Implications of Foraminiferal Assemblages and Geochemical Proxies in the Numanha Formation, Northern Benue Trough, Nigeria

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Abstract

The Numanha Formation within the Yola Arm of the Northern Benue Trough represents an important Upper Cretaceous stratigraphic interval that records significant paleoenvironmental and depositional changes associated with the evolution of the West African intracontinental rift system. Despite its stratigraphic importance, detailed multiproxy investigations integrating micropaleontology and geochemistry remains limited. This study presents a comprehensive analysis of benthonic foraminiferal assemblages and major–trace element geochemistry from twelve shale samples collected from the Numanha stream section within the period of 7th -14th of May,2025 in order to reconstruct depositional environment, oxygenation conditions, sediment provenance, and basin dynamics during the Coniacian. Quantitative foraminiferal analysis reveals assemblages dominated by arenaceous benthonic taxa, particularly *Haplophragmoides* ssp (55.59%) and *Ammobaculites* ssp (35.90%), with minor occurrences of *Ammotium* spp, *Miliammina* spp, *Reophax* spp, and *Trochammina* ssp, while planktonic foraminifera are completely absent. Geochemical analyses done using the VANTA Portable XRF machine reveal elevated concentrations with mean values such as Si>128, 862, Al>57, 004, Fe>52, 125, Ti>5, 090, K>4, 995, Zr>332 and indicating a moderate to strong influx of terrigenous material. In contrast, the enrichment of Ni>94.4, V>76.77, and Mo>3.62 suggests intermittent dysoxic to suboxic bottom water conditions. When integrated with micropaleontological evidence, these geochemical proxies suggest that deposition occurred within an inner-neritic to marginal marine shelf environment. This setting was likely characterized by high sediment supply, restricted water circulation, and episodic marine transgressions. The combined dataset supports a depositional model involving a proximal mud-dominated shelf developed during the Coniacian transgressive–regressive cycle within the Northern Benue Trough. These findings contribute to improved paleoenvironmental reconstruction, sequence stratigraphic interpretation, and evaluation of source-rock potential in the Upper Cretaceous succession of the Yola Arm.

Keywords: Numanha Formation; foraminifera; benthic foraminifera; geochemistry; paleoenvironmental; sequence stratigraphy

Introduction

The Benue Trough of Nigeria represents one of the most significant Cretaceous intracontinental rift basins in West Africa and forms part of the tectono-sedimentary system related to the opening of the South Atlantic Ocean (Burke et al., 1971; Zaborski, 1998; Obaje et al., 2006, Hamis et al,2024). The trough extends in a NE–SW direction for over 1000 km and contains a thick succession of continental to marine sediments deposited from the Aptian to Maastrichtian (Petters, 1978; Zaborski et al., 1997; Obaje, 2009, Valdon et al,2023). These sediments provide valuable records of paleogeographic evolution, sea-level fluctuations, and paleoenvironmental conditions within the West African margin during the Cretaceous.The Northern Benue Trough, particularly the Yola Arm, preserves a well-developed Upper Cretaceous succession comprising the Yolde, Dukul, Sekuliye, Numanha, and Lamja formations (Zaborski et al., 1997; Obaje et al., 2000). Among these units, the Numanha Formation represents a shale-dominated interval that is considered to be of Coniacian age and is interpreted to have been deposited in a shallow marine shelf environment under varying degrees of marine influence (Petters, 1982; Zaborski, 2003; Valdon et al., 2023).

Understanding the depositional environment of the Numanha Formation is important not only for regional stratigraphic correlation but also for hydrocarbon exploration, since mud-dominated Cretaceous successions in the Benue Trough have been shown to possess significant source-rock potential (Obaje & Hamza, 2000; Obaje et al., 1999; Abubakar et al., 2024). Previous studies have demonstrated that paleoenvironmental reconstruction in such basins is most reliable when multiple proxies are integrated, particularly micropaleontological and geochemical indicators (Tyson, 1995; Murray, 2006; Tribovillard et al., 2006).

Foraminifera are among the most widely used microfossils for paleoenvironmental interpretation because their distribution is strongly controlled by salinity, water depth, oxygenation, and substrate conditions (Loeblich & Tappan, 1964; Murray, 1991; Sen Gupta, 1999; Emeka et al., 2023, Emeka et al, 2024, Akkita et al., 2025, Gildeeva et al., 2021, Fajemila,et al., 2017). Agglutinated benthic foraminifera, in particular, are known to dominate in shallow, restricted, or clastic-rich environments where calcareous forms are suppressed due to unfavorable chemical conditions (Petters, 1983; Murray, 2006). Several studies within the Benue Trough have successfully used benthonic foraminiferal assemblages to interpret depositional environments ranging from paralic to inner-neritic settings (Petters, 1979; Obaje et al., 2000; Abubakar et al., 2024).

Some statistical tests such as the coefficient of variation (CV%) for abundance dispersion; Kruskal–Wallis comparison of abundance distributions among samples and Shannon diversity index (H') were determined using the data obtained from the Numanha formation (Table 2)

In addition to micropaleontology, inorganic geochemical proxies provide independent constraints on sediment provenance, redox conditions, and depositional setting. Major elements such as Al, Ti, and K are commonly used to evaluate terrigenous input, whereas trace metals including V, Ni, Mo and Cr are sensitive indicators of oxygenation conditions during deposition (Calvert & Pedersen, 1993; Jones & Manning, 1994, Tribovillard et al., 2006). Integration of these proxies allows more reliable paleoenvironmental

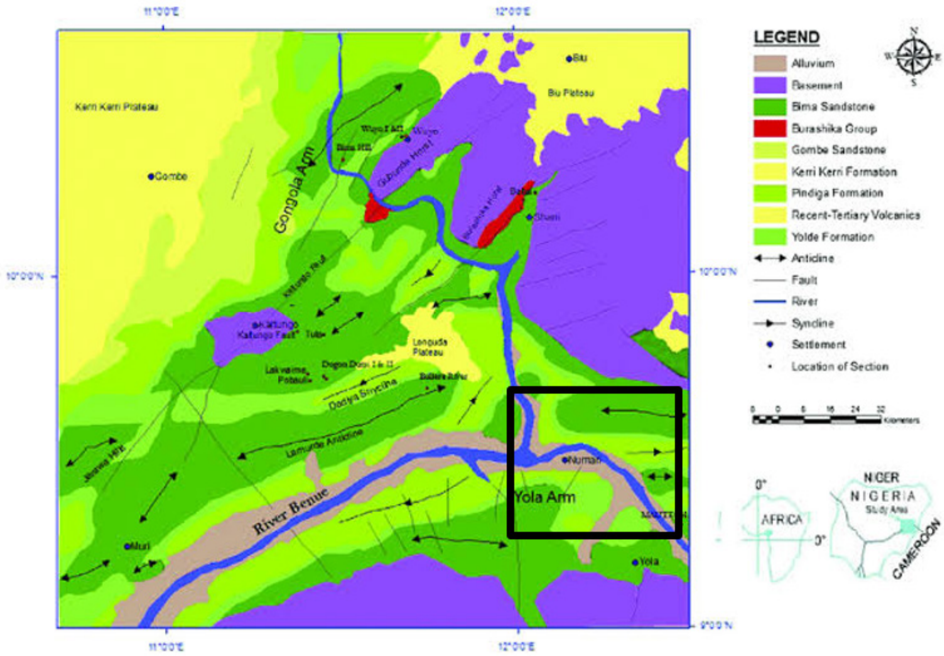

Figure 1 Satellite image showing the location of the study area and its environs

reconstruction than the use of a single dataset. Recent palynofacies and geochemical investigations of the Numanha Formation have suggested deposition in a proximal marine environment influenced by both terrestrial input and fluctuating oxygen levels (Valdon et al., 2023). However, detailed quantitative studies combining foraminiferal assemblages with elemental geochemistry remain scarce, particularly within the Yola Arm where stratigraphic relationships are complex and lateral facies variations are common.

The present study aims to provide a comprehensive multiproxy interpretation of the Numanha Formation by integrating benthonic foraminiferal assemblage analysis with major and trace element geochemistry. The objectives of this work are to: 1) identify and quantify the foraminiferal assemblages within the Numanha Formation, 2) determine the geochemical characteristics of the shale units, 3) reconstruct depositional environment and oxygenation conditions and 4) evaluate sequence stratigraphic implications

This integrated approach provides new insights into the paleoenvironmental history of the Northern Benue Trough and contributes to a better understanding of the Upper Cretaceous sedimentary evolution of the West African rift system.

Geological setting

The Benue Trough of Nigeria is a major intracontinental rift basin that developed during the Early Cretaceous as part of the tectonic processes associated with the separation of the African and South American plates and the opening of the South Atlantic Ocean (Burke et al., 1971; Fairhead & Binks, 1991; Zaborski, 1998).

Structurally, the Benue Trough is subdivided into three main segments: the Southern Benue Trough, the Central Benue Trough, and the Northern Benue Trough (Zaborski et al., 1997; Obaje et al., 2006). The Northern Benue Trough further comprises the Gongola Basin and the Yola Arm, which represent important depocenters of Upper Cretaceous marine sedimentation (Zaborski, 2003).

The Yola Arm forms the easternmost extension of the Northern Benue Trough and contains a well-preserved stratigraphic succession ranging from Aptian–Albian continental deposits to Upper Cretaceous marine shales and sandstones (Petters, 1982; Zaborski et al., 1997). The generalized stratigraphy of

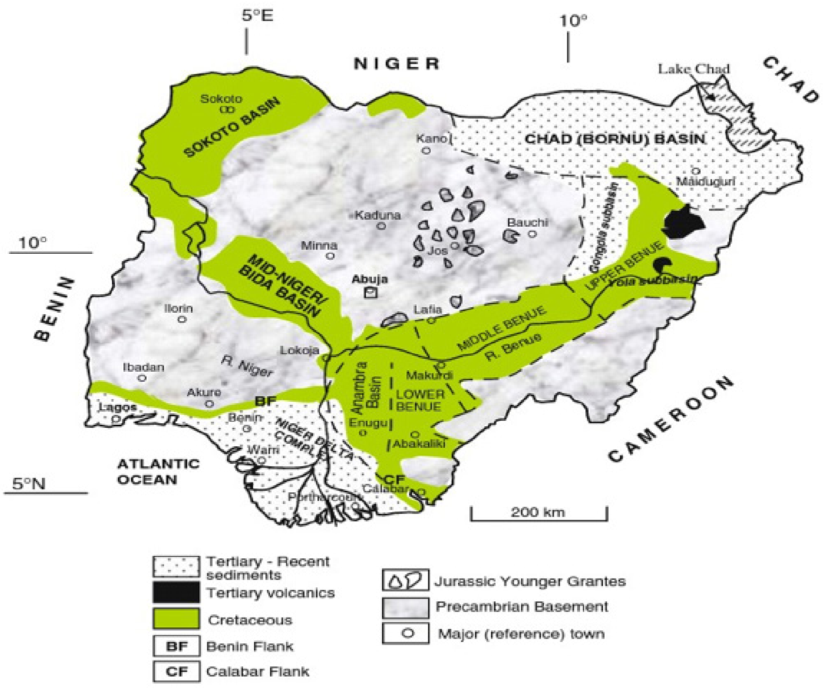

Figure 2 Map of Nigeria showing the location and extent of the Benue trough and other sedimentary basins in Nigeria (Obaje, 2009)

the Yola Arm includes the Bima Formation, Yolde Formation, Dukul Formation, Sekuliye Formation, Numanha Formation, and Lamja Formation.

The Numanha Formation overlies the Sekuliye Formation and is overlain by the Lamja Formation. It is generally considered to be of Coniacian age based on foraminiferal biostratigraphy and regional stratigraphic correlation (Petters, 1982; Zaborski, 2003). Lithologically, the formation consists predominantly of dark grey to bluish-grey shale with occasional siltstone interbeds, indicating deposition under low-energy marine conditions.

Previous studies have suggested that sedimentation within the Numanha Formation occurred in a shallow marine shelf environment influenced by terrigenous influx from adjacent continental sources (Obaje et al., 1999; Valdon et al., 2023). The predominance of fine-grained lithologies, limited macrofauna, and the occurrence of agglutinated foraminifera indicate deposition under restricted circulation conditions with fluctuating oxygen levels (Petters, 1983; Murray, 2006).

The stratigraphic position of the Numanha Formation within the Upper Cretaceous marine succession suggests that it represents a phase of marine transgression followed by gradual regression during the Coniacian, a period characterized by regional tectonic adjustments and eustatic sea-level changes within the Benue Trough (Obaje et al., 2000; Zaborski, 1998).

Methodology

Fieldwork was carried out along the Numanha stream section within the Yola Arm of the Northern Benue Trough, Nigeria. The section exposes a continuous shale-dominated interval assigned to the Numanha Formation. A total of twelve fresh shale samples were collected at measured stratigraphic intervals in order to ensure adequate vertical representation of the formation.

Laboratory preparation of samples followed standard micropaleontological procedures. Approximately 100 g of each sample was disaggregated and soaked in water with a small quantity of hydrogen peroxide to facilitate breakdown of the sediment matrix.

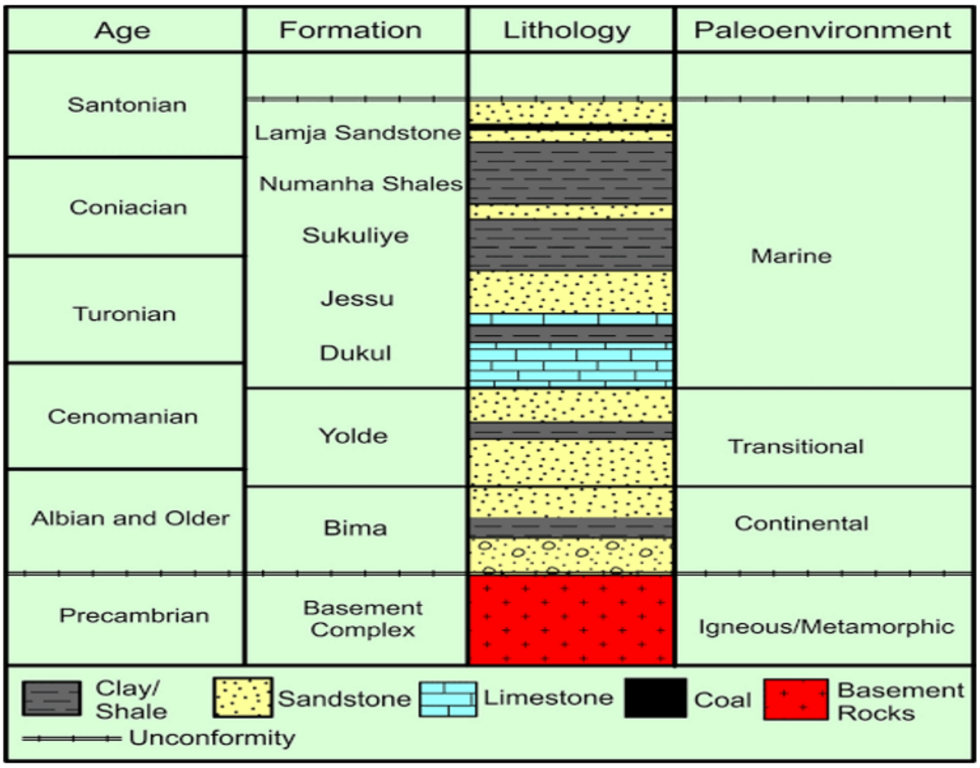

Figure 3 Lithostratigraphic successions of the Yola Sub-Basin Modified after Yandoka (2021)

The disaggregated material was subsequently washed through a series of sieves to separate the coarse fraction containing potential microfossils. This followed standard micropaleontological procedures (Murray, 1991, 2006; Armstrong & Brasier, 2005; Zarkogiannis et al., 2020; Tetard et al, 2021; Alkali, 2023; Adebambo and Fadiya, 2021; Adeola et al., 2021).

The residues were dried and examined under a binocular microscope. Foraminiferal specimens were carefully picked using a fine brush and mounted on micropaleontological slides for identification. Taxonomic identification was carried out using standard foraminiferal reference literature (e.g. Foraminifera.eu, marine species.org, Loeblich and Tappan (1964), Petters (1979, 1982), and subsequent works on West African Cretaceous foraminifera, e.g., Emeka et al., 2023 and 2024). All specimens were counted, and relative abundance percentages were calculated for each genus.

Geochemical analyses were conducted using the Vanta portable X-ray fluorescents machine (Pxrf) to determine the concentrations of major and trace elements in the samples. this method and devices are increasingly been used for research on geochemical analysis, e,g., Ross et al., 2024; Jenkins et al., 2025; Pashkova,et al., 2026 etc. Major and trace elements such as (Al, Ti, Ca, K, Zr, Sr, V, Ni, Mo, Cr, Mn) were determined and elemental ratios were evaluated to infer provenance, depositional energy, and redox conditions.

Element ratios such as V/Ni, Al/Ti, and Sr/Ca were used to interpret depositional conditions following established geochemical models (Calvert & Pedersen, 1993; Jones & Manning, 1994; Tribovillard et al., 2006, Jenkins et al, 2025).

Foraminiferal assemblage data and geochemical results were integrated in order to reconstruct depositional environment, paleo-oxygenation, sequence stratigraphic position, and basin evolution.

This multiproxy approach is widely considered the most reliable method for paleoenvironmental reconstruction in fine-grained marine successions (Tyson, 1995; Murray, 2006; Tribovillard et al., 2006).

Results

Lithology

The Numanha Formation in the studied section is composed predominantly of dark grey to bluish-grey fissile shale characterized by fine lamination and high clay mineral content. The shale exhibits moderate to strong compaction resulting in well-developed fissility and platy

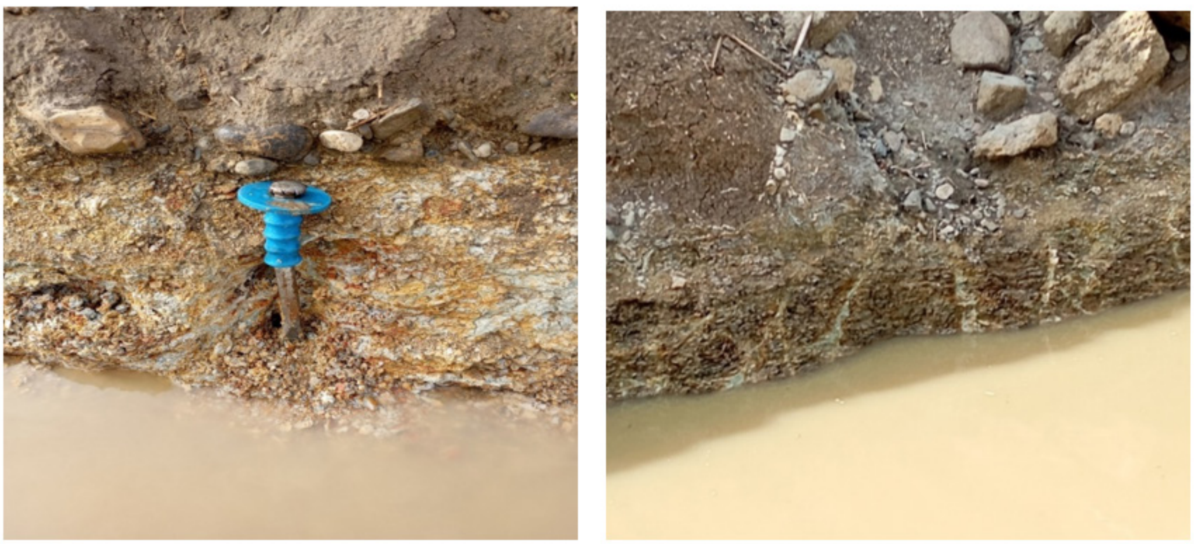

Figure 4 Shale lithology within the Numanha Formation

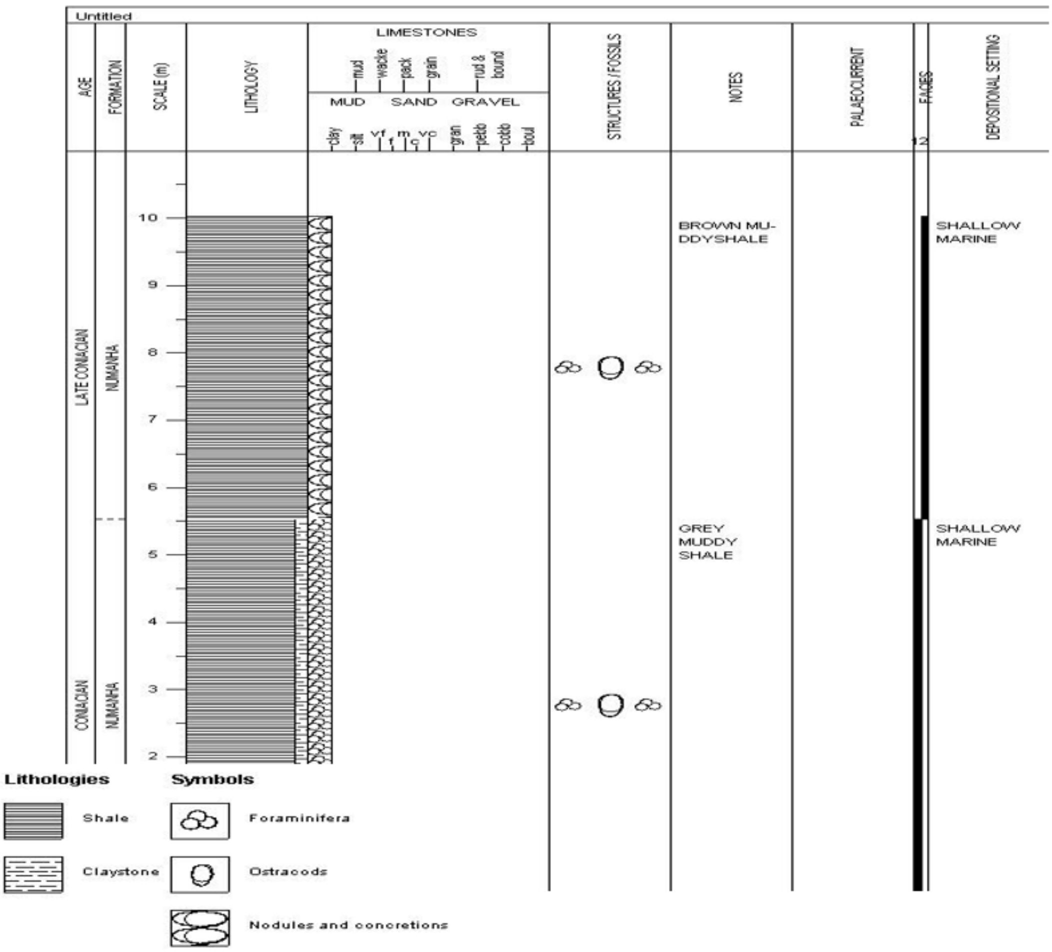

Figure 5 Sedimentary log of the Numanha stream section

fabric typical of low-energy depositional environments.

Grain size ranges from clay to very fine silt, with occasional silty interbeds that indicate minor fluctuations in depositional energy. Thin siltstone and rare fine sandstone streaks occur locally and may display parallel lamination, suggesting episodic influx of higher-energy sediment.

The shale is locally carbonaceous, producing darker coloration that may reflect deposition under reduced oxygen conditions. Disseminated pyrite occurs in several horizons, indicating early diagenetic formation under sub-oxic to dysoxic conditions.

The predominance of fine-grained siliciclastic material suggests sedimentation in a quiet marine setting with high suspension load and low current activity, consistent with inner shelf to marginal marine environments (Tyson, 1995; Murray, 2006; Atar et al., 2020; Adeigbe et al., 2020; Gao et al., 2020; Zang and Dong,2020).

Foraminiferal Assemblages Implications

A total of 4027 foraminiferal specimens belonging to nine genera were recovered from the twelve analyzed samples. The assemblage is composed entirely of benthonic forms, with a complete absence of planktonic foraminifera. The assemblage is strongly dominated by agglutinated benthic foraminifera, particularly *Haplophragmoides* ssp and *Ammobaculites* ssp, which together constitutes more than 90% of the total population.

Agglutinated taxa are typically associated with: High clastic sedimentation, Low carbonate saturation, Shallow marine environments, Restricted circulation, Variable salinity, Low oxygen bottom waters, etc. (Murray, 1991; Petters, 1983; Sen Gupta, 1999)

The high abundance of *Haplophragmoides* ssp (55.59%) suggests deposition in a muddy substrate with relatively low oxygen

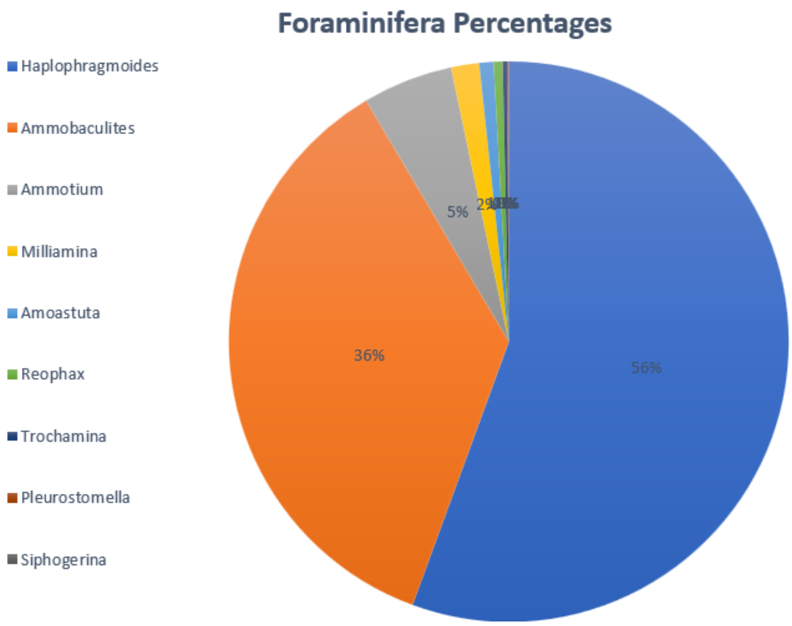

Figure 6 Foraminiferal species and their percentages within the Numanha section

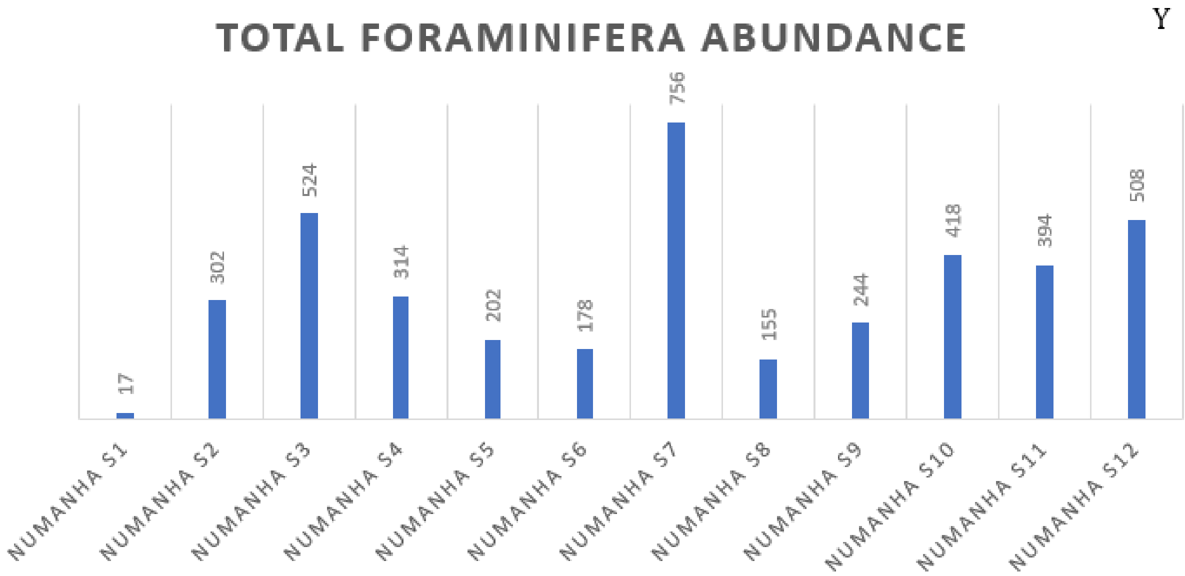

Figure 7 Total individual per samples within the Numanha Formation

conditions. This genus is known to tolerate stressful environments and commonly occurs in inner neritic to marginal-marine settings.

The significant presence of *Ammobaculites* ssp (35.90%) may indicate high sediment supply and unstable substrate conditions, as this genus is adapted to environments with strong terrigenous influence.

Minor occurrences of *Ammotium*, *Miliammina*, and *Reophax* suggest fluctuating salinity and intermittent environmental stress, while the very low abundance of *Trochammina* ssp and *Pleurostomella* sp indicates that more open marine conditions were rare.

The complete absence of planktonic foraminifera is a strong indicator of shallow water depth, since planktonic taxa generally dominates in outer shelf and deeper marine settings (Murray, 2006).

Overall, the assemblage indicates

Inner neritic to marginal marine environment

High clastic influx

Restricted circulation

Dysoxic bottom waters

Shallow shelf deposition

TABLE 1
Logged section indicating foraminiferal distribution across Numanha river section

Sample	Formation	Age	Ammobaculites Numenhensis	Ammobaculites Gombensis	Ammobaculites Pindigensis	Ammobaculites Bauchensis	Ammobaculites Jensensis	Ammobaculites spp	Ammotium cf Nkalagun	Ammotium spp	Ammotium Bornum	Amoastuta c Nigeriana	Amoastuta spp	Haplopragmoides Pindigensis	Haplopragmoides Bauchensis	Haplopragmoides spp	Milliamina Pindigensis	Reophax Minuta	Reophax spp	Reophax guineana	Trochamina spp	Siphogerina spp	Pleurostomella spp?	Total count/Diversity
S1	NUMANHA FORMATION (NUMANHA STREAM SECTION)	CONIACIAN	3						1															16/4
S2			26		56		8		4	2				170	36									302/7
S3			52		64	104			22		6	12		204	54		6			2			2	528/11
S4			19		21	35			27		1	4		140	60	1	3		5			1	1	318/13
S5			25		18	28	12		5			1		78	32	2	4	1		1				207/12
S6			11		11	20			5			5		97	27		3							179/8
S7			21		48	165		6	21		15			339	99	6	24	3		3	6			759/14
S8			9		3	18		1	4		1	1		73	41	1	3							155/11
S9			10		17	55	2		5					96	47	2	10							244/9
S10			30	2	28	110	30		16		2			134	66					4				424/11
S11			28		20	110	2		34				4	132	52		6		2		4			396/12
S12			40		38	114	20	2	34		4	4	2	160	82	2	6							508/13
T			274	2	324	759	74	9	178	2	29	27	6	1623	596	14	65	4	7	10	10	1	3	

Statistical results of the above data plots are as follows: Mean abundance = 334.5 individuals; Coefficient of Variation ≈ 59%, indicating strong variability among samples.

Ranking of Diversity

S12 > S5 > S10 > S3 > S11 > S4 > S7 > S9 > S8 > S6 > S2 > S1

The abundance disparity among samples suggests localized ecological or taphonomic controls, such as fluctuations in sedimentation rate, oxygenation, nutrient supply, or preservation intensity. Despite this, moderate similarity in assemblage structure supports persistence of a shared depositional regime across the Numanha succession.

Most samples show moderate Shannon diversity values, implying neither extreme ecological stress nor highly mature open-marine conditions. The dominance of

TABLE 2
Shannon Diversity Index and other statistical results of the Numanha samples

Sample	Richness	Shannon H'	Evenness
S1	3	0.95	0.865
S2	7	1.287	0.662
S3	11	1.767	0.737
S4	13	1.713	0.668
S5	12	1.848	0.744
S6	8	1.466	0.705
S7	13	1.665	0.649
S8	11	1.499	0.625
S9	9	1.626	0.74
S10	10	1.78	0.773

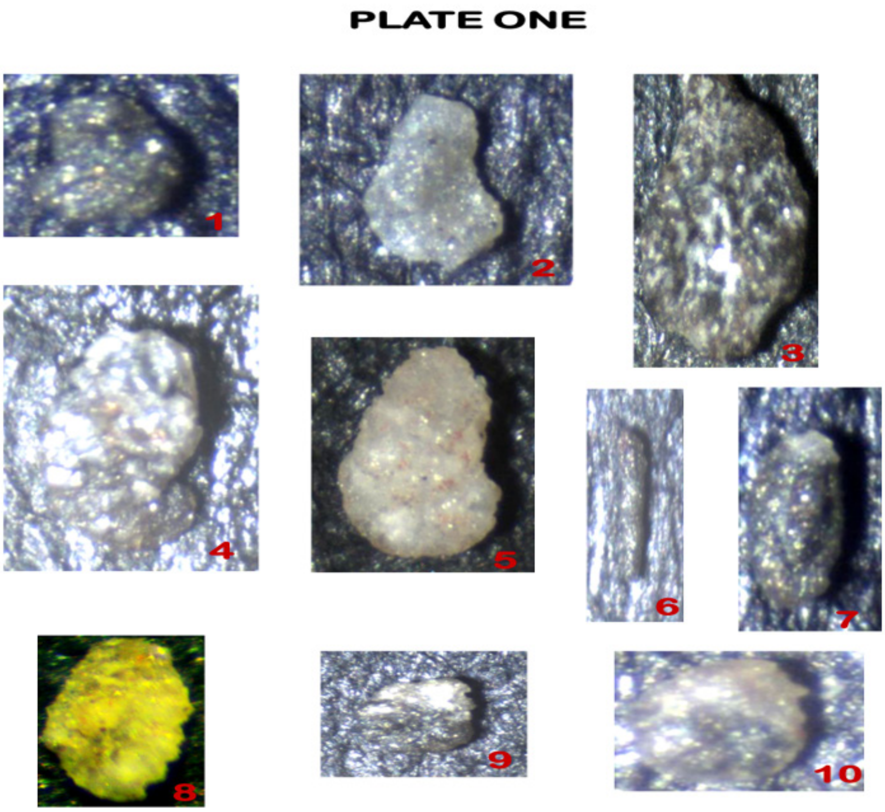

Figure 8 Showing different recovered forams in the Yola Arm1 *Ammobaculites bauchensis* (Petters, 1979) Side view (X300) ,2 *Ammobaculites pindigensis* (Petters, 1979) Side view (X300) ,3 *Ammobaculites jessensis* (Petters, 1979) Side view (X200) ,4 *Ammotium bornum* (Petters, 1982) Side view (X200), 5 *Ammobaculites gombensis* (Petters, 1979) Side view (X200), 6 *Reophax guineana* (Petters, 1979) Side view (X400), 7 *Miliammina pidigensis* (Petters, 1979) Side view (X300), 8 *Ammoastuta nigeriana* (Petters, 1979) Side view (X200), 9 *Ammobaculites* spp (Cushman, 1910) Side view (X300) ,10 *Haplophragmoides bauchensis* (Petters, 1979) Side view (X200)

arenaceous taxa such as Haplophragmoides and Ammobaculites is consistent with marginal marine to shallow shelf settings influenced by siliciclastic influx.

Sample S12 records the highest diversity and richness, suggesting the most stable interval with broader niche availability. Conversely, S1 shows low richness and low diversity, likely reflecting stressed conditions, low population density, or preservational bias.

Geochemical Signatures

Major element concentrations show consistently higher values of Al, Ti, K, Si and Fe, indicating strong terrigenous input and dominant siliciclastic sedimentation, as these elements are typically enriched in land-derived detrital sediments and aluminosilicate mineral phases (Govin et al., 2012; Odewumi, 2024; Itiowe et al., 2021).

The enrichment of Al, Ti, K, Si, and Fe in the studied sediments suggests significant terrigenous influx and predominance of siliciclastic depositional processes, reflecting derivation from weathered continental source rocks rich in quartz, feldspar, clay minerals, and Fe-Ti bearing heavy minerals (Govin et al., 2012).

These values are also consistent with findings from the Northern Benue Trough where elevated Fe and Ti contents were linked to detrital source materials and clastic depositional environments (Adekola et al., 2018).

Obaje et al. (2006) also described Northern Nigerian basins including the Upper Benue Trough as containing thick clastic successions and source-rock-bearing sediments, reinforcing the terrigenous siliciclastic framework.

The enrichment of Al, Ti, K, Si and Fe in the studied sediments indicates substantial

TABLE 3
Some geochemical signatures within the Numanha Formation

Sample ID	Al	Si	K	Ca	Ti	V	Cr	Fe	Ni	Rb	Sr	Zr	Nb	Mo
Numanha S1	56857	128870	4203	10575	4271	78	58	103976	112	41	185	371	21	13
Numanha S1	77416	147580	9260	2539	6017	67	94	19459	33	100	340	110	27	6
Numanha S2	32913	78407	4827	4741	4768	61	102	28185	39	70	353	237	24	5
Numanha S3	64655	146752	5886	4305	5356	58	118	39074	55	70	395	266	23	0
Numanha S4	64679	139236	4888	543	5559	214	71	82479	208	58	207	353	20	9
Numanha S5	56358	125968	4116	2841	4322	58	72	69970	102	52	202	401	18	6
Numanha S6	51420	128598	5153	1753	5333	75	46	57362	133	58	230	441	20	8
Numanha S7	62128	139546	4572	2562	4305	66	65	53537	98	55	246	361	22	0
Numanha S8	64402	144788	4284	1565	5162	73	62	53284	98	53	266	391	17	0
Numanha S9	57197	129399	4044	3506	5322	53	116	43330	97	61	377	363	17	0
Numanha S10	59764	141495	5128	2247	5150	61	88	33489	69	63	627	352	25	0
Numanha S11	46431	111994	4040	3985	5398	67	81	53628	107	57	727	335	17	0
Numanha S12	46842	112573	4540	3793	5290	67	68	39854	77	62	339	341	20	0

continental detrital contribution and siliciclastic sedimentation, comparable to Northern Benue Trough sediments where geochemical signatures and reservoir sands reflect terrigenous provenance and clastic depositional systems (Adekola et al., 2018).

High Zr values suggest contribution from heavy minerals and continental detritus, supporting proximity to a continental source.

Low Ca concentrations indicate limited carbonate deposition, consistent with the absence of calcareous foraminifera.

Trace elements show moderate enrichment in V, Ni, and Mo in several samples.

These elements are commonly associated with reduced oxygen conditions because they are preferentially concentrated in sediments deposited under dysoxic to anoxic environments (Calvert & Pedersen, 1993; Tribovillard et al., 2006).

High V/Ni ratios in some samples suggest periods of reduced bottom-water oxygenation, possibly related to restricted circulation or increased organic productivity.

The combination of high terrigenous input and intermittent redox-sensitive element enrichment indicates deposition in a shallow marine shelf influenced by both continental influx and episodic oxygen depletion.

The geochemical dataset from the Numanha samples shows noticeable variations in elemental concentrations, reflecting differences in sediment source input, mineral composition, and depositional processes. Descriptive statistical parameters including range, mean, and standard deviation for each element are summarized below in a form suitable for scientific presentation.

Aluminium (Al) values range from 32,913 to 77,416 ppm, with a mean concentration of 57,389 ppm and a standard deviation of 11,867 ppm. Silicon (Si) ranges between 78,407 and 147,580 ppm, averaging 127,601 ppm with a standard deviation of 20,233 ppm. Potassium (K) varies from 4,040 to 9,260 ppm, with a mean of 5,063 ppm and standard deviation of 1,471 ppm.

Calcium (Ca) exhibits a wide range from 543 to 10,575 ppm, with an average concentration of 3,596 ppm and a relatively high standard deviation of 2,494 ppm, indicating strong variability, likely due to carbonate fluctuations.

Titanium (Ti) values range from 4,271 to 6,017 ppm, with a mean of 5,224 ppm and standard deviation of 535 ppm, suggesting relatively consistent heavy mineral input.

Vanadium (V) concentrations range from 53 to 214 ppm, averaging 77 ppm with a standard deviation of 43 ppm. Chromium (Cr) varies between 46 and 118 ppm, with a mean of 80 ppm and standard deviation of 23 ppm. Iron (Fe) shows a broad distribution from 19,459 to 103,976 ppm, with a mean of 51,356 ppm and a high standard deviation of 22,867 ppm, indicating considerable fluctuations in ferruginous mineral abundance or redox conditions.

Nickel (Ni) ranges from 33 to 208 ppm, with a mean value of 94 ppm and standard deviation of 47 ppm. Rubidium (Rb) varies between 41 and 100 ppm, averaging 62 ppm with a standard deviation of 15 ppm. Strontium (Sr) shows concentrations from 185 to 727 ppm, with a mean of 361 ppm and standard deviation of 165 ppm, reflecting notable variability possibly linked to carbonate or feldspar contributions.

Zirconium (Zr) ranges from 110 to 441 ppm, with a mean of 327 ppm and standard deviation of 98 ppm, suggesting variable zircon enrichment. Niobium (Nb) concentrations range from 17 to 27 ppm, averaging 21 ppm with a low standard deviation of 3 ppm. Molybdenum (Mo) values range from 0 to 13 ppm, with a mean of 3.6 ppm and standard deviation of 4.3 ppm, indicating generally low concentrations with localized enrichment.

Discussion

Paleoenvironmental Interpretation Based on Foraminiferal Assemblages

The foraminiferal assemblages recovered from the Numanha Formation consist exclusively of benthonic taxa, with a complete absence of planktonic forms throughout the studied interval. The assemblage is strongly dominated by agglutinated genera, notably *Haplophragmoides* ssp (55.59%) and *Ammobaculites* ssp (35.90%). Other taxa, including *Ammotium* ssp, *Miliammina* ssp, *Reophax* ssp, *Trochammina* ssp, and *Pleurostomella* ssp, occur in subordinate proportions, while *Siphogerina* is represented only rarely. Agglutinated benthic foraminifera are widely regarded as indicators of shallow marine, marginal marine, or restricted environments characterized by high siliciclastic influx, low carbonate saturation, and fluctuating oxygen levels (Murray, 1991; Sen Gupta, 1999; Murray, 2006). Their dominance in the Numanha Formation therefore suggests deposition in a proximal marine setting where clastic sediment supply was high and chemical conditions were unfavorable for calcareous forms.

The overwhelming abundance of *Haplophragmoides* ssp is particularly significant. This genus is commonly associated with inner neritic to paralic environments, where muddy substrates, variable salinity, and reduced oxygen conditions prevail (Petters, 1983). Its high percentage in the studied samples indicates a relatively stressed benthic habitat with limited water circulation.

Ammobaculites ssp, which constitutes 35.90% of the assemblage, is also typical of shallow shelf environments influenced by strong terrigenous input. This genus is tolerant of unstable substrates and commonly occurs in environments with high sedimentation rates (Murray, 2006). The combined dominance of *Haplophragmoides* ssp and *Ammobaculites* ssp therefore strongly supports an inner neritic depositional setting.

Minor occurrences of *Ammotium* ssp and *Miliammina* ssp indicate occasional fluctuations in salinity and oxygenation. These genera are known to occur in environments ranging from marginal marine to shallow shelf settings and are often associated with stressed ecological conditions (Sen Gupta, 1999).

The very low abundance of *Pleurostomella* ssp and *Trochammina* ssp, together with the complete absence of planktonic taxa, further confirms that the Numanha Formation was not deposited in open marine conditions. Planktonic foraminifera typically dominate outer shelf to deep marine environments, and their absence suggests water depths within the inner neritic zone (Murray, 2006).

These interpretations agree with previous studies on Upper Cretaceous formations in the Northern Benue Trough (Petters, 1982; Obaje et al., 2000; Abubakar et al., 2024).

General Ecology of the Foraminiferal Assemblages

The foraminiferal assemblages recovered from the Numanha Formation reflect a benthic ecosystem adapted to fine-grained, siliciclastic, low-energy marine conditions, where sedimentation was dominated by mud accumulation. In such environments, the substrate is typically soft, cohesive, and rich in suspended particles, creating favorable conditions for benthic foraminifera that can exploit both surface and subsurface microhabitats.

From a modern ecological perspective, studies on living benthic foraminifera show that mud-dominated settings are commonly associated with communities structured by organic matter availability, oxygen gradients, and sediment texture. In these environments, foraminifera occupy a range of ecological niches, from epifaunal forms living on the sediment surface to infaunal organisms inhabiting deeper sediment layers. This vertical distribution is largely controlled by the availability of food and the penetration of oxygen into the sediment column (Haynert et al., 2020; Richirt et al., 2020).

The dominance of forms typical of fine-grained substrates suggests that the Numanha assemblages were part of a system with moderate to high organic matter input, likely derived from continental sources and deposited under calm hydrodynamic conditions. Modern analogues indicate that such organic enrichment supports diverse benthic communities, as foraminifera utilize detrital and microbial organic matter as a primary food source (Haynert et al., 2020). This results in an ակտիվ benthic trophic structure where foraminifera play a key role in nutrient recycling within the sediment.

Oxygen availability is another critical ecological control. In quiet marine environments where fine sediments accumulate, oxygen levels within the sediment can become reduced (dysoxic conditions) due to the decomposition of organic matter. Living foraminiferal studies demonstrate that many benthic taxa are well adapted to such fluctuating oxygen regimes, exhibiting tolerance to low-oxygen conditions while still requiring periodic oxygenation for survival (Richirt et al., 2020). The coexistence of different ecological groups within the assemblage therefore suggests a dynamic system characterized by intermittent oxygenation rather than persistent anoxia.

Furthermore, investigations of modern continental shelf and slope environments reveal that benthic foraminiferal communities in mud-rich settings are typically stable but sensitive to subtle environmental changes, including variations in sedimentation rate, organic flux, and bottom-water circulation (Santa-Rosa et al., 2021). These factors influence species distribution, abundance, and diversity, making foraminifera reliable indicators of paleoenvironmental conditions.

Geochemical Proxies and Bottom-Water Oxygenation

Major element data from the Numanha shale show consistently high concentrations of Al, Ti, K, and Fe. These elements are typically associated with clay minerals and continental detritus and therefore indicate strong terrigenous input during deposition (Calvert & Pedersen, 1993).

High Zr values further support a continental source, as zircon is commonly derived from weathered igneous and metamorphic rocks. This suggests that the basin was located close to a continental landmass supplying large volumes of siliciclastic sediment.

Low Ca concentrations in most samples indicate limited carbonate deposition, which is consistent with the absence of calcareous foraminifera in the assemblage. This relationship confirms that environmental conditions were unfavorable for carbonate-secreting organisms.

Trace elements such as V, Ni, and Mo show moderate enrichment in several samples. These elements are sensitive to redox conditions and are commonly enriched in sediments deposited under dysoxic to anoxic environments (Jones & Manning, 1994; Tribovillard et al., 2006).

Elevated V/Ni ratios observed in some samples suggest periods of reduced oxygen availability at the sediment–water interface. Such conditions may develop in restricted shelf environments where circulation is limited or where organic matter supply is high.

The coexistence of agglutinated benthic

foraminifera with moderate enrichment in redox-sensitive elements indicates that the Numanha Formation was deposited under fluctuating oxygen conditions, ranging from oxic to dysoxic. These conditions likely reflect episodic restriction of bottom-water circulation rather than persistent anoxia.

Integration of Foraminifera and Geochemistry

When considered together, the micropaleontological and geochemical datasets define a coherent paleoenvironmental framework.

The pronounced dominance of agglutinated benthic foraminifera indicates deposition in a shallow-water setting with substantial siliciclastic input, a condition further corroborated by geochemical signatures reflecting a high proportion of terrigenous material. The consistent absence of planktonic foraminifera, coupled with low Ca concentrations, supports deposition on a shallow marine shelf rather than in an open-marine environment.

Intermittent enrichments in V, Ni, and Mo point to fluctuations in bottom-water oxygenation during sediment accumulation. These redox variations were likely driven by changes in relative sea level, sedimentation rates, and/or basin circulation dynamics.

These results agree with the model proposed for many Upper Cretaceous units in the Benue Trough, where sedimentation occurred in a shallow epicontinental sea influenced by both marine transgressions and continental sediment supply (Obaje, 2009; Zaborski, 1998).

Sequence Stratigraphic Implications

The lithology, foraminiferal assemblages, and geochemical signatures together suggest that the Numanha Formation represents deposition during a marine transgressive–regressive cycle within the Coniacian.

The predominance of shale indicates sedimentation during a relatively high sea-level phase when fine-grained material accumulated in a low-energy shelf environment. However, the strong terrigenous signal suggests that the shoreline remained relatively close, indicating deposition in the inner shelf.

Episodes of increased redox-sensitive elements may correspond to maximum flooding intervals, when water circulation became restricted and organic matter preservation increased.

The absence of deeper-water foraminifera suggests that the basin never reached outer shelf or bathyal depths during deposition of the Numanha Formation.

This interpretation is consistent with sequence stratigraphic models proposed for the Northern Benue Trough, where repeated transgressive–regressive cycles occurred during the Late Cretaceous (Obaje et al., 2000; Zaborski, 2003).

Age and Stratigraphic Correlation

The occurrence of species such as *Ammobaculites pindigensis*, *Haplophragmoides bauchensis*, and *Ammotium bornum* is consistent with assemblages reported from Coniacian strata in the Northern Benue Trough (Petters, 1979; Petters, 1982).

Also, the results of this study are strongly supported by previous regional and international studies, indicating that the age interpretation and paleoenvironmental conclusions are reliable. The dominance of agglutinated benthic foraminifera, especially *Ammobaculites*, *Haplophragmoides*, and *Ammoastuta*, is widely recognized as characteristic of restricted shallow-marine, lagoonal to inner neritic environments with variable salinity and low oxygen bottom waters. Haig (2020), working on modern *Ammobaculites* ("living fossil") assemblages from southwestern Australia, demonstrated that this genus thrives in marginal marine to estuarine settings, confirming that its occurrence here is environmentally diagnostic of shallow-water stressed conditions rather than deep marine settings.

Similarly, the recent study by Hamis et al. (2024) on the Kanawa Member of the Pindiga Formation in the Northern Benue Trough reported assemblages containing *Ammobaculites subcretacea*, *A. pindigensis*, *A. bauchensis*, *Haplophragmoides bauchensis*, and *H. pindigensis*, and interpreted them as indicating Late Cretaceous (Turonian–Santonian) shallow marine carbonate ramp to lagoonal deposits. This closely matches recovered taxa and depositional interpretation, thereby validating the assignment of a Coniacian age within the Upper Cretaceous marine succession

Since earlier works by Petters (1979, 1982) and Zaborski (2003) also documented similar arenaceous foraminiferal assemblages from the Pindiga, Dukul, and related formations of the Northern Benue Trough, assigning them to the Turonian–Coniacian interval. Therefore, the close agreement between our faunal assemblage, stratigraphic position, and previously published records strongly confirms the accuracy of results, particularly the interpretation of a Coniacian shallow marine depositional setting within the Northern Benue Trough.

These taxa have been recorded from the Pindiga, Dukul, and Numanha formations and are considered characteristic of Upper Cretaceous shallow marine deposits in northeastern Nigeria.

Based on these assemblages and stratigraphic position, the studied interval is assigned a Coniacian age, which agrees with previous stratigraphic interpretations (Zaborski, 2003; Valdon et al., 2023).

Depositional Model for the Numanha Formation

The integrated micropaleontological and geochemical evidence indicates that the Numanha Formation was deposited within a shallow epicontinental shelf setting in close proximity to a continental sediment source.

The basin was characterized by high siliciclastic sediment supply, restricted circulation, fluctuating redox conditions, variable salinity, and overall shallow water depths. Sedimentation most likely occurred during a phase of marine transgression that inundated the continental margin but did not evolve into fully open-marine, deep-water conditions.

Episodes of dysoxia appear to have developed during intervals of reduced circulation, facilitating the preservation and accumulation of organic-rich muds. This paleoenvironmental model is consistent with existing interpretations of the Upper Cretaceous Benue Trough as a shallow inland sea with intermittent connections to the Atlantic Ocean (Burke et al., 1971; Zaborski, 1998; Obaje, 2009).

Conclusions

The Numanha Formation is characterized by a foraminiferal assemblage dominated by agglutinated benthic taxa, particularly Haplophragmoides and Ammobaculites, reflecting deposition under shallow marine and restricted conditions. The complete absence of planktonic foraminifera further constrains the depositional setting to the inner neritic zone.

The integrated micropaleontological and geochemical evidence indicates that the Numanha Formation was deposited within a shallow epicontinental shelf setting in close proximity to a continental sediment source with episodes of dysoxia appearing to have developed during intervals of reduced circulation.

Geochemical signatures indicate a strong terrigenous influence, coupled with moderate enrichment in redox-sensitive trace elements, suggesting fluctuating bottom-water oxygenation during sediment accumulation. The integration of micropaleontological and geochemical proxies supports deposition within a proximal, mud-dominated shelf environment during the Coniacian.

Stratigraphically, the Numanha Formation represents part of a transgressive–regressive cycle within the Northern Benue Trough. These findings provide important constraints for refining paleoenvironmental models and assessing hydrocarbon source-rock potential in the Upper Cretaceous succession of the Yola Arm. The Numanha formation is deposited during the Coniacian.

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