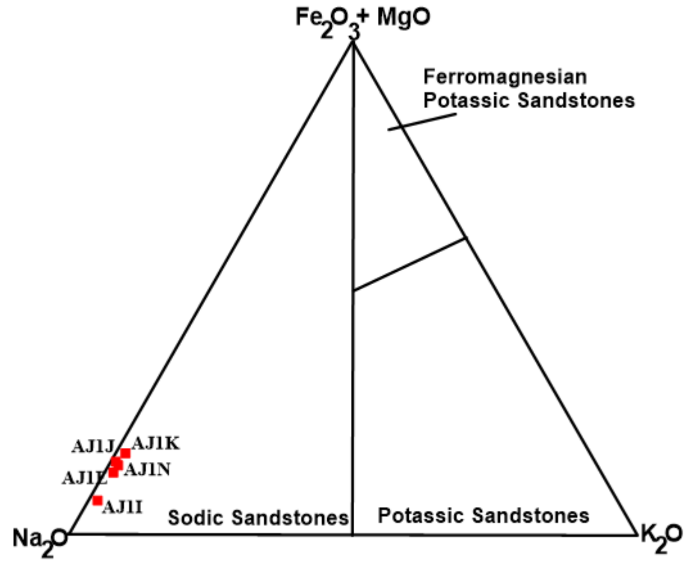


Figure 7. Ternary diagram of $Na_2O$-$K_2O$-($Fe_2O_3$+MgO) of the Ilaro sandstone [35].

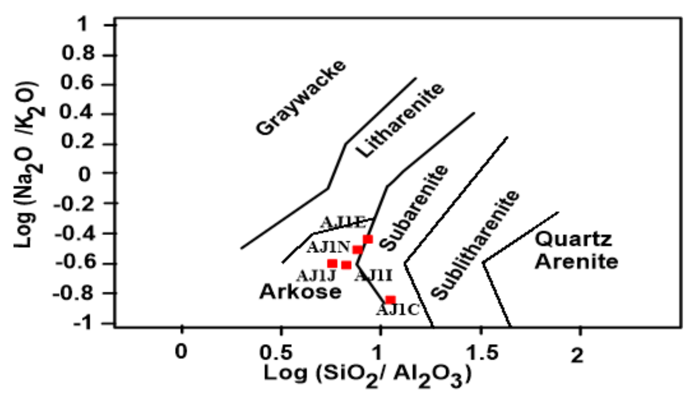


Figure 8. Plot of log ($SiO_2/Al_2O_3$) vs log ($Na_2O/K_2O$). The sandstones plotted under Arkose [36].

versus Ta/Yb (Figure 13) indicates the tectonic setting of active continental margins. The $TiO_2$ vs. $Al_2O_3$ plots (Figure 14) showed that basalt and granite rocks were the main sources of the sediments. For the investigation of origin and tectonic context, several trace elements have been shown to be highly helpful [2, 40] due to poor mobility and short residence time in sea water. Elements including La, Ce, Nd, Hf, Th, Zr, Sc, Nb, and Y are the most helpful in determining provenance and tectonic setting [41, 42].

Low Cr concentrations indicate sediments from felsic rocks, whereas high Cr and Ni concentrations indicate sediments derived from ultramafic rocks [43]. In this study, the Cr concentration is comparatively low in all samples, suggesting that the sandstones originated from felsic igneous rock. According to McLennan *et al.* [44], Y/Ni and Cr/V ratios can also be utilized to confirm provenance. According to Table 3, the Cr/V ratios in this study range from 1.24 to 1.97, while the Y/Ni ratios range from 0.59 to 1.12. This assumes that the examined sandstones originated from felsic sources [44].

Table 2. Geochemical composition of Major oxides and ratios for Ilaro sandstones

| S/N | Sample | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | BaO | MgO | $Na_2O$ | $K_2O$ | MnO | $TiO_2$ | $P_2O_5$ | $Cr_2O_3$ | LOI | $K_2O/Na_2O$ | $Al_2O_3/TiO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| unit | | % | % | % | % | % | % | % | % | % | % | % | % | % | % wt | % |
| | | wt | wt | wt | wt | wt | wt | wt | wt | wt | wt | wt | wt | wt | | wt |
| 1 | AJ1C | 86.59 | 7.22 | 2.45 | 0.05 | <0.01 | 0.03 | 0.01 | 0.06 | <0.01 | 0.33 | 0.03 | <0.01 | 26.78 | 6 | 21.9 |
| 2 | AJ1E | 83.85 | 8.98 | 2.68 | 0.03 | <0.01 | 0.04 | 0.02 | 0.05 | 0.02 | 0.74 | 0.02 | 0.01 | 20.54 | 2.5 | 12.1 |
| 3 | AJ1I | 79.01 | 10.57 | 3.05 | 0.03 | <0.01 | 0.04 | 0.01 | 0.04 | 0.01 | 0.69 | 0.03 | 0.01 | 21.58 | 4 | 15.3 |
| 4 | AJ1J | 80.01 | 11.43 | 3.16 | 0.03 | <0.01 | 0.03 | 0.05 | 0.04 | 0.01 | 0.79 | 0.03 | 0.01 | 27.86 | 0.8 | 14.5 |
| 5 | AJ1N | 84.91 | 9.25 | 2.74 | 0.03 | <0.01 | 0.02 | 0.05 | 0.03 | <0.01 | 0.42 | 0.02 | <0.01 | 23.65 | 0.6 | 22.0 |
| | Average | 82.9 | 9.49 | 2.82 | 0.03 | - | 0.03 | 0.03 | 0.04 | - | 0.04 | 0.59 | 0.03 | 24.1 | 2.78 | 17.2 |

Table 3. Geochemical composition of trace elements (ppm) of Ilaro sandstone.

| S/N | Sample | Mo | Cu | Pb | Zn | Ag | Ni | Cr | As | U | Au | Th | Sr | Cd | Zr | Sn | La | V | Y/Ni | Cr/V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| unit | | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | ppm | | |
| 1 | AJ1C | 9.51 | 0.07 | 8.2 | 14 | 0.03 | 8.7 | 63 | 1.1 | 1.02 | 0.001 | 5.34 | 18.5 | 0.07 | 120 | <5 | 18.7 | 32 | 0.59 | 1.97 |
| 2 | AJ1E | 9.19 | 0.03 | 325.1 | 14 | 0.15 | 9.5 | 79 | 1 | 1.5 | 0.0016 | 11.95 | 17.2 | 0.03 | 549 | <5 | 26.8 | 44 | 1.09 | 1.80 |
| 3 | AJ1I | 23.61 | 0.07 | 6.4 | 12 | 0.03 | 8.9 | 73 | 1.1 | 1.24 | 0.0006 | 10.63 | 21.2 | 0.07 | 332 | <5 | 28.1 | 51 | 1.02 | 1.43 |
| 4 | AJ1J | 7.32 | 0.05 | 6.6 | 12 | 0.04 | 8.1 | 72 | 1.3 | 1.24 | <0.0005 | 11.09 | 22.9 | 0.05 | 360 | <5 | 29.8 | 58 | 1.12 | 1.24 |
| 5 | AJ1N | 6.49 | <0.01 | 51.4 | 8 | 0.04 | 7.4 | 70 | 1.2 | 0.93 | <0.0005 | 5.62 | 17 | <0.01 | 148 | <5 | 23.5 | 43 | 0.92 | 1.62 |

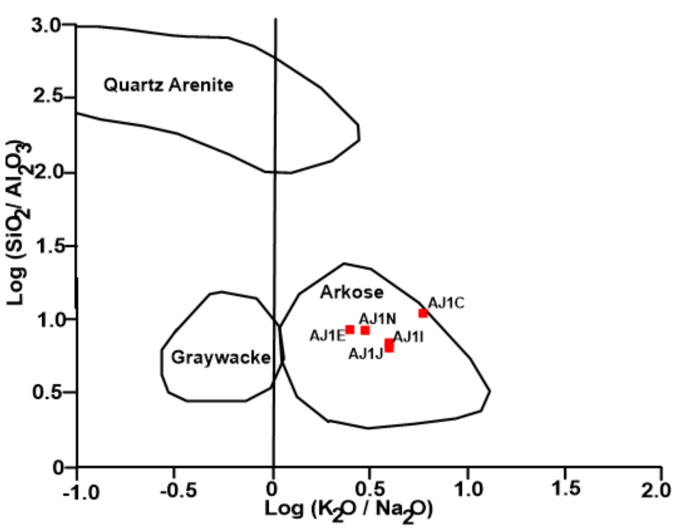


Figure 9. Plot of log ($SiO_2/Al_2O_3$) versus log ($K_2O/Na_2O$). Ilaro sandstone plotted in the arkose field [38].

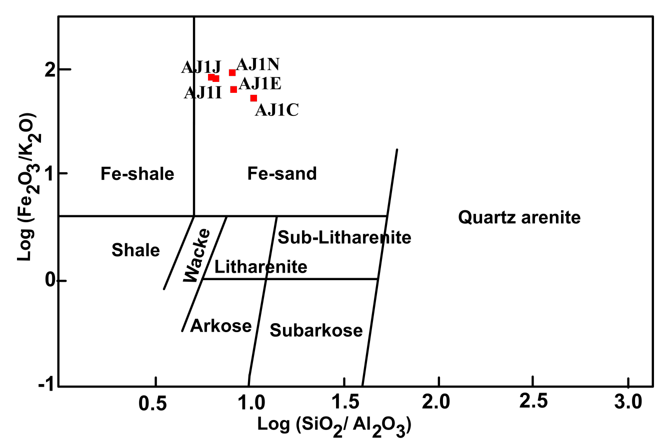


Figure 10. Plot of ($SiO_2/Al_2O_3$) vs. log ($Fe_2O_3/K_2O$). The sandstones were classified under Fe- sand [37].

### 3.7. *Paleoclimate and paleoenvironments*

Using major and trace element geochemistry, the paleoredox condition of the sandstones was determined. The accumulation of some trace metals in sediments can reveal the redox conditions during deposition [45]. Fe/Al, V/Ni, and $SiO_2$ vs. $A_2O_3$+$K_2O$+$Na_2O$ ratios have been utilized to assess paleoredox conditions [46]. The plot of V against Ni (Figure 15) indicates the sediments were formed in an oxic-dyoxic environment, whereas the plot of Fe/Al (Figure 16) indicates an oxic condition. The plot of $SiO_2$ versus $Al_2O_3$+$K_2O$+$Na_2O$ (Figure 17) revealed that the Ilaro sandstones were formed under humid conditions. Climate and rates of tectonic uplift influence the degree of chemical weathering [30]. The increasing intensity of chemical weathering suggests decreasing tectonic activity [47]. From this study, the climate shift toward warmer and more humid conditions indicates chemical weathering at the source area. The paleoenvironmental and paleoclimatic reconstructions suggest that the Ilaro sandstone was deposited in oxic-dyoxic, non-marine conditions. The sandstones of Ilaro are non-marine and deltaic (Figure 18). The depositional environment of the Ilaro sandstones was also deduced using the ternary diagram [48]. This entails chemical classification based on the elements of ($Al_2O_3$), ($K_2O$ + $Na_2O$ + CaO), and ($Fe_2O_3$ + MgO) (AKF). The samples plotted in Figure 19 are depicted in the continental zone, implying a non-marine and deltaic environment.

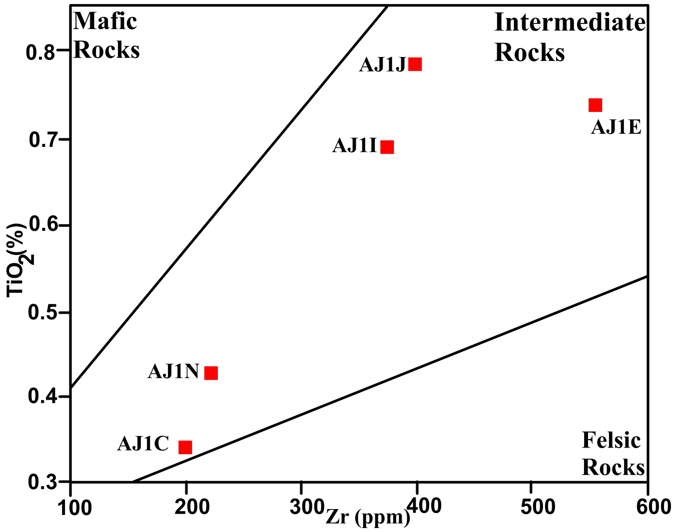


Figure 11. $TiO_2$-Zr plot for the Ilaro sandstones showing provenance from intermediate rocks after [39].

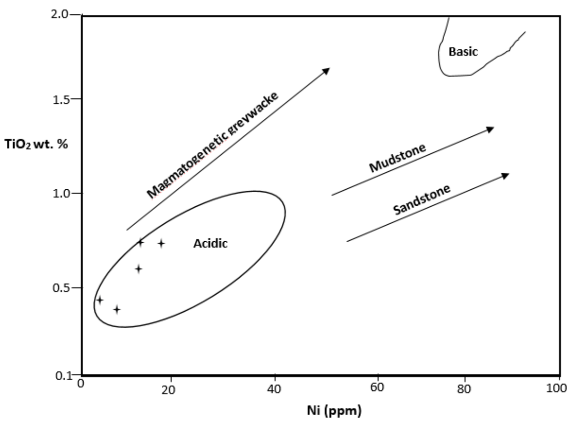


Figure 12. Bivariate plots of $TiO_2$ against Ni for the Sandstones indicating acid source provenance [49].

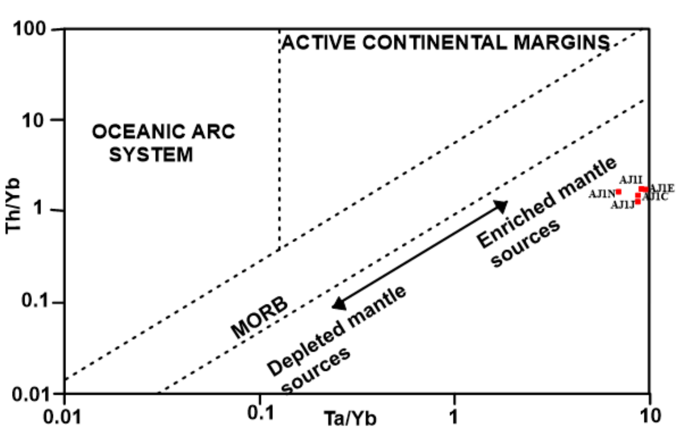


Figure 13. Plot of Th/Yb vs. Ta/Yb. The sandstones were from enriched mantle source [50].

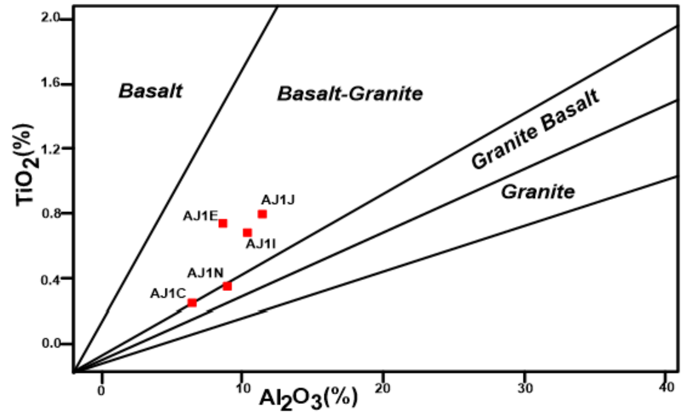


Figure 14. Provenance diagram of $TiO_2$ versus $Al_2O_3$ in study area shows Basalt-Granite field [39].

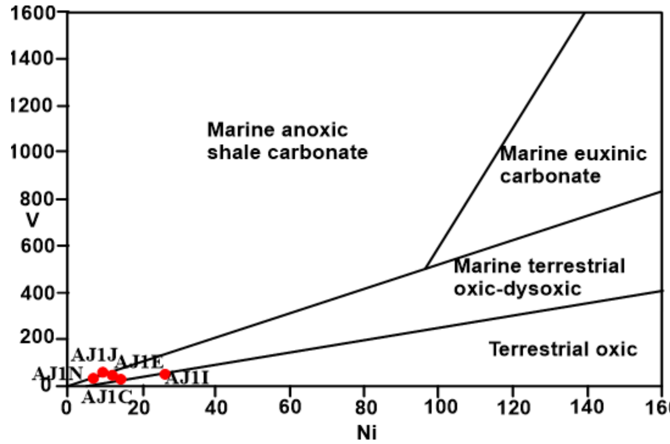


Figure 15. Bivariate plot of vanadium (V) versus nickel (Ni) of the Ilaro sandstone indicating terrigenous and marine source inputs and were deposited under oxic-dysoxic conditions [46].

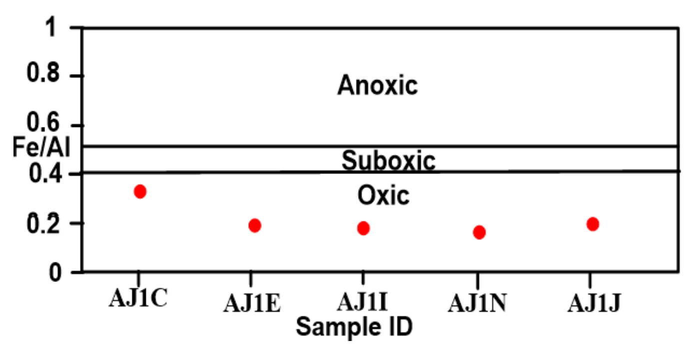


Figure 16. Fe/Al plot of the Ilaro sandstones indicating oxic deposition adapted from [51].

### 3.8. *Tectonic settings and paleoweathering*

The geochemical composition of Ilaro sandstones was employed to infer the origin and plate tectonic setting. The plots of ($Fe_2O_3$ + MgO) vs $TiO_2$, ($Fe_2O_3$ + MgO) vs ($K_2O$+$Na_2O$) and ($Fe_2O_3$ + MgO) vs ($Al_2O_3$ / $SiO_2$) (Figure 20) discrimination of the sandstones showed most of the sandstones were deposited in the passive margin, while few plotted within the

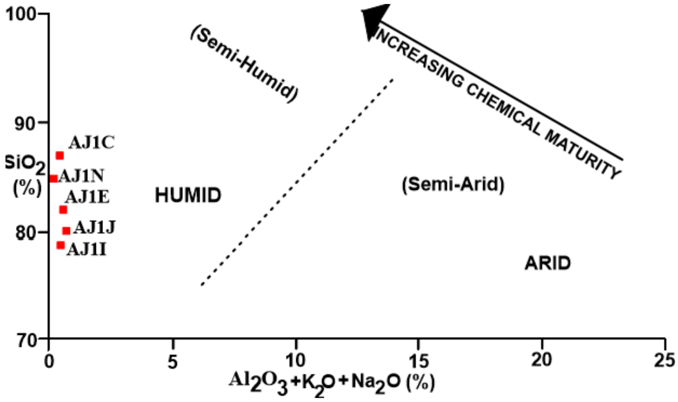


Figure 17. Bivariate plot of $SiO_2$ vs. ($Al_2O_3$ + $K_2O$ + $Na_2O$). The sandstones were deposited in humid paleoclimatic condition [52].

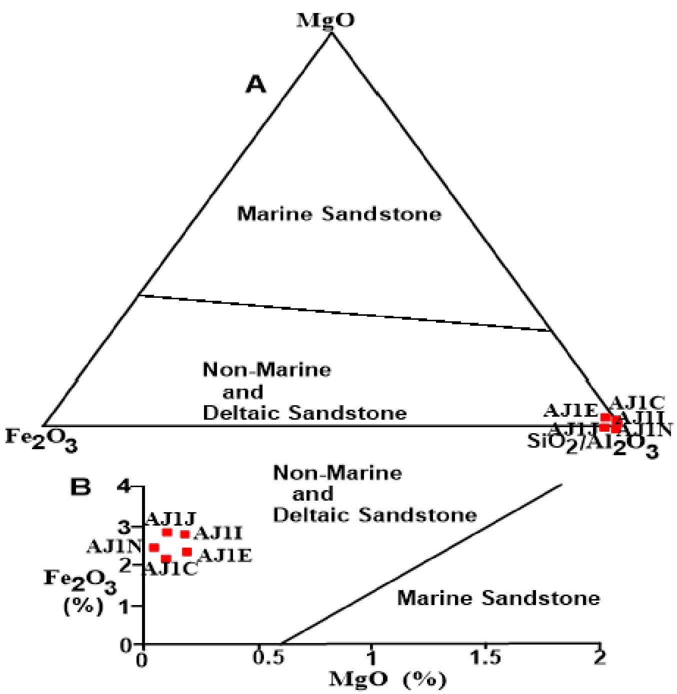


Figure 18. Ternary diagram indicates the sandstones are non-marine. (B) Plot of $Fe_2O_3$ against MgO also indicates non marine sands [53].

active margin region. Sandstones derived from active continental margins are thought to reflect the composition of the Upper Continental Crust [1], whereas sediments from passive continental margins are mature and are typically deposited within intracratonic basins or continental margins [54, 55]. According to the work of Crook [56], the ratio of $K_2O/Na_2O$ versus $SiO_2$ diagram (Figure 21) indicates that the sediments were deposited in passive margin environments. When the sandstone samples were plotted on the $SiO_2/Al_2O_3$ versus $Na_2O/K_2O$ diagram (Figure 22), the same pattern were observed**.** The paleoweathering indices CIA (Chemical Index of Alteration), ICV (Index of Compositional Variability), and CIW (Chemical Index of Weathering) were used to determine the intensity of chemical weathering and compositional maturity of the sandstones. The greater the value of these indices (0 to 100), the

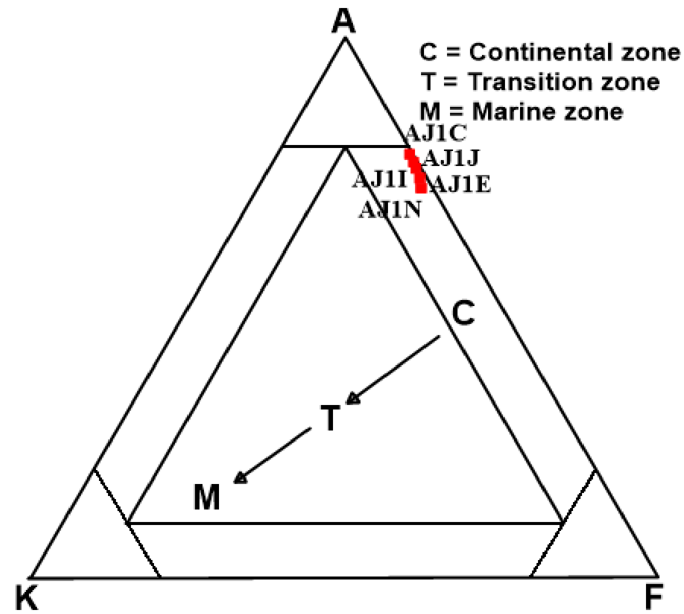


Figure 19. Plot of ($Al_2O_3$) - ($K_2O$+$Na_2O$+CaO) - ($Fe_2O_3$+MgO) (A-K-F) ternary diagram for the Ilaro sandstones [48].

more intense the chemical degradation in the source regions [3, 57]. In this study, the CIA values range between 98.63 and 99.63, which indicates intensive chemical weathering (Table 4). Also, the CIW ranges between 98.54% and 99.38%, suggesting intense weathering. The CIA values were plotted in an A-CN-K (A=$Al_2O_3$; CN = CaO+Na2O; K=$K_2O$) ternary diagram (Figure 23). All the samples fall above the plagioclase-feldspar line and cluster towards the illite area in the A-CN-K plot. This indicates intense weathering (Figure 23). The observed relationship between Th/U and Th in the plot provides further evidence of significant weathering originating from the upper continental crust, as depicted in Figure 24.

Similarly, the ICV values are greater than 1 (Table 4), indicating intense chemical weathering. Therefore, the Ilaro sandstones are compositionally immature and were deposited within the craton. The PIA (Plagioclase Index of Alteration) is between 99.42% and 99.75% and plots towards the $Al_2O_3$-$SiO_2$ edge, indicating a high degree of weathering. The Ruxton ratios also confirm that the sandstones are highly weathered.

### *3.9. Petrographic composition*

The result of the petrographic study shows the minerals present in the analyzed samples. The studied sandstones consist predominantly of abundant quartz grains, with an average of 67%. It is the main framework mineral. Other minerals include opaque minerals with an average content of less than 6%, muscovite (average 1%), and ferruginized ground mass (25.7%). Most of the quartz grains exhibit a combination of monocrystalline and polycrystalline structures. These grains are characterized by angular to sub-angular shapes and are found within a ground mass that has undergone ferruginization, as shown in Figure 25.

Table 4. Weathering Indices of selected sandstones samples.

| Sample code | CIA | CIW | ICV | PIA | Ruxton Ratio |
|---|---|---|---|---|---|
| AJ1C | 98.63 | 98.54 | 97.26 | 99.51 | 20.35 |
| AJ1E | 98.97 | 99.04 | 97.94 | 99.56 | 15.79 |
| AJ1I | 99.59 | 99.33 | 99.19 | 99.71 | 12.69 |
| AJ1J | 99.63 | 99.38 | 99.26 | 99.42 | 11.88 |
| AJ1N | 99.40 | 99.24 | 98.81 | 99.75 | 15.58 |

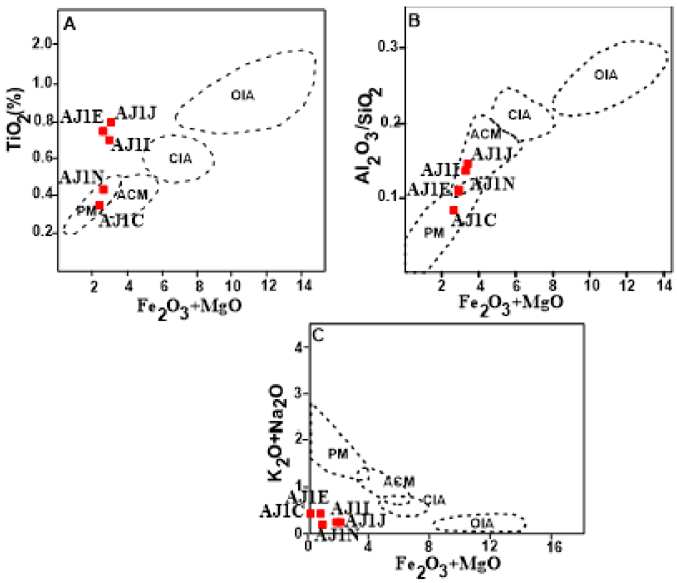


Figure 20. Tectonic discrimination plots of Bhatia [1]. Note: OIA- Oceanic Island Arc, CIA- Continental Island Arc, ACM- Active Continental Margin, PM- Passive Continental Margin.

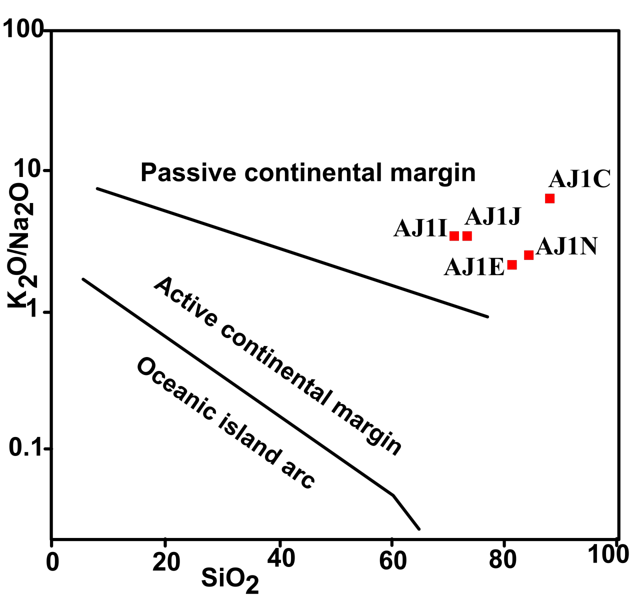


Figure 21. Plot of $K_2O/Na_2O$ versus $SiO_2$. The sandstones plotted in the passive continental margin after [55].

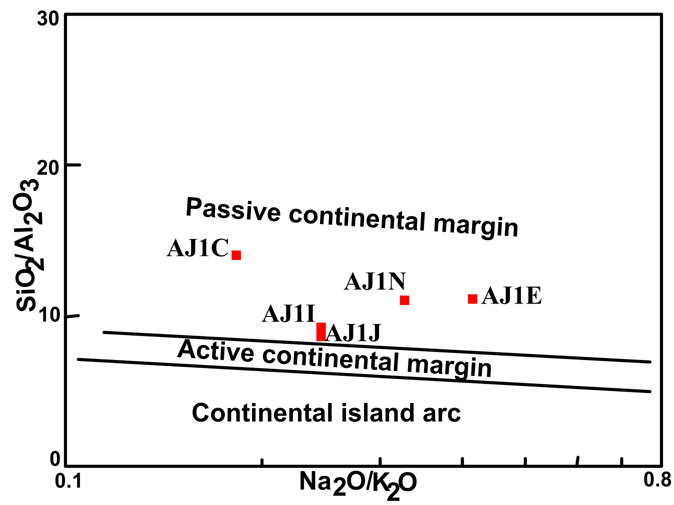


Figure 22. Plot of $SiO_2/Al_2O_3$ versus $Na_2O/K_2O$ tectonic setting discrimination diagram. The sandstones fall in the Passive continental margin after [55].

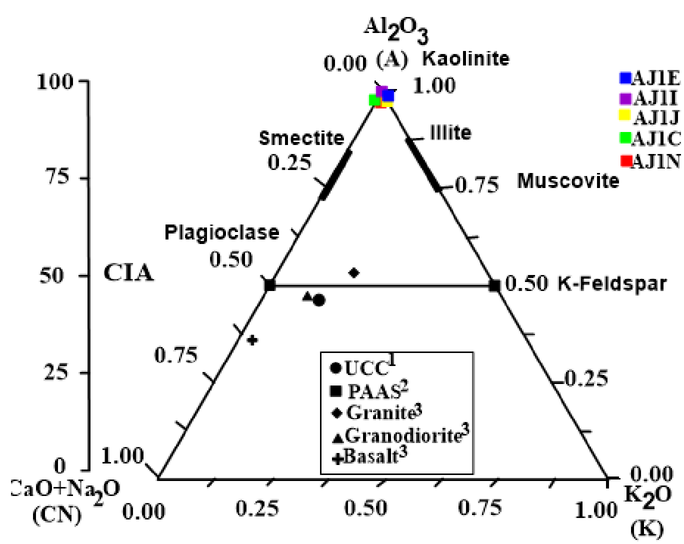


Figure 23. A-CN-K plot showing the weathering trend of the studied samples after [3].

### 3.9.1. Provenance and transportation history

The monocrystalline quartz grains suggest an igneous source, while the polycrystalline grains suggest a metamorphic source. The presence of monocrystalline and polycrystalline

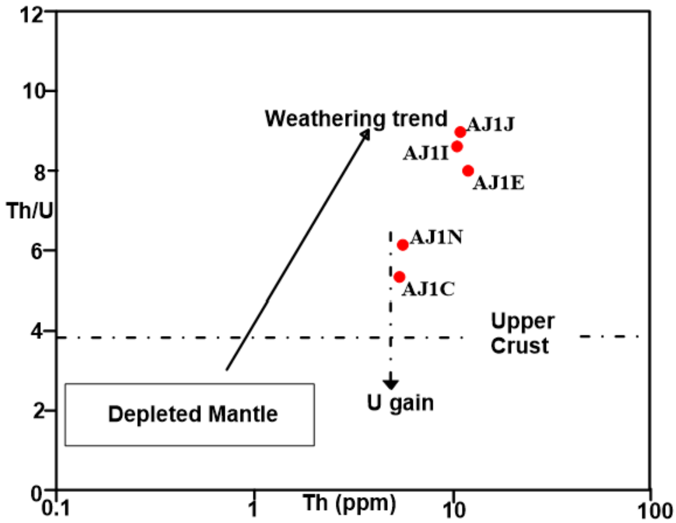


Figure 24. Th/U vs. Th plot indicating sandstones are highly weathered and derived from upper continental crust for the Ilaro sandstones after [44].

quartz grains was observed in samples AJ1C, AJ1E, AJ1F, and AJ1N (Figure 25). Hence, the sediments could be inferred to have both igneous and metamorphic sources. The sediments could be inferred to have been deposited in proximity to the source rock because the examination of the petrographic slides showed that the quartz minerals are angular to sub-angular, indicating a short distance of travel from the source.

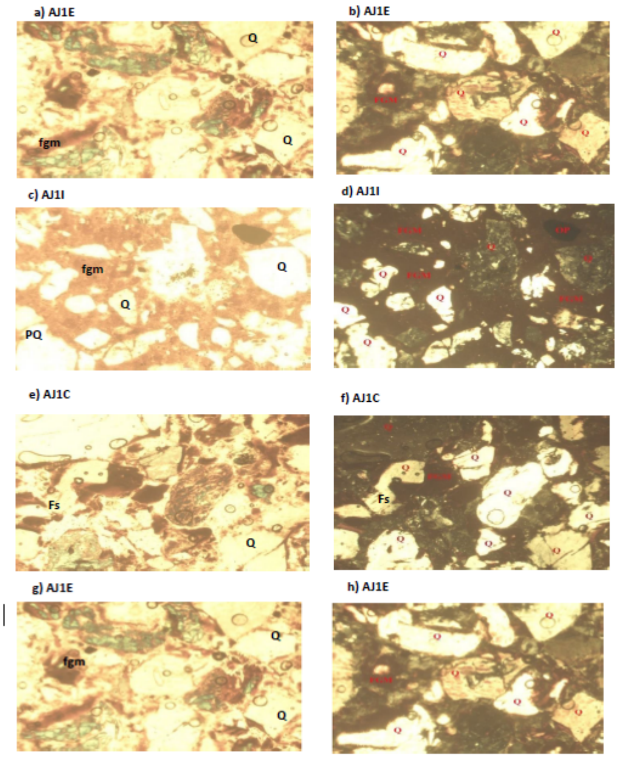


Figure 25. a-h (Plane polarized and Cross polarized photomicrographs of selected sandstone samples) (Q-quartz, Fgm-Ferruginised ground mass, Fs- feldspar, Pq-polycrystalline quartz).

## 4. Conclusion

In conclusion, the sandstones exhibit a coarse-grained texture, display poor sorting, are texturally immature, and have skewed values that are predominantly nearly symmetrical, indicating that the sandstones were deposited by fluvial processes. The sandstones in the studied area have an average composition of $SiO_2$ (82.87%); $Al_2O_3$ (9.49%) makes up > 90%, while MgO, CaO, $Na_2O$, $K_2O$, and $P_2O_5$ are 1% each. Based on the chemical classification (major oxide ratio), the sandstones were classified as predominantly Fe sand, sub-arenite, and arkose and have been subjected to intense chemical weathering. The average $Al_2O_3/TiO_2$ ratio suggests intermediate or acid source rock for Ilaro sandstones. The redox indicators used suggested the sediments were deposited in a non-marine environment under oxygenated conditions. Discrimination diagrams provided evidence suggesting that the sandstones under investigation predominantly originated from passive margin tectonic settings. The studied sandstones consist predominantly of abundant quartz grains (67%), opaque minerals (6%), muscovite (1%), and ferruginized ground mass (25.7%). The petrographic analysis showed that quartz minerals are angular to sub-angular, indicating a short distance of travel for the sediments from the provenance. The sandstones are texturally immature to sub-mature.

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