

Providing Clues on the Paleo-weathering of Ogwashi Asaba Formation, Niger Delta Basin: Evidence from Geochemistry

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Abstract

Representative outcrop samples of sandstones belonging to the Ogwashi-Asaba Formation, Niger Delta, were investigated using geochemical proxies. The purpose was to appraise the paleo-weathering as well as to infer the paleoclimatic conditions that prevailed during their deposition. The sediments are geochemically classified as sublithic arenites, quartz arenites, and Fe- sands. The relative depletion of most major elements in the sandstones suggests high mobility during weathering processes. High values of weathering indices such as Chemical Index of Alteration (CIA: 95.21–95.90; 95.65 ± 0.24), Chemical Index of Weathering (CIW: 96.01–96.64; 96.43 ± 0.22), Plagioclase Index of Alteration (PIA: 95.98–96.61; 96.40 ± 0.22), Mineralogical index of alteration (MIA): 90.42–91.79, 91.29 ± 0.48) and low values of the Weathering index of Parker (WIP): 13.37 – 19.08; 17.04 ± 2.59) suggests intense weathering in the source area. The intense degree of weathering was further affirmed by the Al_2O_3 -(CaO+Na₂O)-K₂O ternary relationship and the CIA versus SiO₂ correlations. A warm/humid climate is suggested for the sandstones based on the CIA values and the SiO₂ vs. ($\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$) correlation, which is widely used for paleoclimatic studies. Weathering indices that include iron in their calculations were not included in this investigation since they do not distinguish between ferric and ferrous iron.

Keywords: Paleo-weathering, Weathering indices, Major oxides, Niger Delta, Ogwashi-Asaba Formation

1. Introduction

The bulk chemical composition of sedimentary rocks can be used as tools to infer the factors that controlled sediment characteristics during and after their deposition. The geochemical record of siliciclastic sedimentary rocks is affected by many factors such as chemical weathering, transport distance, sorting processes during transport, sedimentation, and post-depositional diagenetic reactions (McLennan, 1989; Bauluz 2000). If the influence of these factors is minimal, the geochemical signatures of the rock will reflect the nature and proportion of their detrital components and hence can provide clues on source area weathering, source rocks, tectonic settings, climate, relief, and slope of the source areas (e.g., Bhatia, 1983; McLennan et al., 1993; Cullers, 2000; Gu et al., 2002; Armstrong-Altrin et al., 2004; Hofmann, 2005; Paikaray et al., 2008; Hofers et al., 2013; Tao et al., 2014; Madhavaraju et al., 2016; Ramachandran et al., 2016; Maharana et al., 2018; Tang et al., 2020).

Weathering in the source area is an important process that influences the composition and genesis of sedimentary rocks by dislodging mineral grains from parent rocks for erosion and sedimentation processes. Chemical weathering is generally limited to the interactions between the waters derived directly from precipitation (generally rainwater containing organic and inorganic acids derived from the decay of litter in the soil zone) and rocks and their weathering residues (Nesbitt and Young, 1984, 1989). This definition ignores reactions that take place between permanent or perched groundwaters and rocks (or residues). Interactions between groundwaters, rocks, and the materials of the weathering profile are termed diagenetic processes. Chemical weathering intensely affects the major element geochemistry and mineralogy of sediments (Nesbitt and Young, 1982; Johnsson et al., 1988; McLennan, 1993). Elements such as Na, K and Ca are largely removed from source rocks during chemical weathering. The amount of these

elements surviving in soil profiles and sediments derived from them are sensitive indicators of the intensity of chemical weathering (Nesbitt et al., 1997). If the rocks are free from alkali related post-depositional modifications, then their alkali contents ($K_2O + Na_2O$) and K_2O/Na_2O ratios can provide useful clues on the intensity of weathering of source in source areas (e.g., Lindsey, 1999). However, one major constraint in interpreting the intensity of weathering is the discriminations of compositional features that may be connected to the climatic influence on newly formed sediments from others that resulted from the reworking of previous cycle sedimentary units with their weathering histories (Cox et al., 1995; Gaillardet et al., 1999; Bauluz et al., 2000).

The lignite-bearing Ogwashi-Asaba Formation, which is the surface equivalent of the Agbada Formation, has received considerable attention from various authors; however, very little has been forthcoming about paleo-weathering signatures of the sediments that constitute its lithic fill. The current study is focused on the application of geochemical signatures to unravel the source area weathering and paleoclimatic signatures of the Ogwashi Asaba Formation, Niger Delta Basin. This research presents an improved understanding of the area, particularly from a geochemical perspective, while taking into cognizance the discriminative compatibility of various weathering indices.

1.1 Background

Previous studies (e.g., Price and Velbel 2003; Madhavaraju et al., 2016., Periasamy and M Venkateshwarlu, 2017; Bal-Akkoca et al. 2019., Sengun and Koralay, 2019., Ghosh et al., 2020) have utilized various indices to decipher weathering in the source area. Weathering indices reflect the effects of climate on the weathering of parent rocks, characterise neotectonic-related transformation,

quantify the properties of the regolith, and allow for a better explanation of elemental mobility during weathering processes (Neall, 1977; Fedo et al., 1996; Sharma and Rajamani, 2000). The ideal index should permit comparison of studies carried out at different locations, on various materials, and in weathering profiles of different ages (Price and Velbel, 2003). The index should also be easy to apply and based on elements commonly found in surface environments (Harnois, 1998). The criteria for evaluating various weathering indices are discussed in Price and Velbel (2003). The weathering indices utilized in this research are discussed below. It is noteworthy to mention that weathering proxies that include iron in their calculations were not included in this study, because they cannot distinguish between ferric and ferrous iron.

1.1.1 Chemical Index of Alteration (CIA)

The Chemical Index of Alteration (CIA) introduced by Nesbitt and Young (1982), illustrates the ratio of Al_2O_3 (assumed to be immobile during weathering) to the mobile cations Na^+ , K^+ , and Ca^{2+} (Bahlburg and Dobrzinski, 2011). High CIA values suggest the depletion of mobile Ca^{2+} , Na^+ , and K^+ cations during weathering in relative to immobile components (Al^{3+} , Ti^{4+}) (Nesbitt and Young, 1982). Its low values indicate a lack of chemical alterations and cool and/or arid climate conditions (Fedo et al., 1995). High CIA value (up to 100) is suggestive of kaolinite weathering. CIA values for Illite range between 75-90, muscovite is 75, and feldspars are 50. Fresh basalts exhibit CIA values in the range of 30–45, and fresh granites and granodiorites 45–50 (Nesbitt and Young, 1982; Fedo et al., 1995). Since CIA is interpreted as a measure of the extent of conversion of feldspars (which dominate the upper crust) to clays such as kaolinite (Nesbitt and Young, 1984, 1989; Fedo et al., 1995; Maynard et al., 1995), it has been utilized in various paleosol studies

(e.g., Sutton et al., 1990; Sutton and Maynard, 1992, 1993; Gall, 1994). CIA calculations involve K_2O , which is a mobile oxide. This limits its application to sediments in which potassium has been leached. CIA is computed as $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where Al_2O_3 , CaO , Na_2O , and K_2O are in molar proportions and CaO^* is restricted to the amount of CaO incorporated in the silicate fraction only

1.1.2 Chemical index of weathering (CIW)

The chemical index of weathering (CIW) proposed by Harnois (1988) is similar to the CIA; however, K_2O is removed from the equation. It is also an evaluation of the extent of conversion of feldspars to clays (Nesbitt and Young, 1984, 1989; Fedo et al., 1995; Maynard et al., 1995). The CIW prevents the issues related to the remobilization of K during diagenesis or metamorphism. During computation of CIA, since aluminium associated with potassium feldspars is not considered, the values may be very high in rocks rich in K-feldspar, regardless of whether they are chemically weathered or not (Fedo et al., 1995). The CIW is expressed as $CIW = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O)] \times 100$, where Al_2O_3 , CaO , and Na_2O are in molar proportions and CaO^* is limited to the CaO in the silicate fraction only.

1.1.3 Plagioclase index of alteration (PIA)

The Plagioclase Index of Alteration (PIA) was proposed by Fedo et al. (1995) as an alternative to the CIW. Since plagioclase is abundant in silicate rocks and dissolves relatively rapidly, the PIA may be used when plagioclase weathering needs to be monitored (Fedo et al., 1995). PIA monitors and measures progressive weathering of feldspars to clay minerals (e.g., Fedo et al., 1995; Armstrong-Altrin et al., 2004). Completely altered materials (e.g., kaolinite, gibbsite) have a maximum PIA value of 100, whereas unweathered

plagioclase has a PIA value of 50. The PIA is calculated using the relationship; $PIA = [(Al_2O_3 - K_2O) / (Al_2O_3 + CaO^* + Na_2O - K_2O)] \times 100$, where CaO^* is the CaO residing only in the silicate fraction while Al_2O_3 , CaO , Na_2O , and K_2O are in molar proportions.

1.1.4 Mineralogical index of alteration (MIA)

The mineralogical index of alteration (MIA) was suggested by Voicu *et al.* (1997). The index reveals the degree of weathering for each analysed sample independent of the depth of sampling. MIA value of 100 % means complete weathering of a primary material into its equivalent weathered product (Voicu and Bardoux, 2002). Other values indicate incipient (0-20%), weak (20-40%), moderate (40-60%), and intense to extreme (60-100%) weathering. The mineralogical index of alteration is computed using the relationship; $MIA = 2 * (CIA - 50)$.

1.1.5 Weathering Index of Parker (WIP)

The Weathering Index of Parker was introduced by Parker (1970), and the index is based on the mobility of elements such as sodium, potassium, magnesium, and calcium (alkali and alkaline earth metals) during weathering processes. These elements are the most mobile of the major elements; hence there is no need to assume that sesquioxide concentration remains roughly constant during weathering (Price and Velbel, 2003). The WIP is useful for evaluating changes in the amount of Na^+ , K^+ , Ca^{2+} , and Mg^{2+} cations, if the alteration of feldspars into clay minerals is the major chemical (hydrolytic) weathering process, and there are similar mobilities between the major cations (Parker, 1970). Moreso, the WIP is suitable for the assessment of weathering of rocks where hydrolysis is the main weathering process (Gupta and Rao, 2001). Parker (1970) applied the WIP to acid, intermediate and basic igneous rocks; however, since the index relies solely on

the mobile alkali and alkaline earth, its application to intensely weathered materials (i.e., sedentary ferricretes and bauxites) is quite uncertain (Eswaran et al., 1973). Smaller values of WIP suggest stronger chemical weathering, which is opposite to how CIA values are interpreted. The Weathering Index of Parker is calculated using the relationship; $WIP = 100 [(2Na_2O / 0.35) + (MgO / 0.9) + (2K_2O / 0.5) + (CaO / 0.7)]$.

1.2. Geologic setting and stratigraphy

The study area (Fig. 1) is located in the Niger Delta region of Nigeria. The Niger Delta (Southern Nigeria) is located in the Gulf of Guinea on the Atlantic coast of west Africa and west coast of central Africa. The stratigraphy and evolution of the basin are well documented (e.g., Short and Stauble, 1967; Burke, 1972; Weber and Daukoru, 1975; Evamy et al., 1978;

Avbovbo, 1978; Whiteman, 1982; Doust and Omatsola, 1990; Kulke, 1995; Osokpor and Ogbe, 2019). Briefly, the Niger Delta Basin was formed along a failed arm of a triple junction system that is connected to the break-up of the South American landmass from the African continent in the Late Jurassic to mid-Cretaceous (Burke et al., 1972). Following the separation of the continental plates, the opening of the Atlantic Ocean led to marine incursion marked by distinctive marine sedimentation in the Benue Trough and the Anambra Basin during the Lower Cretaceous in Nigeria. As the influx of Niger River clastics from the adjacent highlands gradually increased during the early Tertiary, the Niger Delta formed at the point where the Benue Trough adjoined the Atlantic Ocean (Doust and Omatsola, 1990).

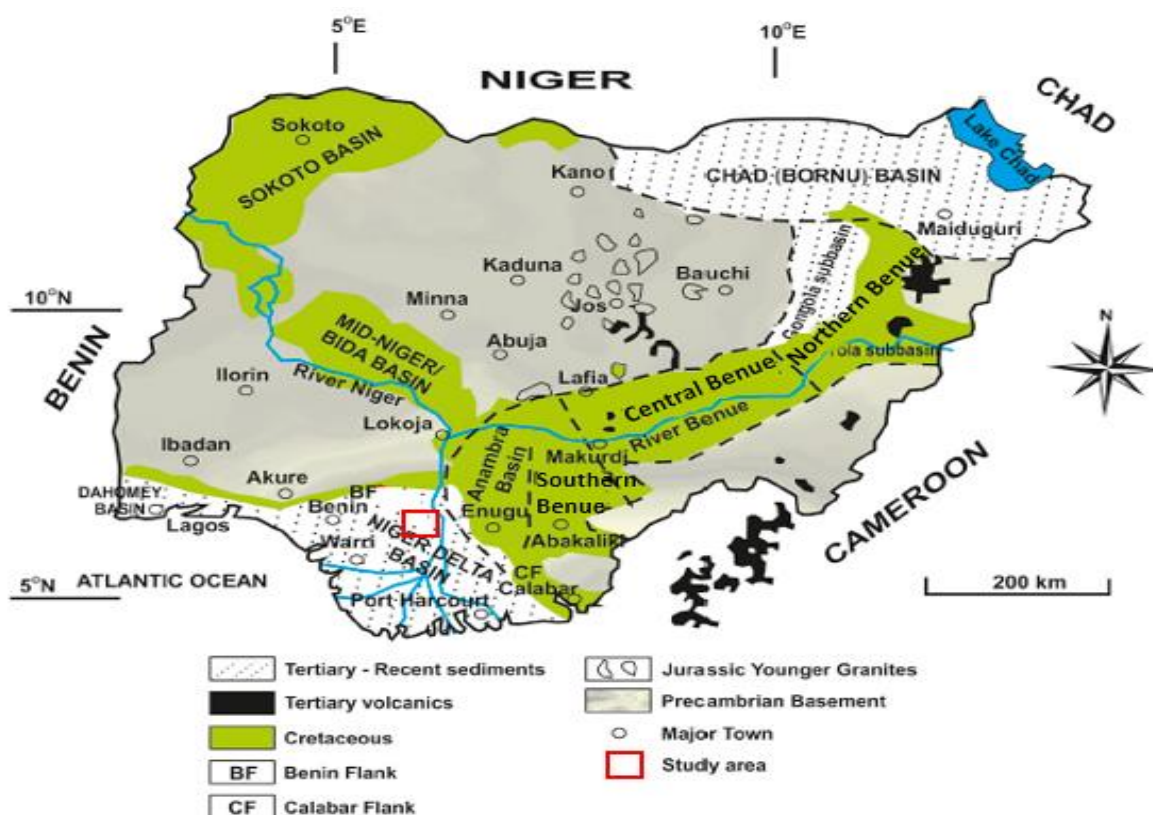


Figure 1: A simplified geologic map of Nigeria (Modified from Ogala et al., 2020)

The sediments of the Niger Delta Basin are mainly Cenozoic in age and are estimated

to have a maximum thickness in the range of 10000-15000m (Merki, 1972). The

stratigraphy of the Niger Delta is divided into the outcropping and the subsurface units (Nwajide, 2013). The subsurface units (Fig. 2) consists of the Akata Formation, Agbada Formation, and the Benin Formation. These formations have been discussed in several publications (Short and Stäuble, 1967; Avbobvo, 1978; Doust and Omatola, 1990; Kulke, 1995; Reijers, 2011). The Benin Formation, which was deposited in a continental-fluviatile environment, is composed mainly of sands, gravel, and back swamp deposits. In contrast, Agbada Formation consists of mostly interbeds of sands/sandstones and shales and was deposited in a transitional to marine paralic environment. The Akata Formation, which is at the base of the delta, is composed chiefly of marine shales; however, it contains silty and sandy beds which were deposited as turbidites, and continental-slope channel fills.

The outcropping units consist of the Imo Formation, Ameki Formation, Ogwashi-Asaba Formation, and the Benin Formation. The lithologic characteristics of these units are summarised in Table 1. The Ogwashi-Asaba Formation, which is the focus of this study, consists of sandstone, carbonaceous shale, clay, sandy clay with lignite intercalations (Ogala et al., 2012), and it is the outcropping lateral equivalent of the Agbada Formation. The general mesoscopic feature of the outcropping lignite bearing sections in these locations is that of cyclic successions of basal lignite units being overlain by mudstone that passes upwards into sandstone (Ogala et al., 2020). The age of the Ogwashi-Asaba Formation has been dated as Oligocene-Miocene age (Reyment, 1965) and Priabonian-Aquitania (Okeke and Umeji, 2016).

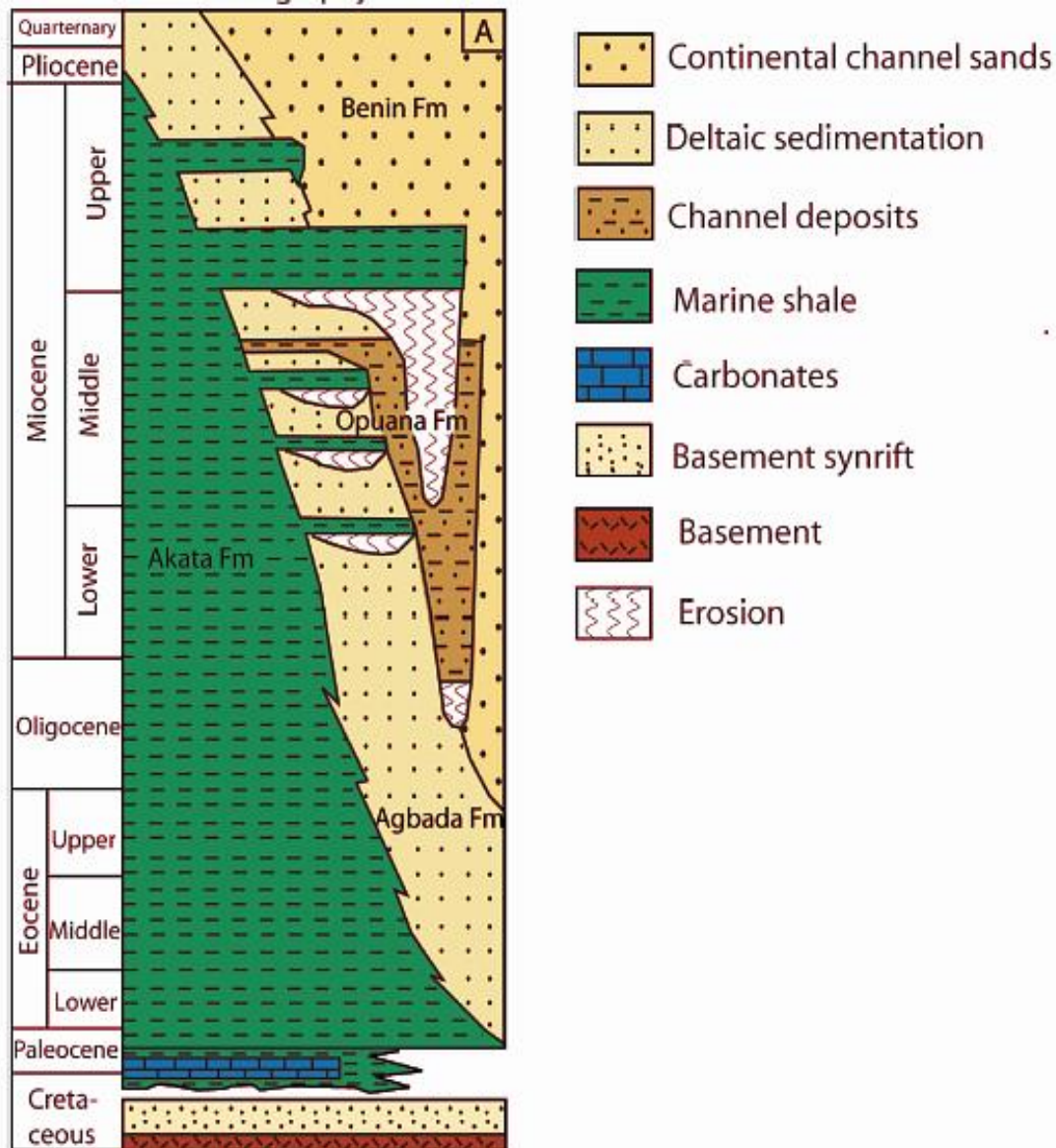


Figure 2: Regional scheme of stratigraphy of the three diachronous subsurface lithologic units (Akata, Agbada, and Benin Formation) in the Niger Delta (after Maloney et al., 2010).

Table 1: Outcropping units of the Cenozoic Niger Delta

Basin	Time scale	Lithostratigraphic unit	Brief lithologic description	
Niger Delta Basin	Pleistocene	Benin Formation	Coastal plains sands; cross-bedded, coarse, pebbly continental sands, with clay lenses and lignites; has marine shale breaks with foraminifera, ostracods, and molluscs	
	Pliocene			
	Miocene			
	Oligocene	Ogwashi-Asaba Formation	Clays, silts, sands with thin to thick lignite seams	
	Eocene	Ameki Group	Nsugbe Formation	Mainly sands with some conglomerate bands, calcareous clays, and silts with thin shelly limestone, rich in foraminifera, minor silt, and clay intercalations
			Nanka Formation	Blue-grey shales with sand lenses, marls, and fossiliferous limestones, sandstone members: Ebenebe, Umuna, and Igbaku sandstones; shales with foraminifera and ostracods
			Ameki Formation	
	Paleocene	Imo Formation	Ebenebe Sandstone	
			Umuna Sandstone	
			Igbaku Sandstone	

2. Methodology

Representative outcrop sand samples of the Ogwashi Asaba Formation were obtained from a quarry site in Ibusa. 25g of each sample was weighed, using a highly sensitive electrical weighing balance (Mettler Toledo, PL602-S), at the Geology Laboratory of the Department of Earth Sciences, Federal University of Petroleum Resources Effurun, Delta State. During preparation, the samples were dried at 60°C and pulverized to 85% passing 200 mesh (75 microns), using a mild-steel pulverizer (PUL85). The pulverized samples were then packed into suitable bags and sent to Acme (Bureau Veritas) analytical laboratories, Canada, for major oxide geochemical analysis. A predetermined amount of the sample was roasted to determine the loss on ignition (LOI) before the XRF analysis. The roasted sample was then fused in a platinum-gold crucible with a commercial lithium tetraborate flux. The molten

material was cast in a platinum mold, and the fused discs were analyzed for major elements using an X-ray Fluorescence Spectrometer

3. Results and discussion

3.1 Results

The major oxide geochemistry for the sediments is presented in Table 2. In comparison to UCC (Upper Continental Crust; Rudnick and Gao 2003) and PAAS (Post-Archean Australian Shales; Taylor and McLennan, 1985), the sands are enriched in SiO₂ but are depleted in other oxides suggesting their high mobility during weathering processes (Cullers, 1988) which led to the removal of ferromagnesian minerals and feldspars. The comparative depletion of Na₂O content for the sandstones can be attributed to the relative absence of Na feldspars. Al₂O₃ (1.29±0.15; Table 2) and K₂O (0.01±0.00; Table 2) contents are poor in the sandstone, indicating minimal presence of

K-feldspar, clay minerals, and mica. Correspondingly, the generally low concentrations of TiO_2 (0.35 ± 0.18 ; Table 2) suggests low abundances of Ti-opaque minerals and rutile in the sediments. The lack of MnO (0.01 ± 0.00 ; Table 2) is probably due to dissimilatory manganese reduction by microbes or source-area composition. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (75.86 ± 10.75 ; Table 2) suggests high silica to alumina content, whereas the low ratio of $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ (0.01 ± 0.00 ; Table 2) reflects low K-bearing mineral contents relative to alumina. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (4.49 ± 1.91 ; Table 2) signify slightly high alumina relative to titanium oxide.

3.2. Discussion

3.2.1 Geochemical Classification

Several researchers have utilized major element geochemical signatures for the classification of clastic sediments. The classification diagrams (Fig. 3 and Fig. 4) of Heron (1988) and Petijohn et al. (1972) suggest the sediments are mainly sublithic arenites, quartz arenites, and Fe- sands. The shift of the sandstone to various fields is probably due to a wide range in the variation of the relative proportion of matrix, feldspar, and lithic components (Lindsey et al., 2003).

Table 2: Major element concentration (wt. %) for the sandstones

SAMPLE	OGW 1	OGW2	OGW3	OGW 4	OGW 5	OGW 6	OGW 7	Min	Max	Mean	Stdev	UCC	PAAS
SiO ₂	95.50	97.00	96.90	95.90	96.33	95.51	95.92	95.50	97.00	96.15	0.61	66.00	62.80
Al ₂ O ₃	1.43	0.99	1.23	1.35	1.25	1.42	1.33	0.99	1.43	1.29	0.15	15.40	18.90
Fe ₂ O ₃	1.73	1.16	1.24	1.39	1.38	1.68	1.35	1.16	1.73	1.42	0.21	5.04	7.22
CaO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	3.59	1.30
MgO	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	2.48	2.20
Na ₂ O	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.00	3.27	1.20
K ₂ O	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	2.80	3.70
MnO	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.00	0.10	0.11
TiO ₂	0.64	0.16	0.16	0.31	0.32	0.54	0.30	0.16	0.64	0.35	0.18	0.64	1.00
P ₂ O ₅	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.15	0.16
LOI	0.10	0.00	0.10	0.20	0.10	0.10	0.20	0.00	0.20	0.11	0.07	-	-
Fe ₂ O ₃ /K ₂ O	173.00	116.00	124.00	139.00	138.00	168.00	135.00	116.00	173.00	141.86	21.26	1.80	1.95
SiO ₂ /Al ₂ O ₃	66.78	97.98	78.78	71.04	77.06	67.26	72.12	66.78	97.98	75.86	10.75	4.29	3.32
K ₂ O/Na ₂ O	0.50	1.00	0.50	0.57	0.57	0.50	0.50	0.50	1.00	0.59	0.18	0.86	3.08
Al ₂ O ₃ /TiO ₂	2.23	6.19	7.69	4.35	3.94	2.63	4.43	2.23	7.69	4.49	1.91	24.06	18.90
K ₂ O/Al ₂ O ₃	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.18	0.20
MgO/Al ₂ O ₃	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.00	0.16	0.12
CIA	95.85	95.61	95.21	95.90	95.58	95.82	95.55	95.21	95.90	95.65	0.24	52.76	70.39
CIW	96.55	96.62	96.01	96.64	96.38	96.53	96.30	96.01	96.64	96.43	0.22	58.88	82.72
PIA%	96.53	96.58	95.98	96.61	96.35	96.50	96.27	95.98	96.61	96.40	0.22	53.49	79.05
MIA	91.70	91.22	90.42	91.79	91.16	91.65	91.11	90.42	91.79	91.29	0.48	38.76	6.56
WIP	13.37	19.08	13.37	19.08	17.65	17.65	19.08	13.37	19.08	17.04	2.59	-	-

PAAS: Post-Archean Australian Shales, from Taylor and McLennan (1985)

UCC: Upper Continental Crust from Rudnick and Gao (2003)

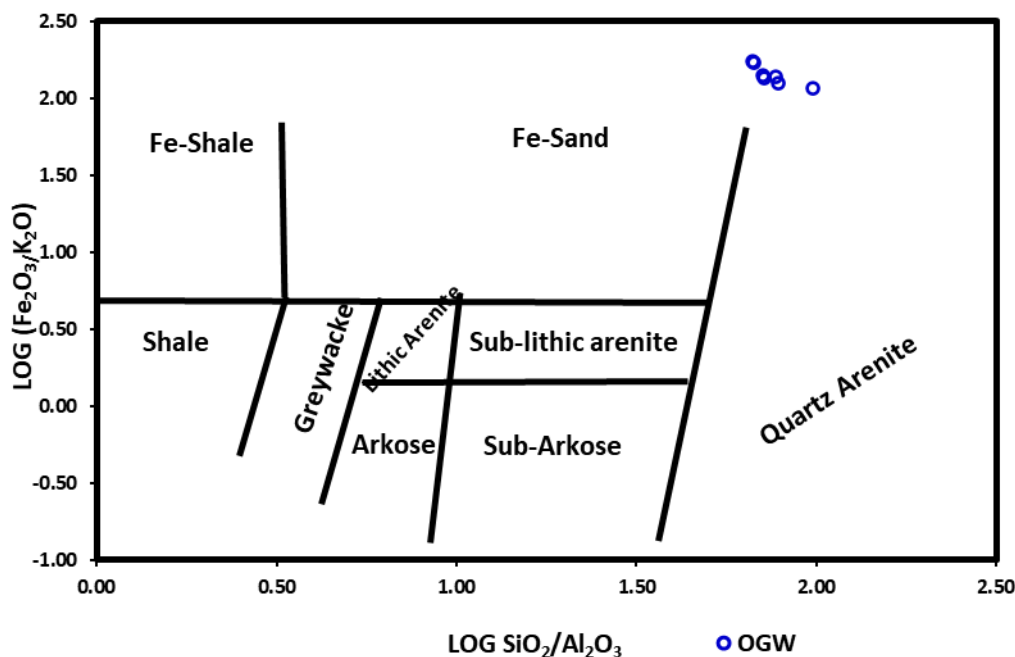


Figure 3: Log ($\text{SiO}_2/\text{Al}_2\text{O}_3$) vs. log ($\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$) diagram (Herron 1988)

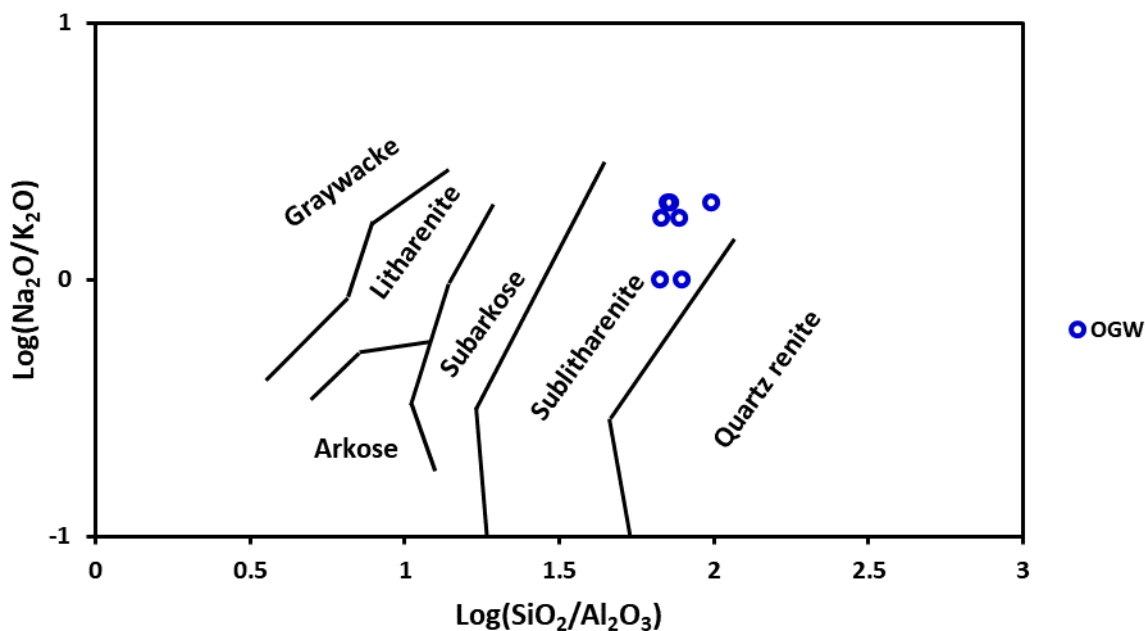


Figure 4: Log ($\text{SiO}_2/\text{Al}_2\text{O}_3$) vs. log ($\text{Na}_2\text{O}/\text{K}_2\text{O}$) diagram for the sands (Pettijohn et al., 1972)

3.2.2 Paleo-weathering

Several authors have explored CIA as a proxy for the evaluation of chemical weathering intensity (e.g., Nesbitt and Young, 1982; McLennan et al., 1993; Li

and Yang, 2010; Xiao et al., 2010; Bahlburg and Dobrzinski, 2011; Roy and Roser, 2013; Rose et al., 2013; Yang et al., 2014; Ding et al., 2016; Dinis et al., 2016; Bal-Akkoca et al. 2019). The calculated

CIA values (95.65 ± 0.24 ; Table 2) for the sediments under investigation suggests intense weathering in the source area. CIA computation involves K_2O , which is a mobile oxide; this restricts its applicability in sediments where potassium has been leached. Hence, some researchers, such as Condie (1992) considers CIW as a better measure of the intensity of chemical weathering over the CIA. The CIW values (96.43 ± 0.22 ; Table 2) for the examined sediments reflect intense weathering in the source area. This result indicates that the CIW and CIA indices display a similar trend for the sediments. The low values of standard deviation indicate a very narrow dispersion of data relative to average values.

PIA monitors and quantifies progressive weathering of feldspars to clay minerals (e.g., Fedo et al., 1995; Armstrong-Altrin et al., 2004). During the initial stages of weathering, Ca is leached more rapidly relative to Na and K. As weathering progresses, the total alkali content ($K_2O + Na_2O$) is expected to decrease with an increase in (K_2O/Na_2O) ratio (Price and Velbel, 2003). This occurs as a result of the destruction of feldspars, among which plagioclase is more preferentially removed than K-feldspars (Nesbitt and Young, 1984; Nesbitt et al., 1996). The high PIA values (96.40 ± 0.22 ; Table 2), for the sandstones, suggests that

most of the plagioclase has been converted to clay minerals. The MIA (91.29 ± 0.44 ; Table 2) and WIP (17.04 ± 2.59) trends also reflect intense weathering in the source area, and they are consistent with data obtained using the CIA, CIW, and PIA. Thus, the calculated indices are complementary and show similar trends.

Many researchers encourage the use of $Al_2O_3-(CaO^*+Na_2O)-K_2O$ ternary plot in evaluating the chemical weathering trends instead of depending only on a simple comparison of numerical value (Nesbitt and Young, 1984; 1989, Nyakairu and Koeberl, 2001). This is because geological systems are not simple, and a single calculated value may not adequately reflect their complexities. The A-CN-K trilinear plot proposed by Nesbitt and Young (1982) monitors the progress of weathering by depicting the relationship between Al_2O_3 (aluminous clays), $CaO+Na_2O$ (Plagioclase) and K_2O (K-feldspar) (Nesbitt and Young, 1984). The CIA vs. SiO_2 plot of Nesbitt and Young (1982) is also interpreted in a similar way to the A-CN-K diagram, with the kaolinitic region indicating intense weathering and significant removal of the alkali and alkali earth elements. The A-CN-K ternary diagram (Fig.5) and the CIA vs. SiO_2 (Fig. 6) bivariate plot reveals similar trends, suggesting intense weathering in the source area.

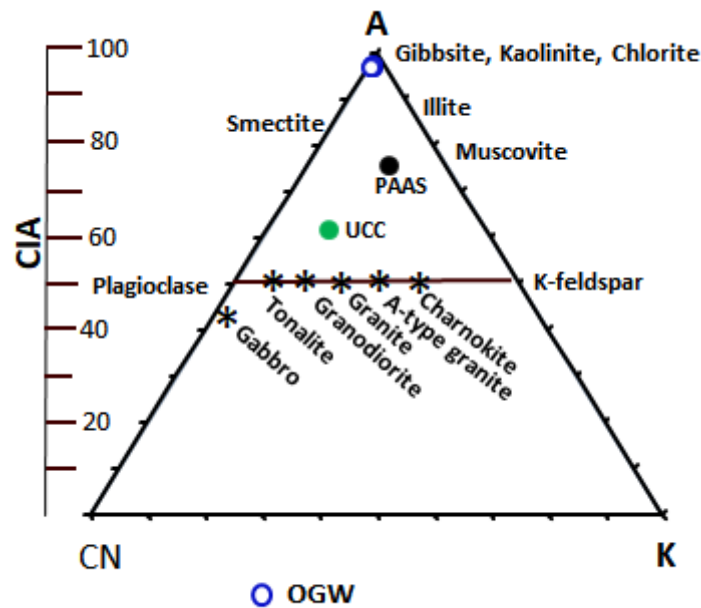


Figure 5: Ternary plot of $Al_2O_3-(CaO^*+ Na_2O)-K_2O$ for the sediments (Nesbith and Young, 1982; Fedo et al. 1995). Note that the sediments are clustering around a point.

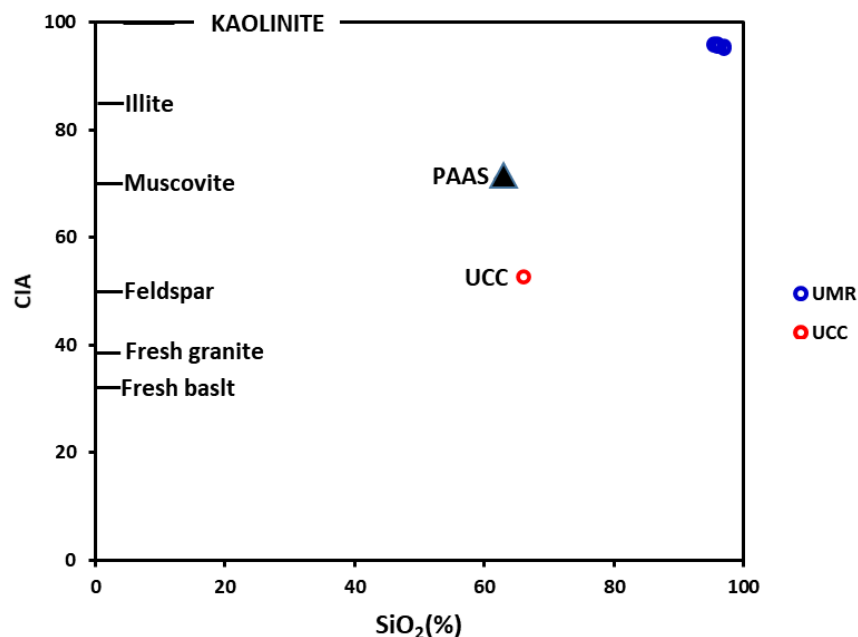


Figure 6: Plot of CIA versus SiO_2 (Nesbitt and Young 1982).). Note that the sediments are clustering around a point

3.2.3 Paleoclimate

Paleoclimatic studies help in the understanding of weathering processes in the source area. Major elemental signatures provide useful clues about the climatic conditions which prevailed during the deposition of sedimentary rocks (Suttner and Dutta, 1986). Climate

generally affects the alteration of minerals, transport, and source rock chemistry. The CIA provides semiquantitative insights on the paleoclimate of the source rock. Since the degree of weathering is primarily a function of climate and tectonic-uplift rates (Wronkiewicz and Condie, 1987), increased weathering intensity might

suggest a decrease in tectonic activity and/or a change in climate toward warm and humid conditions. Hence weak chemical weathering trends are usually associated with arid and cool conditions, whereas warm temperatures and high precipitation are comparatively linked to intense silicate chemical weathering (Nesbitt and Young, 1982). When CIA values are ≤ 50 , it suggests cool and/or arid conditions without abundant rainfall (Fedot et al., 1995; Tang et al., 2012), whereas

values >80 are associated humid climates where there is a high-degree alteration of source rocks (Mourabet et al., 2018). The high CIA values for the sandstones under investigation are interpreted to reflect a steady-state of weathering, probably under a warm/humid climate. In addition, the bivariate plot of Suttner and Dutta (1986) was utilized to evaluate the maturity of the sandstone as a function of climate. On this diagram, the sandstones plot essentially in the field of humid climate (Fig. 3.8).

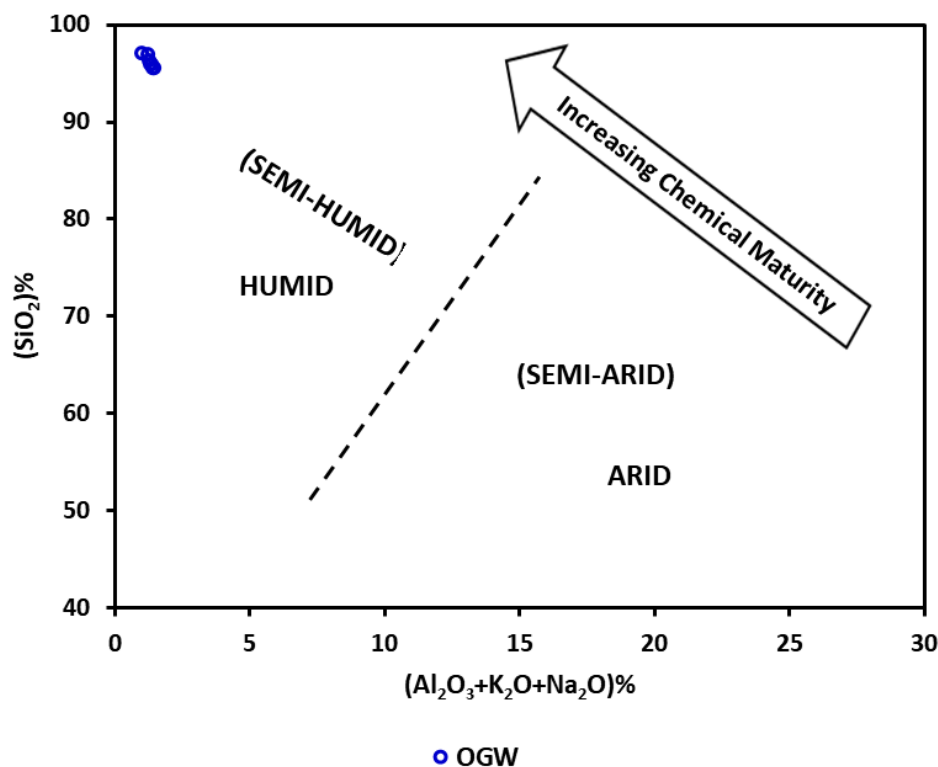


Figure 7: Chemical maturity of the investigated sandstone expressed by a bivariate plot of SiO_2 vs. $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$; fields after Suttner and Dutta (1986)

Conclusion

The application of inorganic geochemical data sets to unravel the source area weathering in the Ogwashi Asaba Formation, Niger Delta Basin, was carried out. The sandstones are geochemically classified as sublithic arenites, quartz arenites, and Fe-sands. The sediments are highly depleted in most of the major

elements suggesting an intense degree of chemical weathering in the source area. High (CIA, CIW, PIA, and MIA) and low (WIP) values of weathering indices, the chemical weathering trends monitored by the A-CN-K diagram as well as the CIA versus SiO_2 plot, clearly reflect an intense degree of weathering in the source area. A humid/warm paleoclimate was inferred for

the sediments based on the CIA values and the SiO_2 vs. $(\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O})$ correlation.

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