

Understanding the Origin, Tectonic Framework, and Environment of Deposition via Geochemical Characterization of the Siliciclastic Sediments in the Shendam area, Middle Benue Trough, Northcentral Nigeria

By

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Abstract

This study presents a comprehensive geochemical analysis of siliciclastic sediments from the Shendam area in the Middle Benue Trough, Northcentral Nigeria, to elucidate their origin, tectonic setting, and depositional environment. The sediments, primarily derived from intermediate to felsic igneous rocks, exhibit significant chemical weathering, indicative of prolonged exposure to warm, humid climatic conditions. Geochemical indices, including the Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA), and Chemical Index of Weathering (CIW), reveal intense weathering of the source rocks, with CIA values ranging from 3.64 to 99.41 (avg. 73.20). Provenance analysis, supported by Al_2O_3/TiO_2 ratios and bivariate plots, indicates a mixed source of intermediate and felsic igneous rocks, consistent with the Younger Granites of the region. The tectonic setting, inferred from major and trace element geochemistry, aligns with a passive continental margin, reflecting the broader tectonic evolution of the Benue Trough during the breakup of Gondwana. Paleo-redox conditions, assessed using trace element ratios (e.g., V/Cr , V/Ni , Sr/Ba), suggest deposition in anoxic to dysoxic environments, predominantly in freshwater settings with occasional brackish influence. This study underscores the interplay between source rock composition, weathering intensity, and tectonic activity in shaping the sedimentary record of the Middle Benue Trough, providing valuable insights into the region's geological history and depositional processes.

Keywords: Geochemical Analysis, Siliciclastic Sediments, Tectonic Setting, Provenance, Weathering, Paleoenvironment.

Introduction:

Concentrations of primary and minor elements in terrigenous sediments are commonly utilized as proxies to understand the origin, depositional environments, and tectonic framework of

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sedimentary basins^{5 6 7 8 9 10}. Many scientists have shown that the vital and trace element composition of clastic sedimentary rocks can offer evidence about their origin, climatic conditions, and depositional processes^{11 12 13}. Because sedimentary rocks can hold the geochemical features of their parent rocks, they are a valuable tool for provenance studies^{14, 15}.

Geological setting

The Benue Trough in Nigeria is an intracontinental rift basin (Fig. 1) formed during the early Cretaceous as a segment of the West and Central African Rift System (WCARS) following the breakup of Gondwanaland¹⁶. The Cretaceous period was characterized by elevated global temperatures and widespread rift formation, including the development of the WCARS.

The Precambrian Basement Complex, linked to the Pan-African mobile belt, is connected to the West African and Congo Cratons^{17 18}. In the Mesozoic era, calc-alkaline Younger Granites intruded the Basement Complex, forming characteristic ring structures¹⁹. This Basement Complex consists

⁵ Abubakar, U., Usman, M.B., Aliyuda, K., Dalha, A., Bello, A.M., Linus, L.N., 2021. Major and trace element geochemistry of the shales of Sekuliye Formation, Yola Sub-Basin, Northern Benue Trough, Nigeria: implications for provenance, weathering intensity, and tectonic setting. *Journal of Sedimentary Environments* 6, 473–484

⁶ Ahmad, I., Chandra, R., 2013. Geochemistry of loess-paleosol sediments of Kashmir Valley, India: provenance and weathering. *J. Asian Earth Sci.* 66, 73–89.

⁷ Francovschi, I., Gradinaru, E., Roban, R., Ciobotaru, V., 2014. Geochemistry of Neoproterozoic shales from the Kalius Member: assessing the sedimentary provenance and paleo-weathering. *Buletinul Institutului de Geologie si Seismologie al AS*, 14–23.

⁸ Hussain, S.H., Al-Juboury, A.I., Al-Haj, M.A., Armstrong-Altrin, J.S., Al-Lhaebi, S.F., 2021. Mineralogy and geochemistry of the late Triassic Baluti formation, northern Iraq. *J. Afr. Earth Sci.* 181, 104243.

⁹ Ramos-Vazquez, M.A., Armstrong-Altrin, J.S., 2021. Provenance of sediments from Barra del Tordo and Tesoro beaches, Tamaulipas State, northwestern Gulf of Mexico. *J. Palaeogeogr.* 10, 1–17.

¹⁰ Roser, B. P., & Korsch, R. J. (1986). Determination of tectonic setting of sandstone- mudstone suites using SiO₂ content and K₂O/Na₂O ratio. *Journal of Geology*, 94(5), 635–650. <https://doi.org/10.1086/629071>

¹¹ Armstrong-Altrin, J. S., Nagarajan, R., Madhavaraju, J., Rosalez-Hoz, L., Lee, Y. I., Balaram, V., ... & Avila-Ramírez, G. (2013). Geochemistry of the Jurassic and Upper Cretaceous shales from the Molango Region, Hidalgo, eastern Mexico: Implications for source-area weathering, provenance, and tectonic setting. *Comptes Rendus Geoscience*, 345(4), 185–202.

¹² Capaldi, T. N., McKenzie, N. R., Horton, B. K., Mackaman-Lofland, C., Colleps, C. L., & Stockli, D. F. (2021). Detrital zircon record of Phanerozoic magmatism in the southern Central Andes. *Geosphere*, 17(3), 876–897.

¹³ Ramos-Vazquez, M.A., Armstrong-Altrin, J.S., 2021. Provenance of sediments from Barra del Tordo and Tesoro beaches, Tamaulipas State, northwestern Gulf of Mexico. *J. Palaeogeogr.* 10, 1–17.

¹⁴ Adeoye, J.A., Akande, S.O., Adekeye, O.A., Abikoye, V.T., 2020. Geochemistry and paleoecology of shales from the Cenomanian-Turonian Afowo Formation Dahomey Basin, Nigeria: implication for provenance and paleoenvironments. *J. Afr. Earth Sci.* 169, 103887. *African Earth Sciences* 8, pp. 251–282.

¹⁵ Schieber, J., Zimmerle, W., 1998. The history and promise of shale research. *Shales and Mudstones* 1, 1–10.

¹⁶ Genik, G. J. (1993). Petroleum geology of cretaceous-tertiary rift basins in Niger, Chad, and Central African Republic. *AAPG bulletin*, 77(8), 1405–1434.

¹⁷ Black, R., 1980. Precambrian of West Africa. *Episodes Journal of International Geoscience* 3, 3–8. Bors, J., Gorny, A., Dultz, S., 1997. Iodide, caesium and strontium adsorption by organophilic vermiculite. *Clay Miner.* 32, 21–28.

¹⁸ Wright, J.B., Hastings, D., Jones, W., Williams, H., 1985. *Geology and Mineral Resources of West Africa*. Springer.

¹⁹ Rahaman, M., 1988. Recent advances in the study of the basement complex of Nigeria. *Pre Cambrian geology of Nigeria* 11–41.

of three main lithologic units: the Migmatite-Gneiss Complex, the Schist Belt, and the Older Granites²⁰.

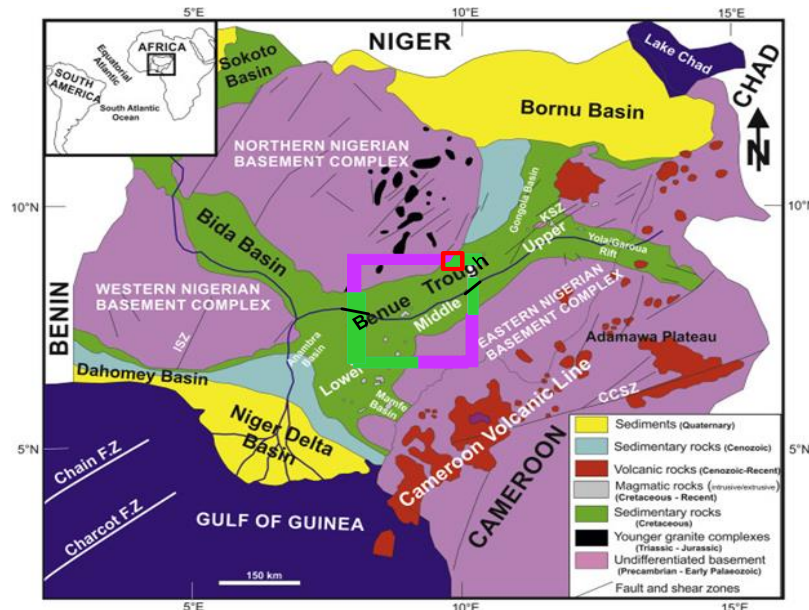


Figure 1: Geological map of Nigeria highlighting the study area within the Benue Trough, marked by a red box²¹

The Benue Trough is roughly 800–1000 km long and 150–250 km wide²². Scholars have put forth various tectonic models to elucidate the Benue Trough's evolution; nonetheless, the precise mechanism accountable for its formation remains unsettled^{23 24 25 26 27 28}. The Benue Trough is divided into three sections: the Lower, Middle, and Upper segments^{29 30 31 32}. It is not possible to

²⁰ Obaje, N. G. (2009). Update on Geology and Mineral Resources of Nigeria (p. 240). Springer Verlag, Heidelberg, Berlin, New York.

²¹ Fatoye F. B., Ibitomi M. A. and Omada J. I. (2014). Lead-Zinc-Barytes mineralization in the Benue Trough, Nigeria: Their geology, occurrences and economic perspective. *Pelagia Research Library Advances in Applied Science Research*, 5(2):86

²² Benkhelil, J. (1982). Benue Trough and Benue Chain. *Geological Magazine* 199, pp.155-168.

²³ King, L.C. (1950). Speculation on the outline and the mode of disruptions of Gondwanaland. *Geological magazine*, 87: pp.353-359.

²⁴ Stoneley, R. (1966). The Niger Delta region in the light of the theory of continental drift. *Geological Magazine*, 103: pp.385-397.

²⁵ Grant, N.K. (1971). The South Atlantic, Benue Trough and Gulf of Guinea Cretaceous triple junction. *Bulletin of the Geological Society of America*, 82: pp.2295-2298.

²⁶ Olade, M.A. (1975). Evolution of Nigeria's Benue Trough (aulacogen); a tectonic model, *Geological Magazine*, 112: pp.575-583.

²⁷ Benkhelil, J. (1989). The origin and evolution of the Cretaceous Benue Trough Nigeria.

²⁸ Guiraud, R. and Maurin, J.C. (1992). Early Cretaceous rifts of Western Central Africa: an overview. *Tectonophysics*, 213: pp.153-164.

²⁹ Carter, J.D., Barber, W., Tait, E.A. and Jones, G.P., (1963). The Geology of parts of Adamawa, Bauchi and Bornu provinces in north-eastern Nigeria. *Bulletin Geological Survey Nigeria* 30, pp1-99.

³⁰ Nwajide, C. S. (2013). *Geology of Nigeria's sedimentary basins*. CSS Bookshops Ltd

³¹ Zaborski, P.M. (1998). A review of the Cretaceous system in Nigeria. *Africa Geoscience Review*, 5: pp.385-483.

³² Zaborski, P. M., Ugodulunwa, F., Idornigie, A., Nnabo, P., & Ibe, K. (1997). Stratigraphy and structure of the Cretaceous Gongola Basin, northeast Nigeria. *Bulletin De Centres Des Recherches Exploration Production Elf-Aquitaine*, 21, 153–186.

draw a precise line sub-dividing or separating each portion, but major locations, such as towns and settlements, that serve as the hubs of the various portions have been thoroughly documented³³.

The Cretaceous sediments in the Middle Benue Trough rest upon the Precambrian Basement Complex³⁴ encompassing over 4,000 meters of Cretaceous-Tertiary sediments, with portions that predate the mid-Santonian period experiencing multiple compressional folds, faults, and uplifts³⁵
³⁶.

The geologic sequence in the Middle Benue Trough in the Shendam area (Table. 1) consisted of six (6) Early Cretaceous lithogenic formations.

Table 1: Lithostratigraphic classifications of Cretaceous rocks in the Middle Benue Trough³⁷

TIME (Ma)	TECTONIC EVENTS	AGE	FORMATION	LITHOLOGY	PALEO-ENVIRONMENT
~72		Maastrichtian	Lafia	Sandstone, siltstone & claystone	Fluvial
~83		Campanian	Volcanics		
~86	Basin Wide Deformation	Santonian			
~90		Coniacian	Agwu	Shale, siltstone, coal, sandstone & limestone	Shallow marine & deltaic
~92		Late Turonian	Ezeaku	Shale, siltstone, sandstone & limestone	Shallow marine & deltaic
~94		Early Turonian	Keana	Sandstone, siltstone & claystone	Fluvio-deltaic
~100	Late Stage Rifting	Cenomanian	Awe	Sandstone, siltstone & claystone	Fluvio-deltaic
~113		Albian	Asu River Group	Shale, sandstone, limestone & siltstone	Marine
		Pre-cambrian	Basement Rocks	Migmatite, gneiss, schist & granite	Metamorphic, igneous

The oldest lithostratigraphic unit in the area, the Albian-aged Asu River Group, unconformably covers the Precambrian crystalline basement rocks^{38 39 40}. The Asu River Group's basal Albian

³³ Obaje, N. G. (2009). Update on Geology and Mineral Resources of Nigeria (p. 240). Springer Verlag, Heidelberg, Berlin, New York.

³⁴ Nwajide, C. S. (2013). Geology of Nigeria's sedimentary basins. CSS Bookshops Ltd

³⁵ Nwajide, C.S. (1990). Sedimentation and paleogeography of the central Benue Trough, Nigeria. In: C.O. Ofoegbu, (Ed.). The Benue Trough structure and evolution, view eg & Sohn, Braunschweig pp.19-38.

³⁶ Obaje, N. G. (2009). Update on Geology and Mineral Resources of Nigeria (p. 240). Springer Verlag, Heidelberg, Berlin, New York.

³⁷ Offodile, M.E. (1976). The Geology of the Middle Benue Nigeria. Special volume Palaeontological Institution University Uppsala 4, pp.1-166

³⁸ Offodile, M.E. and Reymont, R.A. (1977). Stratigraphy of the Keana-Awe area of the Middle Benue Region of Nigeria. Bulletin Geological Institutions University Uppsala (N.S.) 7, pp.37-66.

³⁹ Nwajide, C.S. (1990). Sedimentation and paleogeography of the central Benue Trough, Nigeria. In: C.O. Ofoegbu, (Ed.). The Benue Trough structure and evolution, view eg & Sohn, Braunschweig pp.19-38.

⁴⁰ N. G. (2009). Update on Geology and Mineral Resources of Nigeria (p. 240). Springer Verlag, Heidelberg, Berlin, New York.

Arufu, Uomba, and Gboko Formations are unconformably covered by the Cenomanian Keana and Awe Formations. There are differing opinions about whether the contact between the Awe and Keana Formations is gradational or nonconformable^{41 42}.

The Eze-Aku Formation is thought to have a fluvial or deltaic origin since it is composed primarily of fine-to-extremely coarse-grained, heavily cross-bedded arkosic sandstones with conglomeratic and gritty components^{43 44}. Fine-to-medium-grained sandstones, limestone interbeds, and grey-to-black shales with sporadic clay horizons make up the majority of this formation, which unconformably sits on top of the Keana Formation^{45 46}.

The deposition of the Campanian-Maastrichtian Lafia Formation, which signifies the end of sedimentation in the study area and the Middle Benue Trough, followed post-folding Campanian volcanic activity^{47 48 49}.

⁴¹Offodile, M.E. (1976). The Geology of the Middle Benue Nigeria. Special volume Palaeontological Institution University Uppsala 4, pp.1-166

⁴² Offodile, M.E. and Reyment, R.A. (1977). Stratigraphy of the Keana-Awe area of the Middle Benue Region of Nigeria. Bulletin Geological Institutions University Uppsala (N.S.) 7, pp.37-66.

⁴³Murat, R.C. (1972). Stratigraphy and palaeogeography of the Cretaceous and Lower Tertiary in Southern Nigeria. In: African Geology (Edited by Dessauvage, T.F.J. and Whiteman, A.J.), pp.251-266. Ibadan University Press, Ibadan, Nigeria.

⁴⁴Offodile, M.E. (1976). The Geology of the Middle Benue Nigeria. Special volume Palaeontological Institution University Uppsala 4, pp.1-166

⁴⁵ Offodile, M.E. (1976). The Geology of the Middle Benue Nigeria. Special volume Palaeontological Institution University Uppsala 4, pp.1-166

⁴⁶Offodile, M.E. and Reyment, R.A. (1977). Stratigraphy of the Keana-Awe area of the Middle Benue Region of Nigeria. Bulletin Geological Institutions University Uppsala (N.S.) 7, pp.37-66.

⁴⁷Obaje, N.G., Funtua, I.I., Ligouis, B. and Abaa, S.I. (1998). Organic maturation and coal-derived hydrocarbon potentials of Cretaceous coal measures in the Middle Benue Trough, Nigeria. Journal of Mining and Geology, 34: pp.1116- 2775.

⁴⁸Obaje, N. G., Ulu, O. K. and Petters, S. W. (1999). Biostratigraphic and geochemical controls of hydrocarbon prospects in the Benue Trough and Anambra Basin, Nigeria. NAPE Bull 14:18–54

⁴⁹Yusuf, I., Obaje, N. G., Adeoye, J. A., Adamu, L. M. and Yusuf, T.U (2022). Geology, reservoir diagenesis and quality of Albian-Cenomanian Keana /Awe potential reservoir sandstone in Middle Benue Trough, Nigeria. Lapai Journal of Science and Technology, Vol. 8, No. 1, 16-31.



Figure 2: Field images depicting (a) Medium-grained Sandstone from the Ezeaku Formation at Mban Bridge, (b) Medium-grained Sandstone from the Ezeaku Formation at Lashel, Langtang South, (c) Coarse-grained to Conglomeratic Ferruginous Sandstone of the Lafia Formation around Gamakai, Langtang South, and (d) Coarse-grained to Conglomeratic Ferruginous Sandstone of the Lafia Formation at Faya, Langtang South

Twenty-two (22) Siliclastic sediments from the Shendam area (Figure 3), were sent to the MS Analytical Laboratory in Canada for study. The samples were examined for minor elements and major element oxides. The outcrop samples were processed and dried to satisfy the 85% passing criterion for major element oxide analysis. For samples that were difficult to dissolve in acids, lithium borate fusion was used to decompose the material. The weighed samples were heated to 1000°C in a high-temperature muffle furnace using lithium borate flux during the fusion process. Mineral acids were used to dissolve the fused samples once they had cooled. Using Inductively Coupled Plasma-Optical Emission Spectroscopy, the final solution of each sample was examined, and the measured multi-element concentrations were reported.

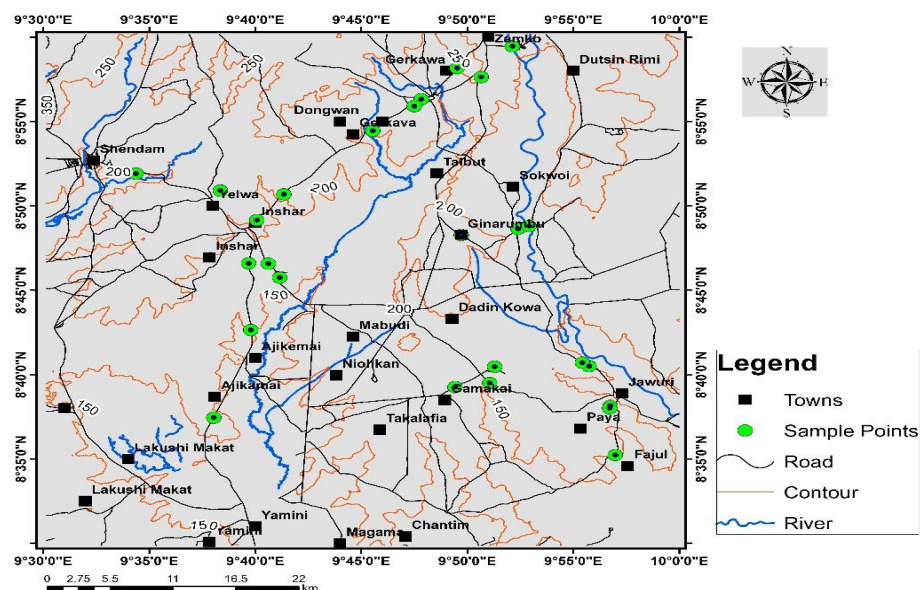


Figure 3: Study area (Shendam) topographic map displaying sample locations

The dried and homogenized rock samples were analyzed for elemental traces. Each sample was weighed and subjected to digestion using a solution of hydrochloric and nitric acids ("aqua regia"). Following digestion, deionized water was added to dilute the samples to a specified volume. The solutions obtained were examined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES). Chemical weathering indices were computed to evaluate the extent of weathering processes in the source region.

Results and Discussions

Principal components

The primary element oxides' geochemical concentrations (SiO_2 and Fe_2O_3) in the study area (0.15-97.77 wt.%, avg. 63.60 wt.%) and (0.94-43.94 wt.%, avg. 10.86 wt.%) are the two most prevalent oxide concentrations respectively.

The average quantity of BaO , CaO , K_2O , and MgO are 3.61, 2.52, 1.10, and 1.38, respectively, while the average concentrations of Cr_2O_3 , MgO , Na_2O , P_2O_5 , and TiO_2 are less than 0.98. The clastic sediments are geochemically classified as quartz arenites in the⁵⁰ major oxide bivariate dispersed map (Fig. 4a). The Bivariate plot of sandstones (Fig. 4b), while plot them as detrital SiO_2 (Fig. 4c). Classification of the sediments as detrital quartz arenitic sandstones is very consistent with the field description of the samples obtained from the research region.

⁵⁰Herron, M. M. (1988). Geochemical classification of terrigenous sands and shales from core or log data. *Journal of Sedimentary Petrology*, 58, 820–829. <https://doi.org/10.1306/212F8E77-2B24-11D7-8648000102C1865D>

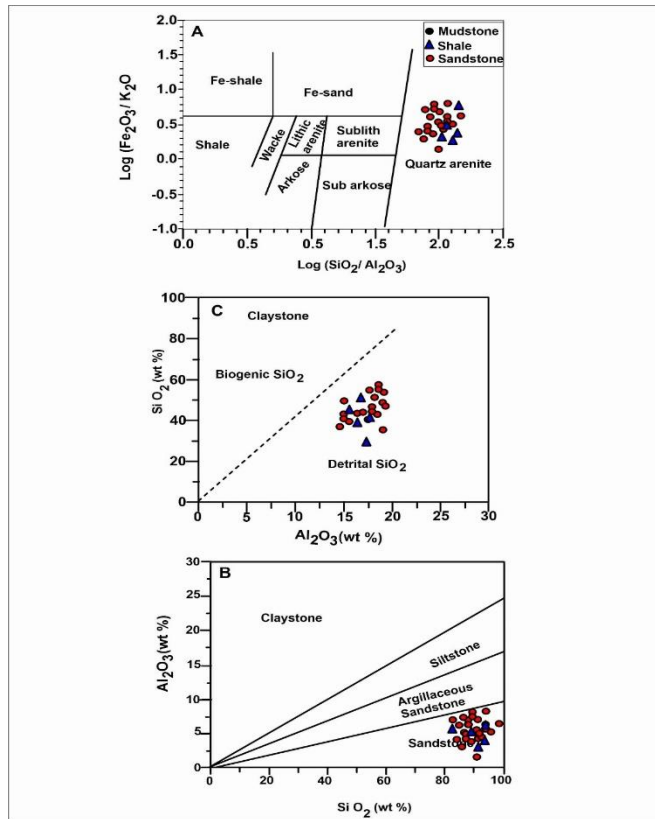


Figure 4: Siliciclastic sediments are geochemically classified according to several plots: (A) a diagram comparing the log ($\text{SiO}_2/\text{Al}_2\text{O}_3$) and log ($\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$) per⁵¹; (B) a bivariate plot of Al_2O_3 against SiO_2 , modified from⁵²; (C) a plot of SiO_2 against Al_2O_3

Trace elements

The Ba (2723.69 ppm), Zr (374.52 ppm), and Cr (129.57 ppm) elements have the highest average concentrations in the samples taken at the research site. The average compositions of V (61.04 ppm), Zn (40.88 ppm), Ni (38.19 ppm), and Rb (37.19 ppm) were found to be less than 70 ppm. The other trace elements, such as Nb (25.43 ppm), Cu (24.44 ppm), and Ga (13.54 ppm), have average compositions below 30 ppm. The trace elements that are below the limit of detection include Cs, Hf, Sn, Ta, Th, U, W, Ag, As, Bi, Cd, Hg, Mo, Pb, Sb, Se, and Ti.

Provenance

The composition of sediments' bulk major and trace elements is essential to provenance investigations. (1). The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio, which remains largely unaffected by post-depositional processes due to the immobility of these elements, is particularly important for identifying

⁵¹ Herron, M. M. (1988). Geochemical classification of terrigenous sands and shales from core or log data. *Journal of Sedimentary Petrology*, 58, 820–829. <https://doi.org/10.1306/212F8E77-2B24-11D7-8648000102C1865D>

⁵² Sprague, R.A., Melvin, J., Conradi, F., Pearce, T., Dix, M., Hill, S., Canham, H., 2009. Integration of Core-Based Chemostratigraphy and Petrography of the Devonian Jauf Sandstones, Uthmaniya Area, Ghawar Field, Eastern Saudi Arabia. *Search and Discovery*.

sediment sources⁵³. $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios in felsic igneous rocks typically range from 21 to 70, in intermediate igneous rocks from 8 to 21, and in mafic rocks from 3 to 8⁵⁴. The clastic sediments in the research area had an average $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio of 22.08, ranging from 4.41 to 88.43 (Fig.5a).

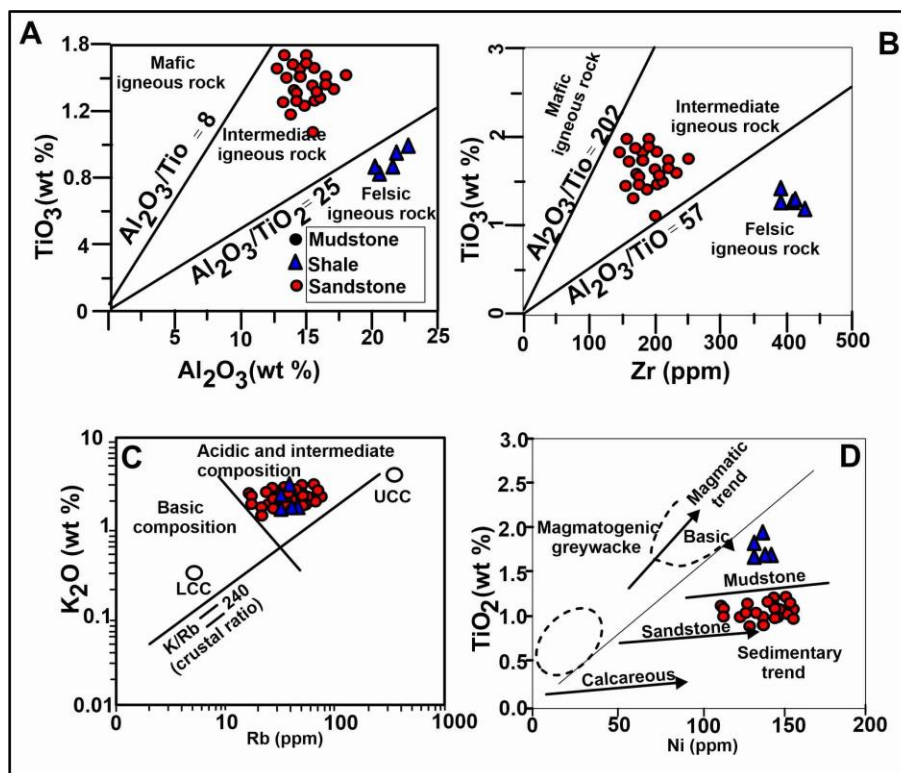


Figure 5. Bivariate plots for provenance discrimination of siliciclastic sediments

Bivariate plots, such as Al_2O_3 vs. TiO_2 (Fig. 5a) and Zr vs. TiO_2 (Fig. 5b), following⁵⁵, classify the siliciclastic sediments predominantly within the intermediate igneous rock field. Additional provenance plots, including K_2O vs. Rb (Fig. 5c) and TiO_2 vs. Ni (Fig.5d), suggest a combination of acidic and intermediate sources within a sandstone sedimentary trend. Additionally, the samples fall into the intermediate and felsic provenance fields according to⁵⁶ major oxide provenance discriminant plot, confirming the theory that the siliciclastic sediments are derived from acidic to intermediate and felsic igneous rocks, especially those of the Younger Granites (Figs. 6 & 7).

⁵³ Ramos-Vazquez, M.A., Armstrong-Altrin, J.S., 2021. Provenance of sediments from Barra del Tordo and Tesoro beaches, Tamaulipas State, northwestern Gulf of Mexico. *J. Palaeogeogr.* 10, 1–17.

⁵⁴ Hayashi, K. I., Fujisawa, H., Holland, H. D., & Ohmoto, H. (1997). Geochemistry of ~ 1.9 Ga sedimentary rocks from northeastern Labrador, Canada. *Geochimica Et Cosmochimica Acta*, 61, 4115– 4137.

[https://doi.org/10.1016/S0016-7037\(97\)00214-7](https://doi.org/10.1016/S0016-7037(97)00214-7)

⁵⁵ Al-Bassam, K., Magna, T., Vodrážka, R., Cech, S., 2019. Mineralogy and geochemistry of marine glauconitic siliciclasts and phosphates in selected Cenomanian–Turonian units, Bohemian Cretaceous Basin, Czech Republic: implications for provenance and depositional environment. *Geochemistry* 79, 347–368.

⁵⁶ Al-Bassam, K., Magna, T., Vodrážka, R., Cech, S., 2019. Mineralogy and geochemistry of marine glauconitic siliciclasts and phosphates in selected Cenomanian–Turonian units, Bohemian Cretaceous Basin, Czech Republic: implications for provenance and depositional environment. *Geochemistry* 79, 347–368.

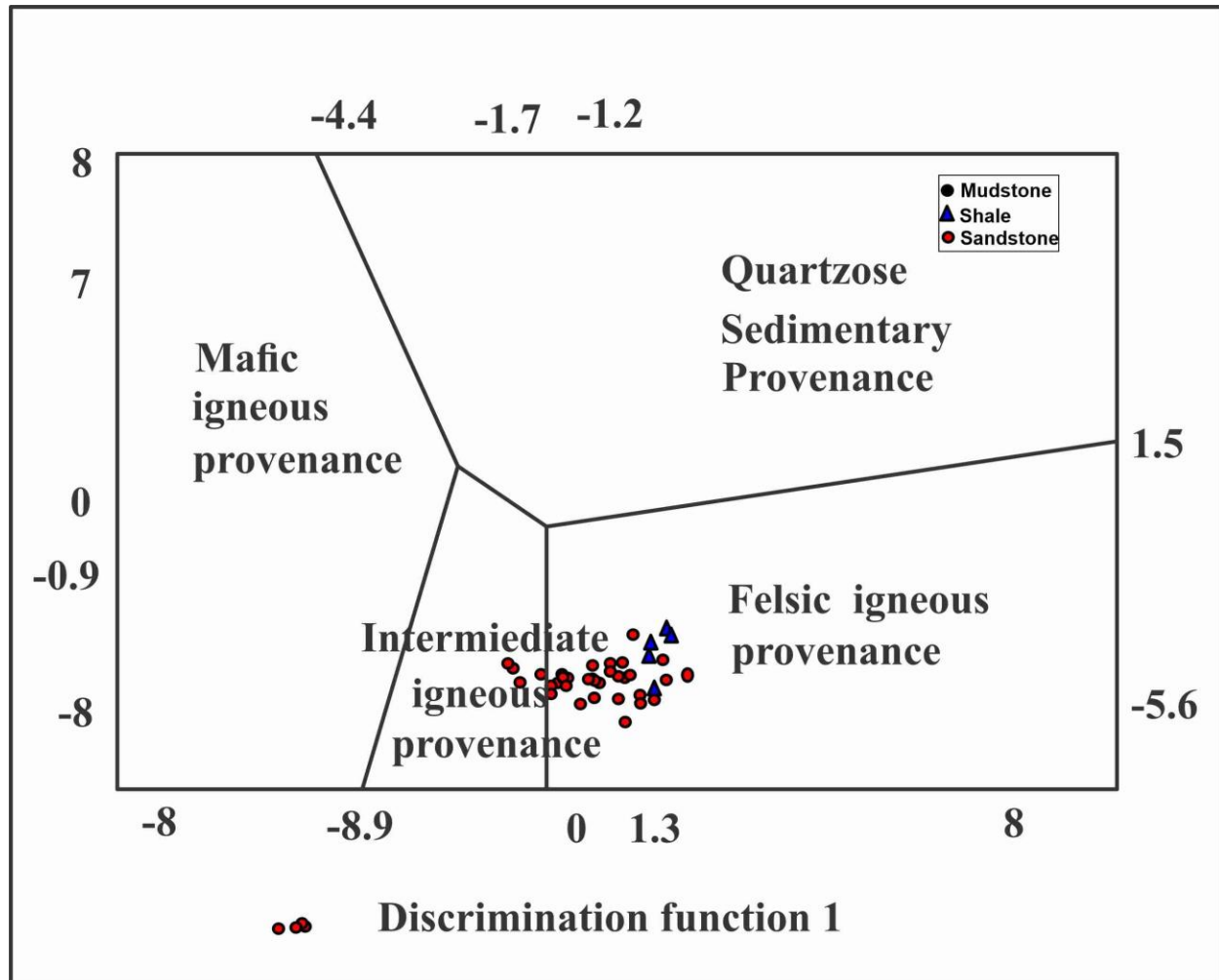
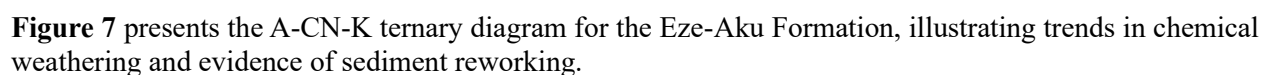


Figure 6: Provenance discriminant plot of major oxides (following⁵⁷).

⁵⁷ Roser BP, Korsch RJ (1988) Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. Chem Geol 67:119–139Capaldi et al., 2020



The degree of chemical weathering and the makeup of the source rocks have the most effects on the quantity of key and trace elements in detrital clastic deposits⁵⁸. To assess the extent of chemical weathering, the main and trace element configurations of clastic sediments are normally examined⁵⁹. Sedimentary archives act as repositories of geochemical fingerprints, which act as crucial tools for deciphering the chemical weathering patterns of sediments and identifying their provenance⁶⁰.

Elements such as Ca, Na, K, and Sr, which are mobile, are released during chemical weathering processes. On the other hand, elements like Rb, Ba, Ti, and Al, which are immobile, remain largely unchanged. To assess the palaeoweathering conditions of the sediments in the Eze-Aku Formation, indices such as the Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA), and Chemical Index of Weathering (CIW) were utilized. Chemical weathering processes in source locations have been assessed using these indicators extensively⁶¹. Plagioclase alteration during

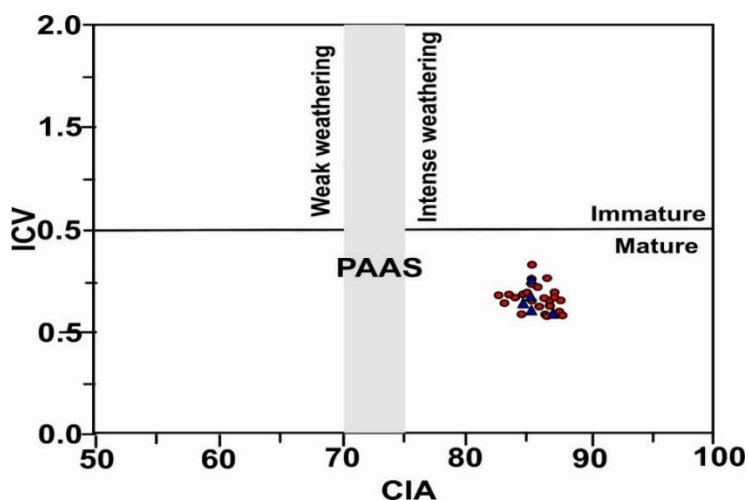
⁶¹Fedo CM, Nesbitt HW, Young GM (1995) Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleo weathering conditions and provenance. *Geology* 23:921–924.

weathering is specifically measured by the Plagioclase Index of Alteration (PIA), where a value of zero denotes no alteration and 100 denotes total change⁶².

The Eze-Aku Formation's PIA values, which vary from 3.20 to 109.09 with an average of 81.34, indicate considerable plagioclase mineral alteration and substantial weathering of the parent rock (Fig. 8).

The Chemical Index of Alteration (CIA), as defined by⁶³, quantifies the extent to which key lithophile elements, including Na and Ca, are removed from source rocks through chemical weathering processes. For the sediments of the Eze-Aku Formation, CIA values vary between 3.64 and 99.41, with an average of 73.20, as detailed in Table 1. These data show that the sandstones have weathered significantly and that K-metasomatism has influenced the sediments.

The Eze-Aku Formation's deposits are situated along an intermediate weathering trend, above the line for weak plagioclase and potassium feldspar weathering (Fig. 7). Furthermore, an ICV versus CIA plot⁶⁴ positions the detrital siliciclastic sediments of the Eze-Aku Formation as compositionally mature, reflecting intense weathering. These layers exhibit significant weathering of the source material, as indicated by their position beneath the Post-Archean Australian Shale (PAAS) reference line (Fig. 8).



⁶² Fedo CM, Nesbitt HW, Young GM (1995) Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleo weathering conditions and provenance. *Geology* 23:921–924.

⁶³ Nesbitt HW, Young GM (1982) Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature* 299:715–717

⁶⁴ Nesbitt, H. W., & Young, G. M. (1984). Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochimica et Cosmochimica Acta*, 48(7), 1523–1534. [https://doi.org/10.1016/0016-7037\(84\)90408-3](https://doi.org/10.1016/0016-7037(84)90408-3)

Figure 8 presents a plot of ICV versus CIA, highlighting the degree of weathering and compositional maturity of detrital siliciclastic sediments within the Eze-Aku Formation (e.g., ⁶⁵).

The Chemical Index of Weathering (CIW) serves as an effective parameter for assessing weathering intensity and evaluating the impact of potassium (K) metasomatism on sediments^{66 67 68 69}. This index quantifies chemical weathering, where a CIW of 50 represents unweathered upper continental crust, while a value of 100 signifies extreme weathering with the complete depletion of alkali elements⁷⁰. The Eze-Aku Formation's CIW values average 82.06 and range from 3.66 to 99.88. These numbers imply that there was substantial chemical weathering of the source rock. The high CIW average indicates a substantial depletion of alkalis (Na and Ca) and highlights the advanced stage of weathering processes that affected the sediments. This degree of alteration reflects a prolonged exposure of the source material to chemical weathering under prevailing environmental conditions, emphasizing the transformation of the parent rock and the likely influence of K-metasomatism during sedimentary processes.

Paleo-Redox conditions

Trace elements sensitive to redox conditions, such as Ni, V, Cr, Th, U, and Co, provide valuable insights into the oxidation-reduction state of depositional environments⁷¹. Key elemental ratios, including U/Th, Ni/Co, V/Ni, and Cu/Zn, are widely used to assess and interpret paleo-redox conditions during the deposition of sediments (e.g., ⁷²). Trace element analysis of the Eze-Aku Formation (Fig. 7) offers significant insights into its depositional environment.

Jones and Manning (1994) noted that elements such as V and Cr are generally insoluble under reducing conditions but tend to dissolve in oxic environments. The presence of these elements in significant quantities in formations such as the Keana/Awe Formation indicates deposition under reducing conditions. The average V/Cr ratio of the Eze-Aku Formation is greater than 0.52,

⁶⁵ Long, X., Yuan, C., Sun, M., Xiao, W., Wang, Y., Cai, K., & Jiang, Y. (2012). Geochemistry and Nd isotopic composition of the Early Paleozoic felsic sequence in the Chinese Altai, Central Asia: evidence for a northward derived mafic source and insight into Nd model ages in accretionary orogen. *Gondwana Research*, 22, 554–566. <https://doi.org/10.1016/j.gr.2011.04.009>

⁶⁶ Ahmad, I., Chandra, R., 2013. Geochemistry of loess-paleosol sediments of Kashmir Valley, India: provenance and weathering. *J. Asian Earth Sci.* 66, 73–89.

⁶⁷ Dar, S.A., Khan, K., Mir, A.R., 2020. Provenance and paleo-weathering of Paleoproterozoic siliciclastic sedimentary rocks of Bijawar Group, Sonrai Basin, Uttar Pradesh, India: using a geochemical approach. *Journal of Sedimentary Environments* 5, 399–413.

⁶⁸ Fedo CM, Nesbitt HW, Young GM (1995) Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleo weathering conditions and provenance. *Geology* 23:921–924.

⁶⁹ Harnois, L., 1988. The CIW index: a new chemical index of weathering. *Sediment. Geol.* 55, 319–322.

⁷⁰ McLennan, S. M., Hemming, S., McDaniell, D. K., Hanson, G. N. (1993). Geochemical approaches to sedimentation, provenance, and tectonics. In: *Geological Society of America Special Paper* (Vol. 284, pp. 21–40). <https://doi.org/10.1130/SPE284-p21>

⁷¹ Galarraga, F., Reategui, K., Martínez, A., Martínez, M., Llamas, J., Márquez, G., 2008. V/ Ni ratio as a parameter in palaeoenvironmental characterisation of nonmature medium-crude oils from several Latin American basins. *J. Petrol. Sci. Eng.* 61, 9–14.

⁷² Akkoca, B. D., Eriş, K. K., Çağatay, M. N., & Biletekin, D. (2019). The mineralogical and geochemical composition of Holocene sediments from Lake Hazar, Elazığ, Eastern Turkey: Implications for weathering, paleoclimate, redox conditions, provenance, and tectonic setting. *Turkish Journal of Earth Sciences*, 28, 760–785. <https://doi.org/10.3906/yer-1812-8>

pointing to an anoxic depositional environment.⁷³ propose that the V/Ni ratio is a reliable indicator of paleo-redox settings in sedimentary environments.

Specifically, a V/Ni ratio exceeding 3 indicates an anoxic environment, values ranging from 1.9 to 3 suggest dysoxic conditions, and ratios below 1.9 are indicative of oxic conditions. In the case of the Eze-Aku Formation, the V/Ni ratios vary significantly, varying between 0 and 14.28, with a mean value of 2.17 (Fig. 5). This range suggests variability in redox conditions during deposition, with most values falling within the dysoxic range, although occasional shifts toward either oxic or anoxic conditions are evident. With slight variability suggesting sporadic dysoxic conditions, these findings imply that the sediments were deposited primarily under anoxic circumstances.

Because it represents the salinity of the depositional environment, the Sr/Ba ratio is another crucial stand-in for interpreting paleosalinity⁷⁴. Freshwater systems typically exhibit lower Sr/Ba ratios (<0.2), while saline marine environments have higher ratios (>0.5). Intermediate Sr/Ba ratios are often indicative of brackish water conditions (e.g.,⁷⁵). In the Eze-Aku Formation, Sr/Ba ratios vary between 0.03 and 5.01, with an average of 0.49. This range suggests that the sediment deposition predominantly occurred in a freshwater environment. However, the occasional higher ratios point to intermittent influences of brackish water, likely due to fluctuations in salinity caused by changes in water influx or marine incursions. These results offer significant understanding of the paleoenvironmental conditions and the depositional dynamics within the formation. Overall, the combination of redox-sensitive trace element ratios and Sr/Ba data indicates that the Eze-Aku Formation was deposited under anoxic to dysoxic conditions in a freshwater to slightly brackish setting, reflecting complex depositional dynamics.⁷⁶

Tectonic setting

Earlier studies have demonstrated that the major and trace element geochemistry of clastic rocks can provide insights into their tectonic environment. (e.g.,^{77 78}). These geochemical markers shed light on the tectonic background and depositional conditions of sedimentary basins.

In this study, the tectonic environment of the Eze-Aku Formation was evaluated using the multidimensional classification diagram proposed by⁷⁹. The geochemical data from the formation

⁷³ Akkoca, B. D., Eriş, K. K., Çağatay, M. N., & Biltekin, D. (2019). The mineralogical and geochemical composition of Holocene sediments from Lake Hazar, Elazığ, Eastern Turkey: Implications for weathering, paleoclimate, redox conditions, provenance, and tectonic setting. *Turkish Journal of Earth Sciences*, 28, 760–785. <https://doi.org/10.3906/yer-1812-8>

⁷⁴ Cao, J., Wu, M., Chan, Y., Hu, K., Bian, L. Z., Wang, L. G., & Zhang, Y. (2012). Trace and rare earth elements geochemistry of Jurassic mudstones in the northern Qaidam basin, northwest China. *Chemie Der Erde*, 72, 245–252. <https://doi.org/10.1016/j.chemer.2011.12.002>

⁷⁵ Wei, W., Algeo, T.J., 2020. Elemental proxies for paleosalinity analysis of ancient shales and mudrocks. *Geochem. Cosmochim. Acta* 287, 341–366.

⁷⁶ Roser BP, Korsch RJ (1988) Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. *Chem Geol* 67:119–139Capaldi et al., 2020;

⁷⁷ Roser, B. P., & Korsch, R. J. (1986). Determination of tectonic setting of sandstone- mudstone suites using SiO₂ content and K₂O/Na₂O ratio. *Journal of Geology*, 94(5), 635–650. <https://doi.org/10.1086/629071>

⁷⁸ Roser BP, Korsch RJ (1988) Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. *Chem Geol* 67:119–139Capaldi et al., 2020

⁷⁹ Ibid.,⁷⁷

were plotted on this diagram, and the results indicate that the formation falls within the passive margin field (Fig. 9). This positioning aligns with the tectonic characteristics commonly associated with passive margin environments. This alignment corresponds with the geological evolution of the Benue Trough which is recognized for its development in a passive margin environment. This suggests that the tectonic processes responsible for the formation's deposition were influenced by the characteristics of a passive continental margin, reflecting the broader regional tectonic context (Fig. 9).

The classification of the Eze-Aku Formation as being part of a passive margin suggests that its sediments were primarily sourced from a stable continental area and deposited in an environment characterized by tectonic stability. This interpretation reinforces the notion that the Benue Trough, situated within the larger West African rift system, developed during the rifting phase associated with the breakup of Gondwana. As a result, the sedimentary deposits within the trough are reflective of the passive margin dynamics that prevailed during this period. The geochemical data further corroborates this view, offering strong evidence for the tectonic processes at play and the overall depositional history of the formation. These results enhance our understanding of the tectonic history of the Benue Trough and the characteristics of its related sedimentary settings.

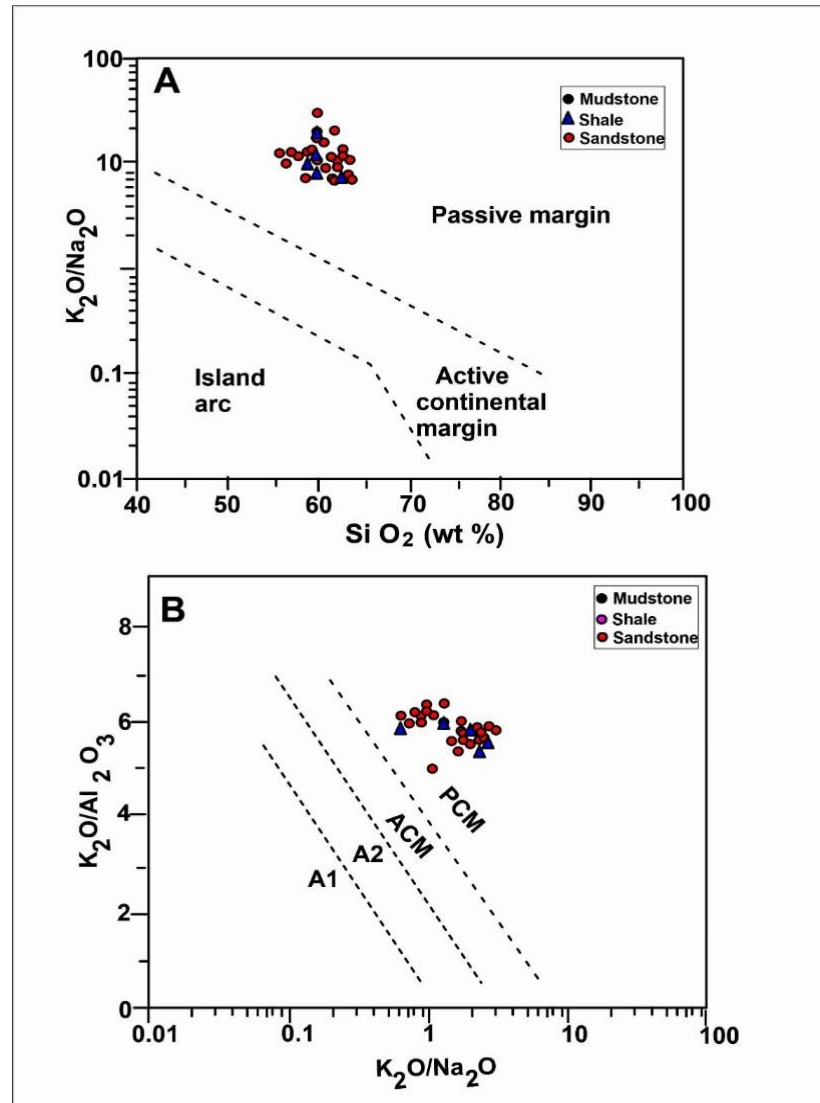


Figure 9 presents tectonic setting discrimination diagrams following⁸⁰. (A) a K_2O/Na_2O versus SiO_2 plot and (B) a SiO_2/Al_2O_3 versus K_2O/Na_2O plot. The abbreviations denote different depositional environments: ACM represents an active continental margin, PM corresponds to a passive margin, A1 signifies an arc setting with basaltic and andesitic detritus, and A2 indicates an evolved arc setting dominated by felsic-plutonic material.

Conclusion

Geochemical analyses of the Eze-Aku clastic sediments from the Shendam area of the Middle Benue Trough have provided valuable insights into their origin and depositional environment. The findings from this study indicate that the source area of the Eze-Aku Formation experienced considerable chemical weathering, resulting in sediments that are compositionally immature.

⁸⁰ Roser, B. P., & Korsch, R. J. (1986). Determination of tectonic setting of sandstone- mudstone suites using SiO_2 content and K_2O/Na_2O ratio. *Journal of Geology*, 94(5), 635–650. <https://doi.org/10.1086/629071>

Provenance analysis points to a primary derivation of these sediments from intermediate igneous rocks, suggesting that the weathered material came from stable continental sources. Additionally, the geochemical evidence suggests that sediment deposition occurred within a passive margin setting, which is consistent with the broader geological context of the Benue Trough.

The geochemical data indicate that the sediments were predominantly deposited in a freshwater setting, with limited marine influence. This is reflected in the sedimentary characteristics and elemental ratios, which are indicative of low salinity and freshwater influences. These findings offer a detailed perspective on the depositional processes and environmental factors that influenced the Eze-Aku Formation, shedding light on its geochemical development and the broader tectonic evolution of the Benue Trough. This study contributes to a better conception of the geological history of the Eze-Aku Formation, shedding light on the sedimentary processes and tectonic evolution that influenced the Middle Benue Trough. It emphasizes the interplay between source rock characteristics, weathering intensity, and depositional settings in shaping the sedimentary record of this region.

Geochemical analyses of the Eze-Aku clastic sediments from the Shendam area in the Middle Benue Trough have yielded significant insights into their origin, weathering history, depositional processes, and tectonic setting. Evidence presented in this study shows that there was significant chemical weathering in the source location, indicative of prolonged exposure to atmospheric and environmental conditions that altered the original mineralogy of the parent rocks. This intense weathering, combined with evidence of sediment recycling, has resulted in clastic sediments that are compositionally immature, retaining signatures of their provenance and depositional processes.

Provenance analysis indicates that the sediments mainly originated from intermediate igneous sources, likely representing a mixture of volcanic and plutonic sources. The geochemical composition, including major and trace element ratios, supports this interpretation, providing a direct link between the source material and the depositional environment. The tectonic setting, inferred from discrimination diagrams and elemental ratios, points to deposition in a passive margin environment. This result aligns with the regional tectonic setting of the Benue Trough, which evolved as a rift basin during the fragmentation of Gondwana. The passive margin context suggests that the sediments were derived from a stable continental source and transported to the basin under relatively quiescent tectonic conditions.

Further evidence from geochemical indicators highlights the depositional environment of the Eze-Aku Formation. Trace element ratios, such as Sr/Ba, point to a predominantly freshwater depositional setting with minimal marine influence, suggesting a river-dominated or lacustrine system during sediment deposition. This interpretation aligns with paleoenvironmental reconstructions that propose a dynamic interaction between terrestrial and marginal marine processes in the Benue Trough during the Cretaceous period.

The study of the Eze-Aku Formation provides critical insights into the complex interplay of geological processes that shaped the Middle Benue Trough. It underscores the role of source rock composition, weathering intensity, and tectonic activity in influencing sedimentary characteristics. Moreover, these findings contribute to a broader understanding of the sedimentary processes and tectonic evolution of intracontinental basins, offering a valuable framework for reconstructing the geological history of similar sedimentary systems worldwide.

By combining provenance analysis, weathering indices, tectonic setting discrimination, and paleoenvironmental indicators, this research enhances our understanding of the depositional history of the Eze-Aku Formation. It sheds light on the sedimentary processes, paleogeography, and environmental conditions that prevailed during its formation, contributing to a more comprehensive view of the Cretaceous geological evolution of the Benue Trough.

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