https://dx.doi.org/10.4314/dujopas.v10i1c.10
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 10 No. 1c March 2024*

Chemostratigraphy of the Cretaceous Yolde Formation in Yola Sub-Basin, Northern Benue Trough, Ne Nigeria

Rufai, Ahmad Fauziyah [1], Nuhu K. Samaila [2], Maigari, Abubakar Sadiq [2], Finthan Boniface [1]

[1]Department of Geology,
Modibbo Adama University,
Yola, Nigeria

[2]Department of Applied Geology,
Abubakar Tafawa Balewa University,
Bauchi, Nigeria

Email: finthanboniface@gmail.com

Abstract

This research aims to determine the chemostratigraphy of the Yolde Formation. The formation has been inadequately studied systematically in the light of chemostratigraphy. The existing works on the formation either lack representativeness in terms of the proxies used or are subjective during their division procedures. From the field studies, five (5) samples of sandstone and shale units of the Yolde Formation were collected. The samples were analyzed for both major and trace elements using an X-ray fluorescence machine. The following geochemical parameters were studied; Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr. From the studies, six (6) chemozones were identified in the Yolde Formation. Transgressive and regressive depositional sequences were observed with a significant sequence boundary of maximum flooding surface which is a time-significant feature. The chemostratigraphic scheme could not only be comparable to the regional sequence stratigraphic scheme but also more objective and higher resolution. This research gives a systematic chemostratigraphic analysis of Yolde Formation, which testifies to the feasibility and potential of the usage of chemostratigraphy for stratigraphic development.

Keywords: Chemostratigraphy, Yolde Formation, geochemistry, chemozones, Yola Arm

Introduction

Chemostratigraphy is a scientific research method that involves the analysis of chemical variations in rock strata to understand and interpret geological processes and events. This approach utilizes the measurement of trace and major elements, such as Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3,, CaO, Cr, Rb/Sc, and Zr, to observe and discuss even subtle changes in stratigraphic succession (Amodio *et al.,* 2008; Ramkumar *et al.,* 2015; oureiyatou *et al.,* 2020; Kwankam *et al.,* 2021; Silesian et al., 2024). By examining the elemental composition of rocks, chemostratigraphy provides valuable insights into the depositional environment, diagenetic alterations, and correlation of sedimentary sequences. The use of trace and major elements in chemostratigraphy allows researchers to identify distinct geochemical signatures within rock layers (Birdwell *et al.,* 2017; Chen *et al.*, 2015; Ramkumar *et al.,* 2015; Sano *et al.*, 2013; Turner, Tréanton, *et al.,* 2015; Weissert *et al.,* 2008). These signatures can be indicative of various

**Author for Correspondence*

geological processes, including changes in sediment sources, climate fluctuations, sea and base level variations, and tectonic activities (Pearce *et al.,* 1999; Weissert *et al.,* 2008; Montero-Serrano *et al.,* 2010; Turner, Molinares-Blanco, *et al.,* 2015; Tréanton, *et al.,* 2015). Furthermore, chemostratigraphy enables the correlation of rock units across different locations based on their chemical fingerprints, providing a powerful tool for understanding regional geological history and reconstructing ancient environments.

In the context of the Yolde Formation in the Yola Arm of the Northern Benue Trough (Fig. 1 and 2), the application of chemostratigraphy presents an opportunity to fill a significant gap in scientific understanding. The Yolde Formation has not been extensively studied using chemostratigraphic methods, making it a crucial area for investigation. By employing chemostratigraphy in this region, the study aim to unravel the complex geological history preserved within the Yolde Formation and contribute to a more comprehensive understanding of the Northern Benue Trough's stratigraphic evolution. Some of the recent works that were carried out on the Yolde Formation are; (Sarki Yandoka *et al.,* 2019; Epuh & Joshua, 2020; Adepehin *et al.,* 2021).

This research endeavour is motivated by the need to expand knowledge about the Yolde Formation through a rigorous scientific approach that integrates chemostratigraphy. The utilization of trace and major elements as geochemical proxies will enable the identification and interpretation of subtle variations in stratigraphic succession within the Yolde Formation. Ultimately, this study seeks to enhance our understanding of the geological processes that shaped the Yola Arm of the Northern Benue Trough and contribute valuable insights to the broader field of stratigraphic research.

Geologic Setting

The length of the Benue Trough is estimated to be 1,000 km, and about 50-150 km wide. The basin is intracontinental and it is trending in the NE – SW direction as a rifted depression in Nigeria. The Benue Trough is a sedimentary basin filled with both continental and marine sediments. The accumulated sediments are estimated to be roughly 6,500 m Carter *et al.,* (1963). All the proposed models for the evolution of the basin have been linked to intraplate rifting. The megastructure of the basin reflects a three-arm rift model (Guiraud, 1990).

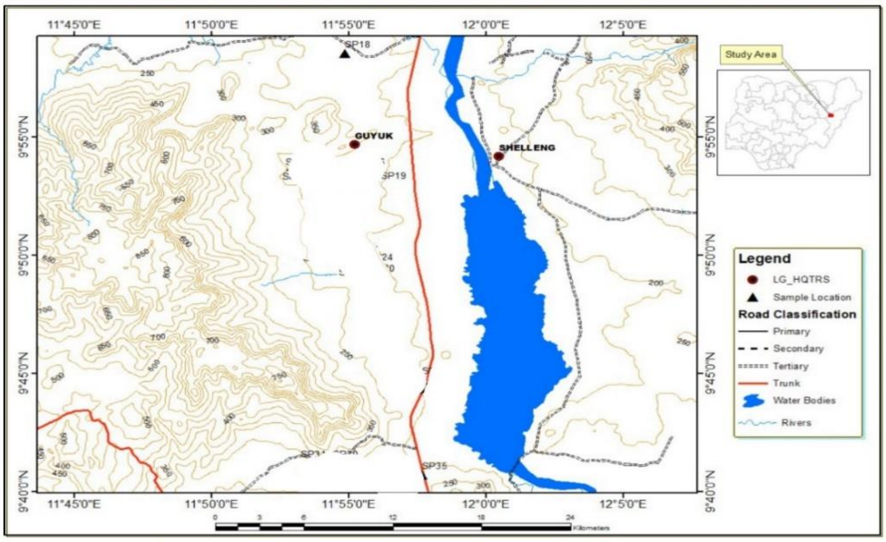

Figure.1. The topographic map of the Study area (Modified after Federal Survey Agency, 2010)

The structure of the basin and its origin due to the rifting tectonic process gave rise to deformation based on gravity data (Grant, 1971). Subsequent authors interpreted the basin as a set of pull-apart structures that started during the Early Cretaceous (Benkhelil, 1983, 1986; R. Guiraud & Maurin, 1992) and this resulted in the formation of a sinistral movement that trends in NE - SW transcurrent fault associated with the opening of Atlantic oceanic crust. Other workers believed that the basin (Benue Trough) is a product of the opening of the equatorial domain of the South Atlantic Ocean (Popoff, 1990; Fairhead & Binks, 1991). The Benue Trough has been divided into three (3) geographical regions: the Southern, Central, and Northern Benue Troughs. The Northern Benue Trough (Fig. 2) reflects a Y-shaped structure which is bounded to the Northeast by basement rocks known as Hawal Massif, and at the Southern margin by Adamawa Massif, while to the west by the sandstone of the Keri Keri Formation Cretaceous (Benkhelil, 1983, 1986; R. Guiraud & Maurin, 1992). The Northern Benue Trough is reported to have evolved into three sub-basins namely: the Muri-Lamurde which is trending northeast, Yola Arm with E – W trending, and N – S trending Gongola Arm (Fig. 2).

The Stratigraphy of the Northern Benue Trough was first developed by Carter, *et al.,* (1963). The thickest, oldest, and most exposed formation within the Yola Arm is the Bima Formation (Fig. 3). The Bima Formation nonconformably lies on the Precambrian basement complex. In sequential succession, the Bima Formation is overlain by the following formations; transitional Yolde Formation, which is overlain by five marine formations namely; the Turonian Dukul Formation, Jessu Formation, Sekuliye Formation, Numanha Formation Lamja Formation Carter et al., (1963). (Fig. 3) for the stratigraphic chart.

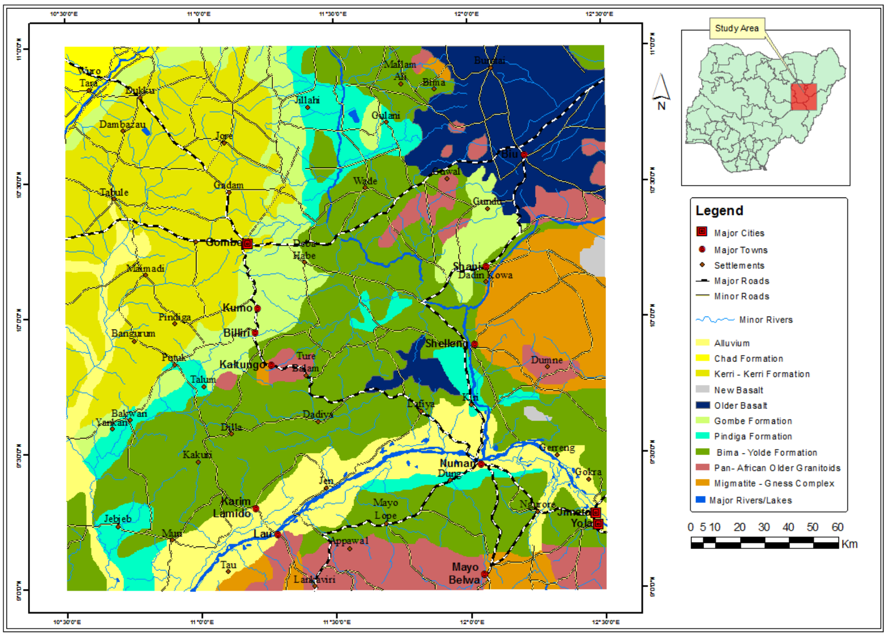

Figure. 2. Geologic map of the Northern Benue Trough (Modified after Guiraud, 1990)

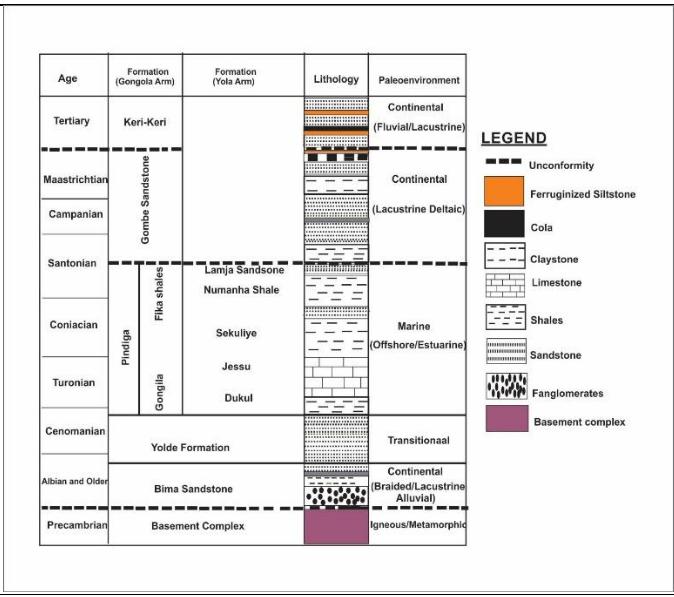

Figure 3. The Stratigraphy of Upper Benue Trough Stratigraphic succession of the Upper Benue Trough (modified by Finthan & Mamman, (2020).

Methodology

The research investigation was carried out in two phases and this involved both field study and laboratory analysis. Five representative samples were collected from the Yolde Formation, the samples were taken at a depth of 50 cm to obtain fresh samples. The samples were given ID and labelled accordingly. The second phase of the methods involves whole-rock and lithogeochemistry which was made possible with the aid of an X-ray fluorescence (XRF) machine with model name Phillips PW 1400 at Activation Laboratory Ontario, Canada. The chemostratigraphic framework for the Yolde Formation was established through constrained clustering analysis (Soureiyatou *et al.,* 2020; Kwankam *et al.,* 2021; Silesian *et al.,* 2024).

Results

The geochemical composition of sedimentary rocks is largely controlled by some peculiar factors e.g., weathering, sorting due to mechanical decomposition, diagenesis, and source rock composition (Von & Correns, 1950; Murat, 1972; Joo *et al.*, 2005). Tectonic setting, paleoclimatic conditions, and even source rock compositions of rocks can be obtained from the geochemistry of sedimentary rocks (Taylor & McLennan, 1985). Previous researchers have established the relationship between sedimentary rocks and their source areas as well as tectonic settings (Crook, 1974; Dickinson & Suczek, 1979; Dickinson, 1983; Bhatia, 1983; Bhatia & Crook, 1986; Roser & Korsch, 1986, 1988). The whole rock geochemistry of clastic sedimentary rocks could probably serve as a pointer to the source rock areas from which the sediments were generated (Taylor and McLennan, 1985). The geochemistry of the sedimentary rocks is principally controlled by weathering, transportation, and diagenesis as stated earlier and these may be identified by utilizing trace elements such as Cr, Zr, Sc, Rb, Al_2O_2, K_2O, CaO, Fe_2O_3, and Ti_2O and the interpretation of such geologic phenomenon were established with the help of the existing literature (Bhatia, (1983) Roser and Korsch, (1986); and Bhatia and Taylor, (1981), the stability of the above elements e.g Cr, Zr, Sc, Rb without losing its originalty in the process of sedimentation and transportation gives impetus for elements to be used as a tool for discriminating chemostratigraphic sequences (Catuneanu, 2002; Catuneanu et al., 2010, 2011; Selim, 2017).

The chemostratigraphy of the Yolde Formation Yola Arm of the Northern Benue Trough has not been established in detail, hence there is a need for this subject matter to be investigated through whole rock geochemistry and it necessitated the aim of this research.

The Geochemistry

The major and trace elements analyzed from the Yolde Formations are presented in (Table 1).

Table 1. The result of the lithogeochemistry and whole analysis for the Yolde Formation in Yola Arm.

Samples	Unit symbols	YF1	YF2	YF3	YF4	YF5
Al_2O_3	%	10.05	6.2	14.02	10.13	14.35
Fe_2O_3(T)	%	1.21	0.76	2.16	4.24	3.15
CaO	%	13.72	0.14	5.48	9.6	4.7
K_2O	%	3.58	2.88	1.31	0.66	1.37
TiO_2	%	0.38	0.255	0.962	0.446	0.871
Sc	ppm	1	2	7	5	8
Sr	ppm	214	74	122	266	181
Zr	ppm	653	328	657	487	527
Cr	ppm	< 20	< 20	50	20	50
Rb	ppm	103	79	54	23	52

Chemostratigraphy of the Yolde Formation

The lithosection of the Yolde Formation has been sub-divided into six chemozones based on the geochemical compositions of the representative samples with a mix of sandstone, shales, and limestone (Fig.4) which display the chemostratigraphic signatures of the data which enhance the visibility of the features of the geochemical intervals. This indicates the elemental enrichment, depletion, and continued trends as related to geochemical profiles. The studied intervals have been divided into distinct chemozones to reflect subtle variations.

The Chemozones

Chemozone I

This chemozone is composed of mudstone with a high content of clay and a low concentration of Rubidium with a high content of Zircon. The subzone has a lower amount of Chromium indicating the availability of insignificant Chromium bearing minerals. The formation characteristically shows a high amount of clay compared to the overlying sandstone chemofacies (see Fig. 4) and this is due to fact that there's abundant amount of Al_2O_3 in analyzed samples (Table 1)..

Chemozone II

This chemozone is overlying the chemozone I at the bottom of the section of the Yolde Formation, it is characterized by thick shales overlain by dark mudstone and sandstone intercalation (Fig. 4). The sandstone is fine-grained and is thinly bedded and are characterized by moderate content of clay with low content of K_2O/AL_2O_3 indicating presence of moderate plagioclase/kaolinite content with high K-feldspar/illite. Low to moderate Ti_2O/Al_2O_3 and high Zr and low to moderate Cr, reflect the availability of the Zircon and Chromium bearing minerals. The presence of Fe_2O/Al_2O_3 signifies the presence of pyrite cement in the sandstone.

Chemozone III

This subzone of the chemofacies is directly overlying the second chemozone in stratigraphic succession. It is composed of sandstone characterized by moderate content of K_2O/Al_2O which is an indicator of increase in K-feldspar/illite and a greater proportion of TiO_2/Al_2O_3 pointing towards higher concentration of Titanium bearing heavy minerals in the Yolde Formation (Fig. 4) and this is due to fact that there's abundant amount of Al_2O_3 in nalyzed samples (Farouk et al., 2018; Roy et al., 2018; Sial *et al.,* 2019; Milad *et al.,* 2020; Paronish *et al.,* 2020; Michael & Craigie, 2021; Tonner, 2022).

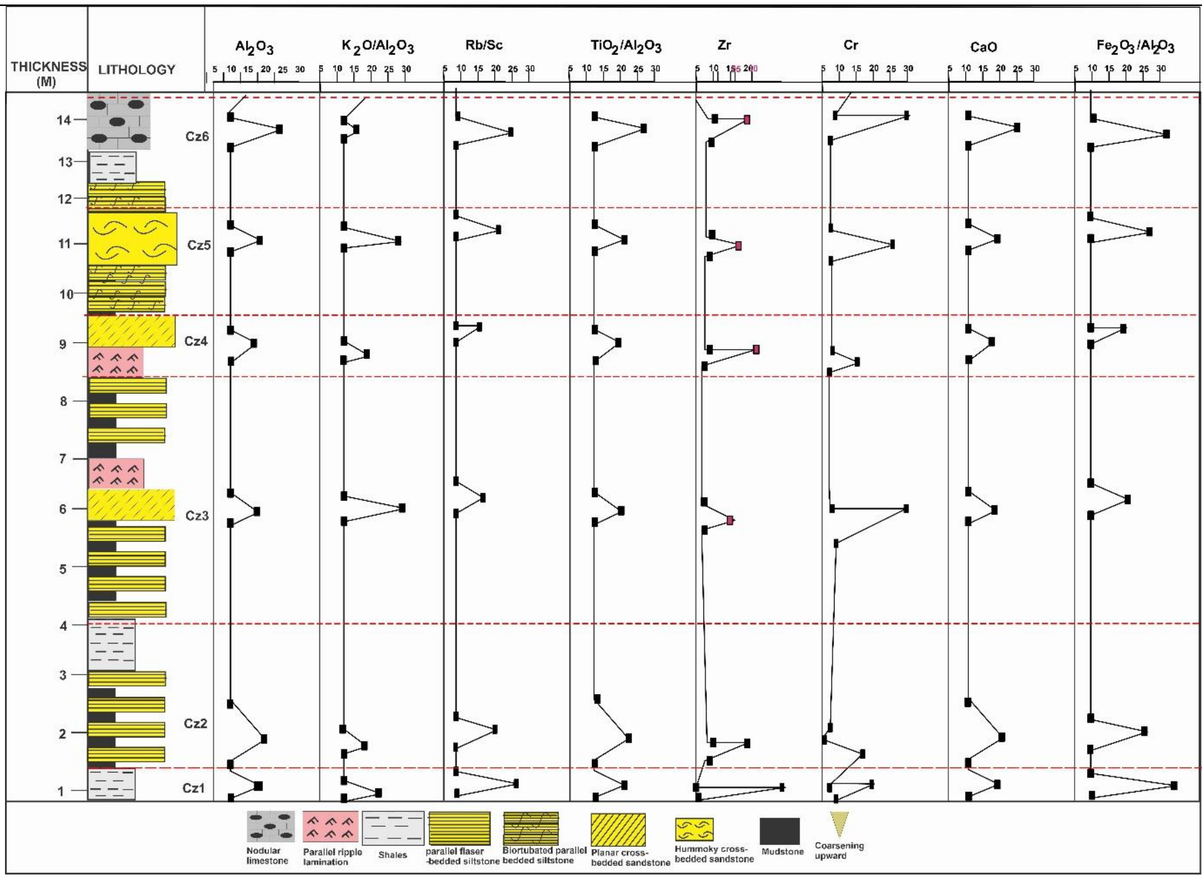

Figure 4. Major and trace elements geochemical signatures for the study intervals in Yolde Formation.

Chemozone IV

The chemozone IV is stratigraphically overlying the chemozone III. It is composed of sandstone facies unit with a high content of K_2O/Al_2O_3 indicating the abundance of K-feldspar/illite similar to the underlying chemozone III. It has a greater content of TiO_2/Al_2O_3 as well as pointing towards the presence of Titanium bearing heavy minerals.

Chemozone V

This unit of the chemofacies is also composed of sandstone facies bearing the geochemical imprints of the Yolde Formation. It is characterized by moderate clay content and with low heavy minerals bearing elements (Cr and Zr).

Chemozone VI

This chemozone is stratigraphically the shallowest of all the chemozones. It is composed of shaly nodular limestone. It has a high amount of CaO, TiO_2, and Fe_2O_3/Al_2O_3.

Discussion

While control on the chemostratigraphic implication based on the concentration of trace elements is unequivocally the amount of Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc and Zr derived from the nearby large landmass and transgressive marine sequences. Zircon (Zr) is particularly significant in indicating subtle changes in depositional sequences, though is not been observed systematically in the Yolde Formation to indicate a time-significant pattern in this study. The multiscale (meters, decimeters), repetitive rhythmic intercalating stacking pattern observed in the chemostratigraphic sequences based on Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, $TiO_2/$ Al_2O_3, CaO, Cr, Rb/Sc, and Zr logs is reminiscent of variations in sediments controlled by base-level and sea level fluctuations, irrespective of the actual variable being analyzed. For example, one can compare the Zr stacking patterns to the sigmoid, sets of the sigmoid, and cosets of the sigmoid (Pomar & Ward, 1994, 1995) and the resultant rhythmic variation in magnetic susceptibility described by (Davies *et al.*, 2014b, 2014a) in the reef complexes of Mallorca. Numerous authors have used geochemistry susceptibility as a proxy for terrestrial input and demonstrated a base-level control (da Silva *et al.*, (2009); da Silva & Boulvain, 2002, 2006; Hladil *et al.*, 2003; Racki *et al.*, 2002). However, if a base-level and sea-level control were responsible for the Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc and Zr chemostratigraphic stacking patterns in Yolde Formation. These chemostratigraphic signatures have shown close correspondence with the carbonate facies cycle stacking patterns defined by (I). While in some cases the tops of Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr cycles correspond to carbonate cycle tops (e.g., cycles 5a and 6a on Fig. 8), there is no consistent correlation between the two types of cycles. Additionally, in places, Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr maxima correspond to the top of upward-shoaling cycles, whereas elsewhere, they are coincident with the top of shallowing cycles (Fig. 4. Therefore, potentially, the Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc and Zr cycles were not created solely in response to base-level fluctuations, but with marine transgressive effect that ushered the lower part of the facies sequences in the Yolde Formation. Although the various Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc and Zr cycles do not always correspond to carbonate cycle, the change in Yolde Formation through Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, $TiO_2/$ Al_2O_3, CaO, Cr, Rb/Sc and Zr chemostratigraphic logs chemical logs occurs in association with the interpreted chemostratigraphic sequences (Fig. 4) and this this just as in WNA and WNB (Playton *et al., 2017*; Soureiyatou *et al.*, 2020; Kwankam *et al.*, 2021; Silesian *et al.*, 2024)

One potential explanation for this change in Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/ Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr stacking patterns in association with the super-sequence MFS is an increase in biohermal/reef-flat facies at the super-sequence MFS in the two sections as observed in WNA and WNB (Playton *et al.,* 2017). According to Playton *et al.,* (2017); Biohermal facies are highly productive, and with increased accommodation associated with the MFS, increasing carbonate production in a reef-flat setting would dilute clastic content, assuming relatively constant clastic supply. However in the Yolde Formation, it is obvious that there are clear, well-defined sandstone beds and shale sequences derived from a nearby landmass and transitional marine facies, it is reasonable to assume that Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc and Zr delivery to Yolde Formation was but riverine and marine, which qualifies it to be transitional as reported by Carter, *et al.,* (1963). This finding may be correct, because cycles 1 through 4 indicate a repeated pattern of gradual increase in silt- to fine-sand-sized terrigenous content of the sediment over approximately 10 m of section, followed by a sharp increase over about 1 m of section. Cycles 5 and 6, by contrast, indicate a repeated pattern of gradual increase in terrigenous content, followed by a gradual decrease in the terrigenous content with limestone capping the section. In this case, the underlying chemostratigraphic 1 through 4 likely represent a prograding sequence, culminating in a maximum regressive surface (MRS). Such stacking patterns reflect consistent with the position in a long-term transgressive system tract (TST) because cycles within longer-term TSTs have part of the flooding/rise preserved within them. This depositional scenario is similarly reflected in the case Yolde Formation in the Yola Arm of the Northern Benue Trough. The terrigenous content of the fluvial depositional facies of the Yolde Formation is linked to base-level fluctuations as it also reflects positive accommodation space, whereas, the underlying transitional marine facies reflect negative accommodation space ((Farouk *et al.*, 2018; Roy *et al.,* 2018; Sial *et al.,* 2019; Milad *et al.,* 2020; Paronish *et al.,* 2020; Michael & Craigie, 2021; Tonner, 2022). Reflecting on these depositional processes, the Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr stacking patterns in cycles 1 through 4 started with high accommodation and reduce to a minimum at the top of a cycle, and there is a rapid increase in accommodation spaces. Therefore, a windblown delivery mechanism means the transgressive–regressive patterns suggested by the Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr concentrations are again consistent with the move toward a super-sequence TST, where overall deepening and preservation of both prograding and retrograding parts of cycles have been clearly expressed. Furthermore, the significant fluctuations of the Al_2O_3, Al_2O_3/Fe_2O_3, KO_2/Al_2O_3, TiO_2/Al_2O_3, CaO, Cr, Rb/Sc, and Zr concentrations in zigzag form suggest that long-term climatic fluctuations are likely the driving factor. Reworking of the clastic component, postdelivery will influence the distribution of sediments on the shoreface. The narrow shoreface has been prone to current sweeping and longshore drift processes, and the complex reentrant and promontory paleogeography of the shoreface (Playford *et al.* 2009) has caused complexity in currents, with resultant highly localized sediment dispersal patterns. Siliciclastic detritus is recorded throughout the shoreface deposits, intricately commingled with the carbonates and also forming discrete sandstone beds (Hillbun *et al.*, 2015). This suggests that the terrestrial component, in this case, in the form of sandstone beds, was not reacting exclusively to the base level. The ubiquitous presence of siliciclastic material in the platform-top setting was due to the constant proximity of the shoreline, which in turn was due to the narrowness of the carbonate platform in this area. This proximity and constant supply of terrestrial detritus may be the reasons that terrestrial content fluctuations do not follow a classic carbonate siliciclastic model with reciprocal sedimentation (Farouk *et al.,* 2018; Roy *et al.,* 2018; Sial *et al.,* 2019; Milad *et al.,* 2020; Paronish *et al.,* 2020; Michael & Craigie, 2021; Tonner, 2022).

Conclusion

This research revealed that the upper part of the Yolde Formation, primarily composed of sandstone, and the lower part, consisting of thick shale and shale/siltstone intercalation, exhibit significant variability in geochemical characteristics. The geochemical analysis revealed transgressive-regressive cycles, with the identification of a prominent maximum flooding surface, serving as a significant sequence boundary in Yolde Formation stratigraphy. This observation aligns with two concurrent global eustasy events. Leveraging these geochemical heterogeneities, a chemostratigraphic framework for the Yolde Formation was established through constrained clustering analysis, leading to the identification of six distinct chemozones. These chemozones demonstrate comparability to regional sequence stratigraphic schemes and offer enhanced resolution.

References

Adepehin, E. J., Oretade, B. S., & Ola, P. S. (2021). Late Cretaceous Palynostratigraphy of Subsurface Sediments of Southern Bornu Basin, Nigeria: Implications for Depositional Environments and Palaeoclimate. *ResearchSquare*. https://doi.org/10.21203/rs.3.rs-782143

Amodio, S., Ferreri, V., D'Argenio, B., Weissert, H., & Sprovieri, M. (2008). Carbon-isotope stratigraphy and cyclostratigraphy of shallow-marine carbonates: the case of San Lorenzello, Lower Cretaceous of southern Italy. *Cretaceous Research*, *29*(5–6), 803–813. https://doi.org/10.1016/j.cretres.2008.05.022

Benkhelil, M. J. (1983). Is the Benue Trough a ridge. *Bull. Centre Rech. Exploration Production Elf*, *7*, 315–321.

Benkhelil, M. J. (1986). Structure evolution geodynamique due basin intercontinental de la Benoue (Nigeria). *Bull. CentresRech. Explor. Prod*, *12*(1), 29–128.

Bhatia, M. R. (1983). Plate tectonics and geochemical composition of sandstones. *Journal of Geology*, *91*(6), 611–627. https://doi.org/10.1086/628815

Bhatia, M. R., & Crook, K. A. W. (1986). Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contributions to Mineralogy and Petrology*, *92*(2), 181–193. https://doi.org/10.1007/BF00375292

Birdwell, J. E., Boehlke, A. R., Paxton, S. T., Whidden, K. J., & Pearson, O. N. (2017). Geochemical and mineralogical characterization of the Eagle Ford Shale: results from the USGS Gulf Coast #1 West Woodway core. *GCAGS Transactions*, *67*, 391–395.

Carter, J.D., Barber, W., Tait, E.A., & Jones, G. P. (1963). The Geology of parts of Adamawa, Bauchi and Bornu Provinces in north-eastern Nigeria. *Bulletin Geological Survey Nigeria*, *30*, 1–108.

Catuneanu, O. (2002). Sequence stratigraphy of clastic systems: Concepts, merits, and pitfalls. *Journal of African Earth Sciences*, *35*(1), 1–43. https://doi.org/10.1016/S0899-5362(02)00004-0

Catuneanu, O., Bhattacharya, J. P., Blum, M. D., Dalrymple, R. W., Eriksson, P. G., Fielding, C. R., Fisher, W. L., Galloway, W. E., Gianolla, P., Gibling, M. R., Giles, K. A., Holbrook, J. M., Jordan, R., Kendall, C. G. S. C., Macurda, B., Martinsen, O. J., Miall, A. D., Nummedal, D., Posamentier, H. W., … Tucker, M. E. (2010). Sequence stratigraphy: Common ground after three decades of development. *First Break*, *28*(1), 41–54.

Catuneanu, O., Galloway, W. E., Kendall, C. G. S. C., Miall, A. D., Posamentier, H. W., Strasser, A., & Tucker, M. E. (2011). Sequence Stratigraphy: Methodology and nomenclature. *Newsletters on Stratigraphy*, *44*(3), 173–245. https://doi.org/10.1127/0078-0421/2011/0011

Chen, L., Lu, Y., Jiang, S., Li, J., Guo, T., Luo, C., & Xing, F. (2015). Sequence stratigraphy and its application in marine shale gas exploration: A case study of the Lower Silurian

Longmaxi Formation in the Jiaoshiba shale gas field and its adjacent area in southeast Sichuan Basin, SW China. *Journal of Natural Gas Science and Engineering*, *27*, 410–423. https://doi.org/10.1016/j.jngse.2015.09.016

CROOK, K. A. W. (1974). Lithogenesis and Geotectonics: the Significance of Compositional Variation in Flysch Arenites (Graywackes). In R. H. Dott & R. H. Shaver (Eds.), *Modern and Ancient Geosynclinal Sedimentation* (pp. 304–310). Society of Economic Paleontologists and Mineralogists. https://doi.org/10.2110/pec.74.19.0304

da Silva, A. C., & Boulvain, F. (2002). Sedimentology, magnetic susceptibility and isotopes of a Middle Frasnian carbonate platform: Tailfer section, Belgium. *Facies*, *46*(46), 89–102. https://doi.org/10.1007/bf02668075

da Silva, A. C., & Boulvain, F. (2006). Upper Devonian carbonate platform correlations and sea level variations recorded in magnetic susceptibility. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *240*(3–4), 373–388. https://doi.org/10.1016/j.palaeo.2006.02.012

da Silva, A. C., Potma, K., Weissenberger, J. A. W., Whalen, M. T., Humblet, M., Mabille, C., & Boulvain, F. (2009). Magnetic susceptibility evolution and sedimentary environments on carbonate platform sediments and atolls, comparison of the Frasnian from Belgium and Alberta, Canada. *Sedimentary Geology*, *214*(1–4), 3–18. https://doi.org/10.1016/j.sedgeo.2008.01.010

Davies, E. J., Ratcliffe, K. T., Montgomery, P., Pomar, L., Ellwood, B. B., & Wray, D. S. (2014a). A Multi-Facetted Approach to Stratigraphy: One that is Applicable to the Oil and Gas Industry? In J. Pais, J. C. Kullberg, & S. Finney (Eds.), *Springer Geology* (pp. 895–899). Springer International Publishing, Cham, Switzerland. p. https://doi.org/10.1007/978-3-319-04364-7_169

Davies, E. J., Ratcliffe, K. T., Montgomery, P., Pomar, L., Ellwood, B. B., & Wray, D. S. (2014b). Magnetic susceptibility (χ) stratigraphy and chemostratigraphy applied to an isolated carbonate platform reef complex; Llucmajor Platform, Mallorca. In T. E. Playton & P. M. Harris (Eds.), *SEPM Special Publications* (Vol. 105, pp. 142–156). SEPM (Society for Sedimentary Geology), Tulsa, Oklahoma. p. https://doi.org/10.2110/sepmsp.105.05

Dickinson, W. R. (1983). Provenance of North American Phanerozoic sandstones in relation to tectonic settings. *Geological Society of America Bulletin*, *94*(2), 222–235. https://doi.org/10.1130/0016-7606(1983)94<222:PONAPS>2.0.CO;2

Dickinson, W. R., & Suczek, C. (1979). Plate tectonics and sandstone composition. *American Association of Petroleum Geologists Bulletin*, *63*(12), 2164–2182. https://doi.org/10.1306/2f9188fb-16ce-11d7-8645000102c1865d

Epuh, E. E., & Joshua, E. O. (2020). Modeling of porosity and permeability for hydrocarbon Exploration: A case study of Gongola arm of the Upper Benue Trough. *Journal of African Earth Sciences*, *162*, 103646. https://doi.org/10.1016/j.jafrearsci.2019.103646

Fairhead, J. D., & Binks, R. M. (1991). Differential opening of the Central and South Atlantic Oceans and the opening of the West African rift system. *Tectonophysics*, *187*(1–3), 191–203. https://doi.org/10.1016/0040-1951(91)90419-S

Farouk, S., Al-Zubi, H., Abdelkader, T., & Ahmad, F. (2018). Facies associations and chemostratigraphy of the Lower Cretaceous Kurnub Group and their boundaries, King Talal Dam section, northwestern Jordan. *Environmental Geosciences*, *25*(1), 1–23. https://doi.org/10.1306/eg.01241817012

Finthan, B., & Mamman, Y. D. (2020). The lithofacies and depositional paleoenvironment of the Bima Sandstone in Girei and Environs, Yola Arm, Upper Benue Trough, Northeastern Nigeria. *Journal of African Earth Sciences*, *169*(2020), 103863. https://doi.org/10.1016/j.jafrearsci.2020.103863

Grant, N. K. (1971). South Atlantic, Benue Trough, and Gulf of Guinea cretaceous triple junction. *Bulletin of the Geological Society of America*, *82*(8), 2295–2298. https://doi.org/10.1130/0016-7606(1971)82[2295:SABTAG]2.0.CO;2

Guiraud, M. (1990). Tectono-sedimentary framework of the early Cretaceous continental Bima formation (upper Benue Trough, NE Nigeria). *Journal of African Earth Sciences*, *10*(1–2), 341–353. https://doi.org/10.1016/0899-5362(90)90065-M

Guiraud, R., & Maurin, J. C. (1992). Early Cretaceous rifts of Western and Central Africa: an overview. In P. A. Ziegler (Ed.), *Tectonophysics* (Vol. 213, Issues 1–2, pp. 153–168). North and South America and Africa. Tectonophysics 213. https://doi.org/10.1016/0040-1951(92)90256-6

Hillbun, K., Playton, T. E., Tohver, E., Ratcliffe, K., Trinajstic, K., Roelofs, B., Caulfield-Kerney, S., Wray, D., Haines, P., Hocking, R., Katz, D., Montgomery, P., & Ward, P. (2015). Upper Kellwasser carbon isotope excursion pre-dates the F-F boundary in the Upper Devonian Lennard Shelf carbonate system, Canning Basin, Western Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *438*, 180–190. https://doi.org/10.1016/j.palaeo.2015.07.035

Hladil, J., Bosak, P., Slavik, L., Carew, J. L., Mylroie, J. E., & Gersl, M. (2003). Early diagenetic origin and persistence of gamma-ray and magnetosusceptibility patterns in platform carbonates: Comparison of Devonian and Quaternary sections. *Physics and Chemistry of the Earth*, *28*(16–19), 719–727. https://doi.org/10.1016/S1474-7065(03)00130-X

Michael, N. A., & Craigie, N. W. (2021). Application of principal component analysis on chemical data for reservoir correlation: A case study from Cretaceous carbonate sedimentary rocks, Saudi Arabia. *AAPG Bulletin*, *105*(4), 785–807. https://doi.org/10.1306/10142019105

Milad, B., Slatt, R., & Fuge, Z. (2020). Lithology, stratigraphy, chemostratigraphy, and depositional environment of the Mississippian Sycamore rock in the SCOOP and STACK area, Oklahoma, USA: Field, lab, and machine learning studies on outcrops and subsurface wells. *Marine and Petroleum Geology*, *115*, 10427. https://doi.org/10.1016/j.marpetgeo.2020.104278

Montero-Serrano, J. C., Palarea-Albaladejo, J., Martín-Fernández, J. A., Martínez-Santana, M., & Gutiérrez-Martín, J. V. (2010). Sedimentary chemofacies characterization by means of multivariate analysis. *Sedimentary Geology*, *228*(3–4), 218–228. https://doi.org/10.1016/j.sedgeo.2010.04.013

Murat, R. C. (1972). Stratigraphy and paleogeography of the Cretaceous and Lower Tertiary in Southern Nigeria. In A. J. Whitman (Ed.), *African geology, University of Ibadan press* (Vol. 1, Issue 1, pp. 251–266). Journal of African Geology.

Obaje, N. G., Pearson, M. J., Suh, C. E., & Dada, S. S. (1999). Organic geochemical characterization of potential hydrocarbon source rocks in the Upper Benue Trough. *Journal of Mining and Geology*, *35*(2), 137–152.

Paronish, T., Toth, R., Carr, T., Agrawal, V., Crandall, D., & Moore, J. (2020). *Multi-Scale Lithofacies and Chemostratigraphic Analysis of Two Middle Devonian Marcellus Shale Wells in Northern West Virginia, USA*. https://doi.org/10.15530/urtec-2020-2763

Pearce, T. J., Besly, B. M., Wray, D. S., & Wright, D. K. (1999). *1-s2.0-S0037073898001286-main.pdf*. *124*, 197–220.

Playton, T. E., Hocking, R. M., Tohver, E., Hillbun, K., Haines, P. W., Trinajstic, K., Roelofs, B., Katz, D. A., Kirschvink, J. L., Grice, K., Montgomery, P., Hansma, J., Yan, M., Pisarevsky, S., Tulipani, S., Ratcliffe, K., Caulfield-Kerney, S., & Wray, D. (2017). Integrated Stratigraphic Correlation of Upper Devonian Platform-to-Basin Carbonate Sequences, Lennard Shelf, Canning Basin, Western Australia: Advances in Carbonate Margin-to-Slope Sequence Stratigraphy and Stacking Patterns. In C. Kerans & J. Weissenberger (Eds.), *New Advances in Devonian Carbonates: Outcrop Analogs,* *Reservoirs, and Chronostratigraphy* (pp. 248–301). New Advances in Devonian Carbonates: Outcrop Analogs, Reservoirs, and Chronostratigraphy: Special Publication 107: SEPM (Society for Sedimentary Geology), Tulsa, Oklahoma. https://doi.org/10.2110/sepmsp.107.10

Pomar, L., & Ward, W. C. (1994). Response of a late Miocene Mediterranean reef platform to high- frequency eustasy. *Geology*, *22*(2), 131–134. https://doi.org/10.1130/0091-7613(1994)022<0131:ROALMM>2.3.CO;2

Pomar, L., & Ward, W. C. (1995). Sea-level changes, carbonate production and platform architecture: the Llucmajor Platform, Mallorca, Spain. In B. U. Haq (Ed.), *Sequence stratigraphy and depositional response to eustatic, tectonic and climatic forcing* (pp. 87–112). p. https://doi.org/10.1007/978-94-015-8583-5_4

Popoff, M. (1990). Les gres de Bima (Alba-Aptien) dans la region de Mayo Lope N. *E. Nigeria*, *5*, 363–364.

Racki, G., Racka, M., Matyja, H., & Devleeschouwer, X. (2002). The Frasnian/Famennian boundary interval in the South Polish-Moravian shelf basins: Integrated event-stratigraphical approach. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *181*(1–3), 251–297. https://doi.org/10.1016/S0031-0182(01)00481-3

Ramkumar, M., Alberti, M., & Fürsich, F. T. (2015). Chemostratigraphy of the Dhosa Oolite Member (Oxfordian), Kachchh Basin, Western India: Implications for Completeness of the Stratigraphic Record and Correlation with Global Oolite Peak. In M. Ramkumar (Ed.), *Chemostratigraphy: Concepts, Techniques, and Applications* (pp. 309–340). Elsevier. https://doi.org/10.1016/B978-0-12-419968-2.00012-1

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

Roser, B. P., & Korsch, R. J. (1988). Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. *Chemical Geology*, *67*(1–2), 119–139. https://doi.org/10.1016/0009-2541(88)90010-1

Roy, P. D., Ramkumar, M., & Nagarajan, R. (2018). Cenozoic Chemostratigraphy: Understanding the Most Recent Era of the Earth's History. In G. A. N., R. C., & F. M. (Eds.), *Geophysical Monograph Series* (Vol. 240, pp. 261–277). Chemostratigraphy across Major Chronological Boundaries. https://doi.org/10.1002/9781119382508.ch13

Sano, J. L., Ratcliffe, K. T., & Spain, D. R. (2013). Chemostratigraphy of the haynesville shale. In J. Gale (Ed.), *AAPG Memoir* (Vol. 105, pp. 137–154). American Association of Petroleum Geologists, Tulsa, Oklahoma. p. https://doi.org/10.1306/13441847M1053602

Sarki Yandoka, B. M., Abdullah, W. H., Abubakar, M. B., Johnson, H., Adegoke, A. K., Arabi, A. S., Bata, T. P., Amir Hassan, M. H., Mustapha, K. A., & Usman, M. B. (2019). Shoreface facies model of Cretaceous Jessu Formation, Yola Sub-basin, Northern Benue Trough, northeast Nigeria: New insights from facies analysis and molecular geochemistry. *Journal of African Earth Sciences*, *152*(December 2018), 10–22. https://doi.org/10.1016/j.jafrearsci.2019.01.006

Selim, S. S. (2017). Facies and sequence stratigraphy of fluvio-lacustrine deposits: Cretaceous Nubian succession of the Saharan platform (SW Egypt). In F. Selim (Ed.), *Proceedings of the Geologists' Association* (Vol. 128, Issue 2, pp. 271–286). Cretaceous Nubian succession of the Saharan platform (SW Egypt), Proc. Geol. Assoc. (2017. https://doi.org/10.1016/j.pgeola.2017.01.009

Sial, A. N., Gaucher, C., Ramkumar, M., & Fereira, V. (2019). Introduction: Chemo-stratigraphy as a formal stratigraphic method. In G. A. N., R. C., & F. M. (Eds.), *Sial* (pp. 3–25). Chemostratigraphy across Major Chronological Boundaries.

Taylor, S. R., & McLennan, S. M. T. C. C. (1985). Its Composition and Evolution. *An Examination of the Geochemical Record Preserved in Sedimentary Rocks (Oxford Universit*.

Tonner, D. (2022). *GEOCHEMICAL CHARACTERIZATION OF THE BONE SPRING FORMATION , DELAWARE BASIN , USING CHEMOSTRATIGRAPHY AND INTEGRATED PETROPHYSICS*.

Turner, B. W., Molinares-Blanco, C. E., & Slatt, R. M. (2015). Chemostratigraphic, palynostratigraphic, and sequence stratigraphic analysis of the Woodford Shale, Wyche Farm Quarry, Pontotoc County, Oklahoma. *Interpretation*, *3*(1), SH1–SH9. https://doi.org/10.1190/INT-2014-0089.1

Turner, B. W., Tréanton, J. A., & Slatt, R. M. (2015). The use of chemostratigraphy to refine ambiguous sequence stratigraphic correlations in marine shales: An example from the Woodford Shale, Oklahoma. *Society of Petroleum Engineers - Unconventional Resources Technology Conference, URTeC 2015*, *173*, 854–868. https://doi.org/10.2118/178574-ms

Von, I. D. V., & Correns, C. W. (1950). Zur geochemie der diagenese. *Geochimica et Cosmochimica Acta*, *1*(1), 49–54. https://doi.org/10.1016/0016-7037(50)90008-1

Weissert, H., Joachimski, M., & Sarnthein, M. (2008). Chemostratigraphy. *Newsletters on Stratigraphy*, *42*(3), 145–179. https://doi.org/10.1127/0078-0421/2008/0042-0145