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Multi-Parameter Investigation of Cretaceous to Palaeocene Sedimentary Sequences in the Anambra and Niger Delta Basins, Nigeria: Organic Matter Characterisation, Palynofacies and Implications for Palaeoclimate and Sea-Level Changes

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ABSTRACT

The Anambra Basin of Nigeria, part of the larger West and Central African Rift System (WCARS) across Africa, contains primarily Cretaceous to Palaeocene shallow to marginal marine and freshwater sedimentary deposits. The organic-rich deposits of the Cretaceous Nkporo and Mamu formations within the Anambra Basin and the Palaeocene Imo Formation of the Niger Delta Basin constitute important conventional source rocks. Despite its economic significance, research on organic matter characterisation, palynofacies, sea-level fluctuations, palaeoclimate, hydrogeography, basin restriction, palaeobathymetry and the factors controlling organic matter preservation remains largely undocumented. The here presented new inorganic and organic geochemical and organic petrography data of the Cretaceous to Palaeocene deposits serve to refine the regional interpretation at a basinal scale and within the supra-regional context of the WCARS. Geochemical palaeotemperature proxies suggest a warm and humid tropical palaeoclimate during the Late Cretaceous within the study area. Furthermore, the measured TOC values indicate poor to very good organic content. Palynofacies analysis revealed high abundances of opaque and translucent phytoclasts and low amounts of palynomorphs with negligible amorphous organic matter (AOM) in the studied mudrocks. Two palynofacies groups suggest shallow-marine conditions in a proximal shelf setting and a heterolithic oxic basin. The palynofacies of the upper Imo Formation reveal higher percentages of dinoflagellate cysts during the early highstand phase, with equidimensional, opaque phytoclasts representing the maximum flooding phase, accompanied by warmer conditions. Additionally, abundant terrestrial phytoclasts, *Deltoidospora* spp., *Classopollis* spp. and geochemical indicators collectively indicate warm tropical climatic conditions consistent with geochemical interpretations. The palaeobathymetry reconstructions suggest a shallow seaway during the Upper Cretaceous in the Anambra Basin.

1 | Introduction

The Cretaceous-Palaeogene (K-Pg) transition was characterised by global and widespread geological events, marked by anoxic episodes, mass extinctions, global sea-level changes, high average temperatures and basin formation (Boström et al. 1972; Benkhelil 1989; Sellwood and Valdes 2006; Hay and Floegel 2012; Umeji and Nwajide 2014; Bolarinwa, Idakwo, and Bish 2019; Scotese et al. 2021; Omietimi 2022; Fairhead 2023; Pearson et al. 2024). In the Cretaceous period, significant tectonic changes occurred in West and East Africa and across the African and South American continents (Fairhead 2023). A few rift systems emerged, while others collapsed and were filled with thick sedimentary sequences, most of which contained organic-rich mudrocks that developed in marine, brackish and fluvial settings (Alalade and Tyson 2010; Abubakar 2014; Makeen et al. 2015; Yandoka et al. 2015; El Beialy, Zobaa, and Taha 2016; Anakwuba et al. 2018; Lai et al. 2018). The regional deposition of dark grey mudrock sequences provides valuable insights for understanding the important palaeo-sedimentary environmental conditions during sediment formation.

The concentration of carbonaceous material (i.e., organic matter) and maceral constituents in siliciclastic sedimentary environments is important in influencing the potential for shale gas generation and formation and the evolution of porosity and permeability systems in mudrocks (Jarvie 2012; Kumar et al. 2017). This has been highlighted in various research studies (Zeng et al. 2015, 2024; Kumar et al. 2017; Wei et al. 2021; Ahmed et al. 2022; Chukwuma et al. 2022; Huang et al. 2023; Yang et al. 2024). The investigation of the factors influencing the distribution pattern of organic constituents and macerals in mudrock sequences has been an essential area of research for a substantial period of time. The accumulation and preservation of organic materials in sediments are influenced primarily by anoxic depositional conditions, primary productivity, climatic variations, hydrodynamic circulation, water depth and sedimentation rate (Kennedy, Pevear, and Hill 2002; Ross and Bustin 2009; Lv et al. 2021; Wei et al. 2021; Chukwuma et al. 2022; Liu et al. 2022; Xiao et al. 2023; Yang et al. 2024). Multiple models and empirical evidence have demonstrated that none of these parameters exert universal control over the accumulation of organic constituents (Chukwuma et al. 2022). However, these parameters are intricately interconnected and may occasionally be separate. Consequently, the origin of sediments rich in organic matter can be attributed to various permutations of these (Ross and Bustin 2009; Zhang, Liu, and Liu 2021; Yang et al. 2024).

Trace and major element geochemistry, organic petrography data (i.e., macerals and palynofacies) and organic geochemical (i.e., TOC, total organic carbon) interpretations have all been successfully used to provide accurate information on climatic variations, palaeobathymetry and the factors influencing organic matter enrichment and preservation in sedimentary basins (Ross and Bustin 2009; Makeen et al. 2015; Harris et al. 2018; Li et al. 2018; Xie et al. 2018; Han et al. 2021; Chukwuma et al. 2022; Xiao et al. 2023). Additionally, these organic-rich rocks provide evidence of the interaction that links depositional environments and the biosphere recorded in the ancient sediments (Zhang, Liu, et al. 2018; Cheng et al. 2021; Adeyilola et al. 2022).

The Anambra Basin in onshore southern Nigeria (Anakwuba et al. 2018) (Figure 1), located in the Lower Benue Trough, is part of the Cretaceous West and Central African Rift System (WCARS) (Obaje et al. 2004; Abubakar 2014; Obasi, Selemo, and Nomeh 2018; Edegbai, Schwark, and Oboh-Ikuenobe 2019). The deposits of the Anambra Basin are overlain by the Palaeocene (Selandian) to Recent deep- to shallow-marine, paralic and fluvial deposits of the Niger Delta Basin (Short and Stauble 1967; Avbovbo 1978; Umeji and Nwajide 2014; Omietimi et al. 2024). The basin is considered second only to the Niger Delta Basin in terms of hydrocarbon potential and serves as a structural link between the Benue Trough to the north and the Palaeogene Niger Delta Basin to the south.

Previous geochemical, seismic and sequence stratigraphic studies of the Anambra Basin have drawn attention to the presence of potential source rock intervals together with reservoir units and seals and an existing trapping framework (Akaegbobi, Nwachukwu, and Schmitt 2000; Obaje et al. 2004; Anakwuba and Onyekwelu 2010; Babatunde 2010; Ekine and Onuoha 2010; Adebayo et al. 2018; Dim et al. 2019, 2020; Okwara, Dim, and Anyiam 2020; Ejeh 2021). The majority of these studies have focused on the eastern part of the basin, where much of the basin fill is exposed in outcrops at the surface. By contrast, the western part of the basin has received relatively little attention (Edegbai, Schwark, and Oboh-Ikuenobe 2019; Omietimi et al. 2021, 2022). In this study, we used subsurface data from the western limb of the basin to provide new insights.

Previous studies have classified the Anambra Basin as primarily gas-prone (Ejeh et al. 2024; Ene, Okogbue, and Onuoha 2019; Obaje et al. 2004; Omietimi et al. 2022). Subsurface studies on samples of the Maastrichtian Mamu Formation and the Campanian Nkporo Formation from the Akukwa-2 well in the central-eastern Anambra Basin indicated fair to good hydrocarbon generation potential, with TOC up to 3 wt% and a prevalence of Type III and II–III kerogen in thermally immature to early mature source rock intervals (Adebayo et al. 2018). Edegbai, Schwark, and Oboh-Ikuenobe (2020) studied samples of the Mamu Formation from outcrops in the western portion of the basin, which were interpreted to consist of terrigenous to transitional marine organic facies deposited under oxic conditions. Omietimi et al. (2022) came to similar conclusions from studies on the Upper Cretaceous Nkporo and Mamu formations in the western part of the basin and the Palaeocene Imo Formation in the Niger Delta Basin, summarising that these units were deposited in brackish to shallow-marine settings with primarily oxic conditions. Ogungbesan and Adedosu (2020) investigated the organic matter content of mudrocks in the Mamu Formation in the western Anambra Basin, which contains mixed terrigenous and marine organic material deposited in deltaic to shallow-marine settings, suggesting a dominance of Type III kerogen with limited Type II–III kerogen (Ogungbesan and Adedosu 2020). The same authors also found that the organic material in the studied formation was early mature. Furthermore, Ejeh et al. (2024) evaluated the hydrocarbon potential of Campano-Maastrichtian to Palaeogene shales within

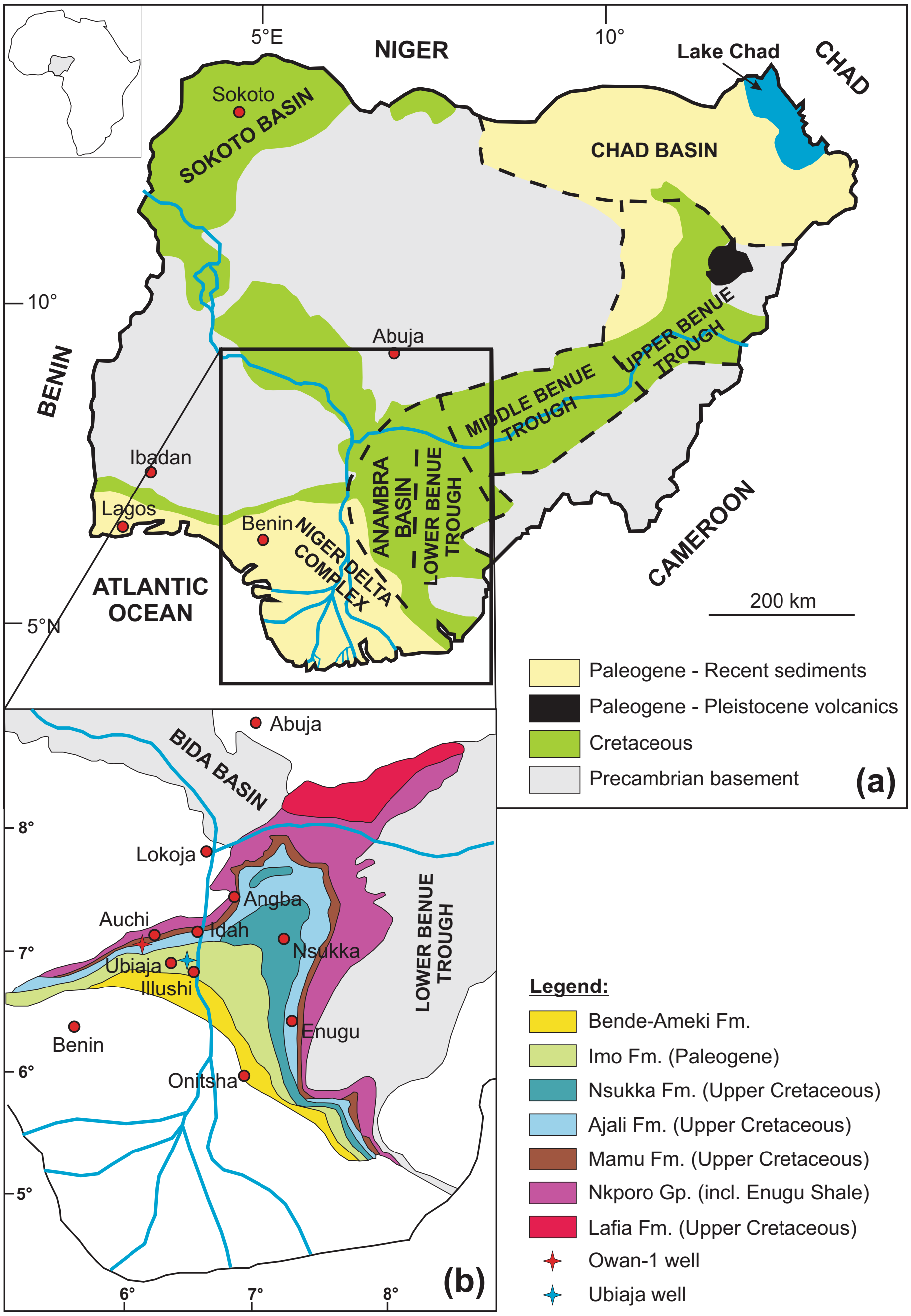

FIGURE 1 | (a) Geologic map of Nigeria showing the Anambra Basin (Obaje 2009; Omietimi et al. 2022); inset: Map of Africa showing the location of Nigeria. (b) Geologic map of the Anambra Basin showing the location of the studied Owan-1 and Ubiaja wells (Nwajide 1990; Omietimi et al. 2022).

the Benin Flank of the Anambra Basin using organic geochemical techniques. Results indicate varying organic matter content, indicating poor to excellent hydrocarbon potential. Predominantly gas-prone (Type III) kerogens were identified, with some samples exhibiting mixed oil- and gas-prone (Type II/III) characteristics. While thermal maturity suggests immature source rocks, the presence of solid bitumens implies a potentially active, deeper petroleum system (Ejeh et al. 2024).

Studies of Campanian-Maastrichtian and Palaeocene sedimentary organic matter (palynofacies and maceral data) and organic and elemental geochemistry (TOC and trace elements) from the subsurface of the western Anambra Basin and Niger Delta Basin are poorly documented. In this context, this study aims to present and interpret data from the Owan-1 and Ubiaja wells (locations in Figure 1). Cores from these two wells provided valuable insights into the stratigraphy and depositional history of the region.

In this study, we used subsurface data to interpret the sea-level fluctuations, palaeobathymetry, sedimentation rates, palaeotemperatures, characteristics of the main contributors of organic materials and the primary controlling factors of sedimentary organic matter accumulation and preservation in the western part of the Anambra Basin and the Niger Delta Basin for the first time. Furthermore, we propose a hypothetical model for organic matter preservation. The results of this contribution are of great importance for reconstructing the palaeoenvironment and highlight the impact of sea-level changes, climatic variations and sedimentation rates in organic matter distribution on Upper Cretaceous to Palaeogene fine-grained siliciclastic rocks globally.

2 | Geological Setting

2.1 | Regional and Tectonic Setting

The Anambra Basin (Figure 1) formed during the thermal subsidence stage of the Benue Trough (Obaje 2009; Anakwuba et al. 2018; Ejeh 2021), which was caused by regional thrust tectonics during the Santonian period and likely extended into the Maastrichtian within the northern margins of the Benue Trough and Chad Basin (Edegbai, Schwark, and Oboh-Ikuenobe 2019). The widespread inversion resulted from compressional palaeo-stresses generated from the interactions between the African and European slabs. These interactions led to varying spreading rates in the Central and South Atlantic Oceans, ultimately rejuvenating transform faults that extended from the Mid-Atlantic Ridge into the West African Rift System (WARS) (Fairhead 2023). The Anambra Basin, covering an area of about 54,000 km^2, is geographically bordered to the west by the Benin fold line, to the east by the Lower Benue Trough and to the south by the offshore Niger Delta Basin (Figure 1). The basin is divided into eastern and western portions by the river Niger (Figure 1). The sedimentary infill of the basin is an integral component of the Cretaceous post-Santonian sedimentary succession in Nigeria. This succession was formed as a result of a eustatic sea-level rise from the Campanian to the Maastrichtian (Figures 2 and 3), during which the Trans-Saharan Seaway was re-established and connected the Tethys Ocean to the Atlantic Ocean via the Bida Basin to the north (Figure 2) (Edegbai, Schwark, and Oboh-Ikuenobe 2019). Seismic, magnetic and gravity studies show thick sedimentary sequences suggesting subsidence and rapid sedimentation in the Upper Cretaceous period (Ekine and Onuoha 2010; Obasi, Selemo, and Nomeh 2018; Ene, Okogbue, and Onuoha 2019; Oguama, Okeke, and Obiora 2021; Omietimi et al. 2021; Oluwajana et al. 2023).

During the Palaeocene, a major transgression in Southern Nigeria resulted in the deposition of prodelta mudstones overlaying the Campanian-Danian sedimentary cycle and marking the formation of the Niger Delta Basin (Short and Stauble 1967; Avbovbo 1978; Omietimi et al. 2024). Significant delta growth has been ongoing since the Eocene, as documented by the continuous deposition of regressive deltaic sequences (Short and Stauble 1967; Avbovbo 1978; Umeji and Nwajide 2014). Notably, the Niger Delta Basin is characterised by a Cenozoic basin-fill history, thus differing from the older basin-fill of the Anambra Basin (Umeji and Nwajide 2014).

2.2 | Stratigraphy

The oldest deposits of the Anambra Basin (Figure 3), the Campanian Nkporo Group, which consists of the Nkporo, Owelli and Enugu formations, are composed of brackish to shallow-marine organic-rich shales and sandstones (Akande and Mücke 1993; Odunze et al. 2013; Dim et al. 2017). The overlying Maastrichtian Mamu Formation consists of estuarine and marginal to shallow-marine sandy and silty shales. Subsequently, the freshwater, subtidal and marginal marine sandstones of the Ajali Formation developed (Tijani, Nton, and Kitagawa 2010). The decline in eustatic sea level from the mid-Maastrichtian to Danian periods (as illustrated in Figure 2) prompted the accumulation of regressive units such as the Nsukka Formation (Edegbai, Schwark, and Oboh-Ikuenobe 2019). The latter two formations mark the depositional transition from the Anambra Basin succession to those of the overlying Niger Delta Basin (Dim et al. 2017; Ejeh 2021). The Cenozoic Imo and Bende-Ameki formations are lateral equivalents of the subsurface Akata and Agbada formations within the Niger Delta Basin

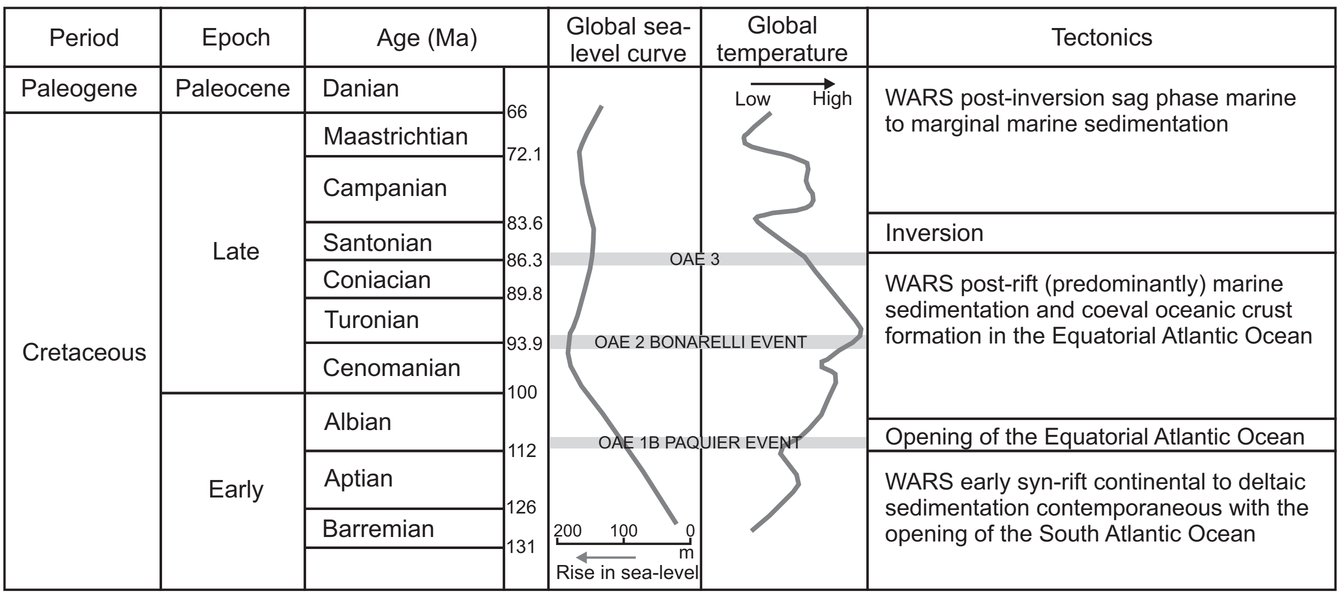

FIGURE 2 | Tectonic changes during the Cretaceous-Palaeogene period (modified from Edegbai, Schwark, and Oboh-Ikuenobe 2019). WARS denotes the West African Rift System, while grey arrows represent the rise in sea level and temperature.

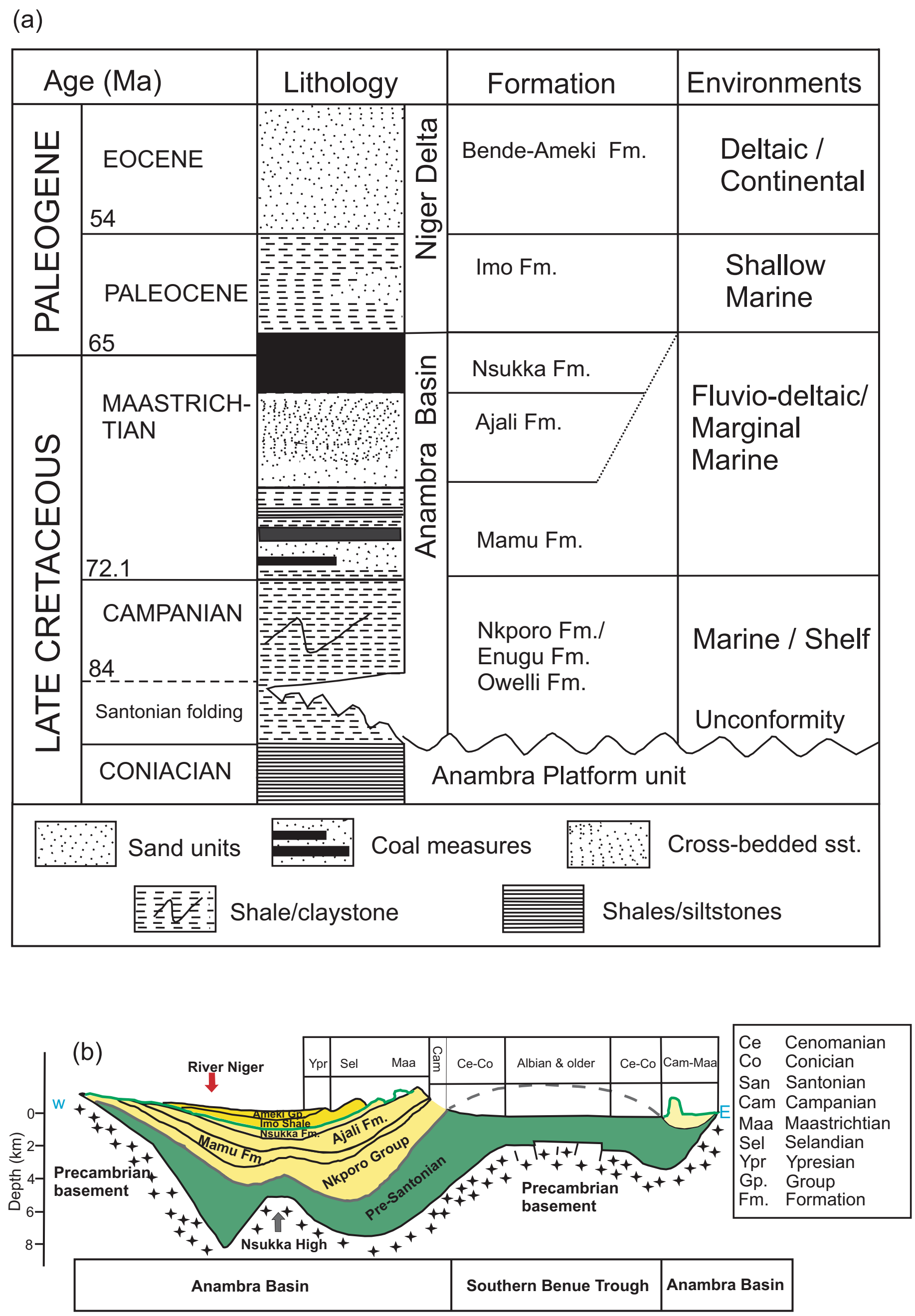

FIGURE 3 | (a) Stratigraphy and depositional environments of the Anambra Basin (Tijani, Nton, and Kitagawa 2010; Ogungbesan and Adedosu 2020; Omietimi et al. 2022). Chronostrat. = chronostratigraphy, Fm. = Formation, sst. = sandstone. (b) A W-E cross-section of the Anambra Basin showing lithostratigraphic units (modified from Edegbai et al. 2019)

(Umeji and Nwajide 2014; Ikegwuonu and Umeji 2016; Okeke and Umeji 2016).

3 | Materials and Methods

Ditch cuttings and core samples were recovered from wells Owan-1 and Ubiaja in the western limb of the Anambra Basin, and samples from the Upper Cretaceous Mamu and Nkporo formations and the Palaeocene Imo Formation were analysed. The investigated samples range in depth from 59.7 to 547.4 m and 22.9 to 647.7 m for the Owan-1 and Ubiaja wells, respectively (Figures 4 and 5).

3.1 | Palynofacies Analysis

Palynofacies analysis was performed on 31 mudrock samples from the Maastrichtian Mamu and Palaeocene Imo formations from the Owan-1 well. The samples were prepared using standard palynological preparation procedures, which included washing the mudrocks and treating them with hydrochloric acid (HCl, 30%) and hydrofluoric acid (HF, 41%) to remove carbonates and silicates. A nylon mesh size of 15 μm was used to sieve the residue, which was mounted with glycerine jelly. Slides were prepared and examined at various magnifications with a Leica DM2500 transmitted light microscope. Using the Tyson (1993) classification, sedimentary organic matter was divided into

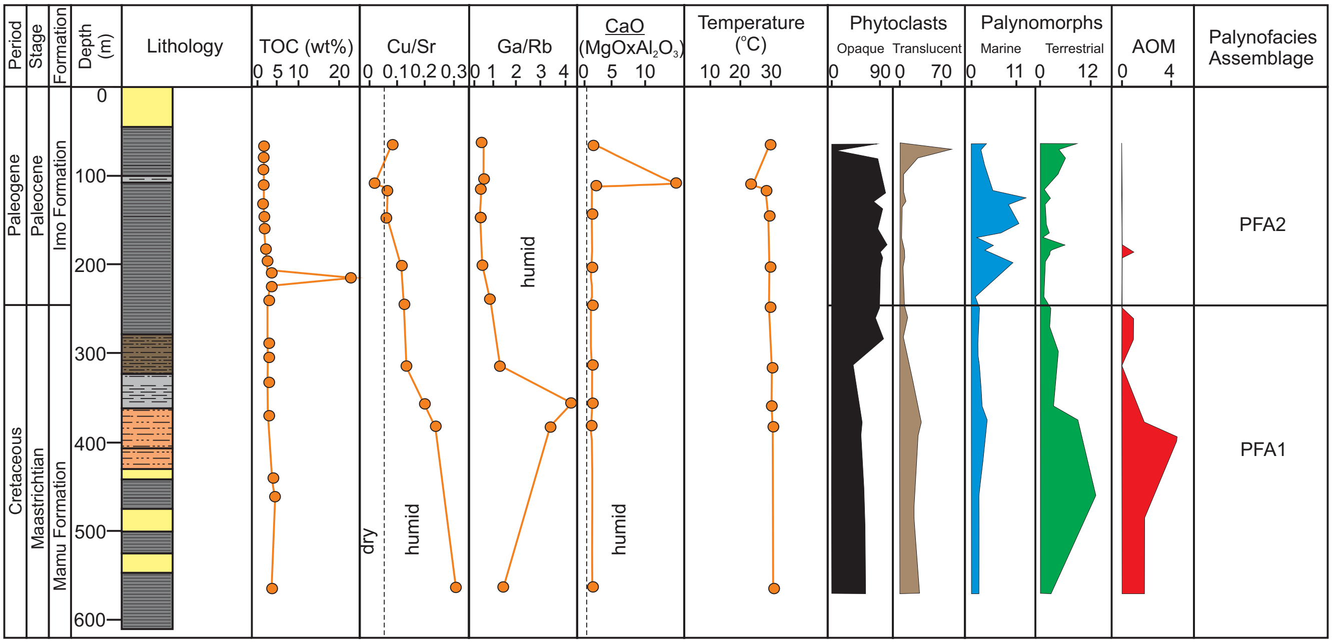

FIGURE 4 | Stratigraphy, TOC, geochemical indicators and palynofacies assemblages in the Owan-1 well. AOM = amorphous organic matter. For legend, see Figure 5.

three palynofacies groups: phytoclasts, palynomorphs and amorphous organic matter (AOM). A minimum of 300 particles were counted for each sample to determine the relative percentages of these components. Palynofacies data were plotted in an APP ternary diagram (Tyson 1989, 1993, 1995) as an indicator of the depositional environment, possible transgressive and regressive trends and the redox conditions.

3.2 | Maceral Analysis

Organic petrographic analysis was carried out on 16 shale samples to determine the maceral composition and observable mineral matter following the SANS 7404-3 (2016) and ISO 7404-3 (2009) standards using a Zeiss AxioImager m2M reflected white light and reflected fluorescence light microscope. A total of 1000 counts were performed on macerals plus mineral particles. The organic petrography was performed at the South African Bureau of Standards (SABS), CSIR Campus, Pretoria. Results are presented as a proportion of the total volume (vol%).

3.3 | Total Organic Carbon

TOC analysis of the studied samples was carried out using a High-Frequency Infrared Absorption Carbon-Sulfur Analyser (CS-902G; Beijing Wanliandaxinke Ltd., China) instrument. Forty mudrock samples from the Owan-1 and Ubiaja wells were selected for the analyses (Data S1; Figures 4 and 5), which were carried out at the Key Laboratory of Petroleum Resources Research, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China. Exactly 2 g of each sample was decarbonated with concentrated hydrochloric acid (HCl) to remove carbonates. Concentrated HCl was applied to the samples for at least 2 h to treat them. To remove the acid, the samples were washed and filtered using a filtration device. Following this, the filter was removed, placed in a LECO crucible and dried for 4 h at 110°C. The standards were then heated to 1200°C in the presence of oxygen to complete the process. Carbon monoxide and carbon dioxide were produced, with the carbon monoxide being transformed into carbon dioxide via a catalyst; an IR cell was used to measure the carbon dioxide. The TOC was calculated by comparing the mass unit response of unknowns after combustion with that of the calibration standard. TOC values ≤ 2 wt% are indicative of oxic–suboxic conditions (Tyson 1995) and may also be characteristic of marginal to shallow marine depositional environments with high clastic supply.

3.4 | Elemental Analyses

The major element oxide analysis was carried out at the Stoneman Lab at the University of Pretoria. Twenty mudrock samples collected from the Owan-1 and Ubiaja drill cores were used for inorganic geochemical analysis (Data S1). The samples were finely ground to a particle size of < 75 μm using a tungsten carbide milling pan. They were then subjected to roasting at 1000°C to ascertain the loss on ignition (LOI) and subsequently fused into a glass bead. The whole-rock major element oxide concentrations were determined using a Thermo Fisher ARL Perform'X Sequential XRF instrument with OXSAS software. Sample preparation and analyses followed the established procedures detailed in Loubser and Verryn (2008), with precision and accuracy better than 5% for the major element oxides. The whole-rock analyses are reported in the Data S1 without any LOI correction for the major elements. For all subsequent interpretations of the geochemical data, the major element analyses were recalculated to establish a 100 wt% anhydrous basis.

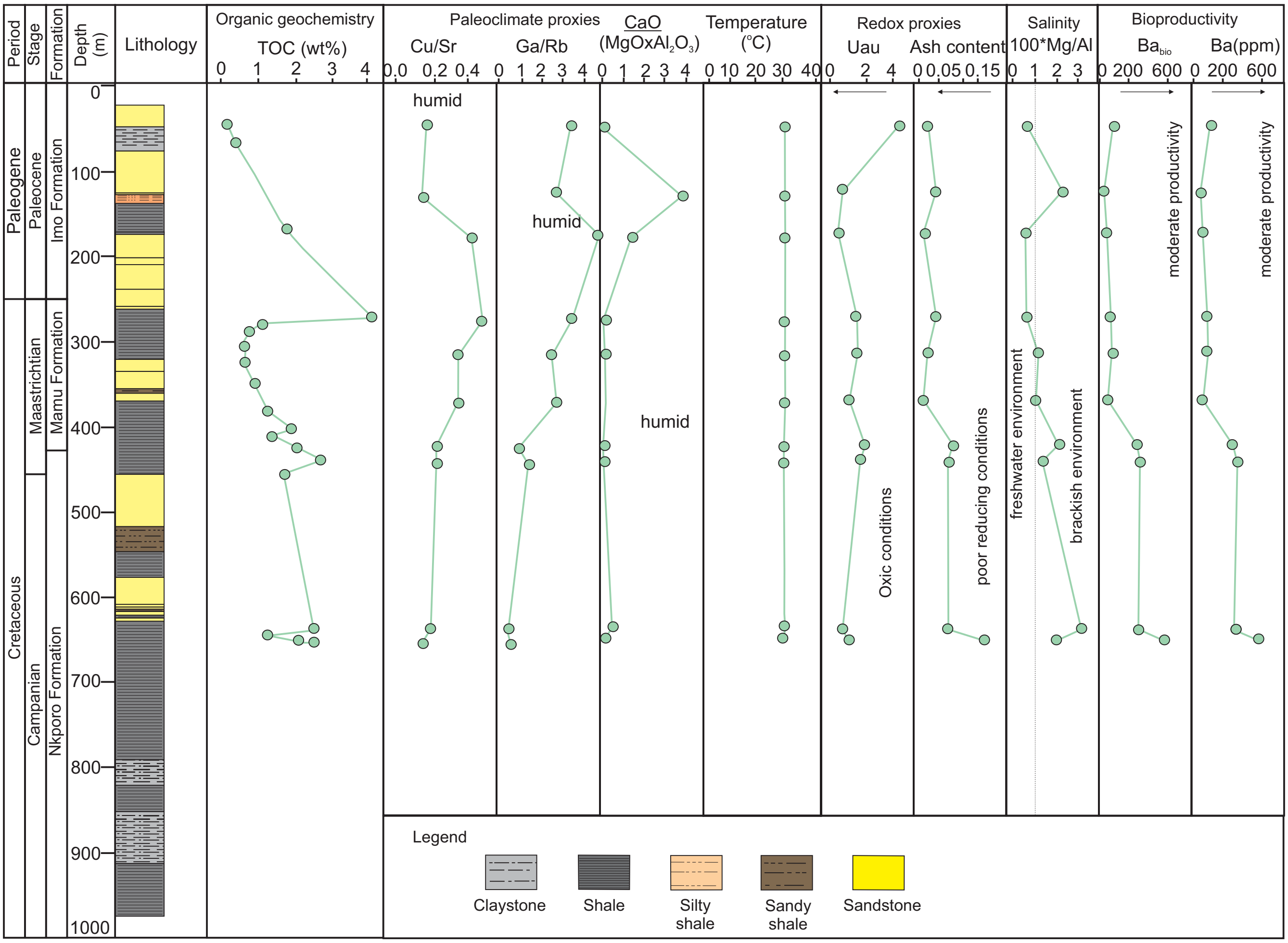

FIGURE 5 | Stratigraphy, TOC and geochemical indicators in the Ubiaja well. Uau = authigenic Uranium.

The trace elements and REE's were measured by inductively coupled plasma mass spectrometry (ICP-MS) at the University of the Witwatersrand using a Thermo Scientific iCAP RQ. The analyses of major and trace elements revealed accuracy and precision > 5%.

3.5 | Palaeoenvironmental Indices

3.5.1 | Palaeotemperature

The empirical formula proposed by Liu et al. (2018, 2022) used for the palaeotemperature calculations is defined as:

$$T = (2578 - y) / 80.8 \quad (1)$$

where T denotes temperature and y represents strontium (ppm) concentration in samples.

3.5.2 | Authigenic Uranium (Uau)

The authigenic uranium (Uau) concentration indicates the levels of oxygen present during deposition (Wignall and Myers 1988; Bai et al. 2015; Liang et al. 2020). The Uau is determined using the calculation:

$$\text{Uau} = \text{U} - \text{Th} / 3 \quad (2)$$

3.5.3 | Ash Content Index

The inorganic ash yield index, in conjunction with other geochemical proxies, can provide insights into the potential redox conditions in marine environments (Hao, Ge, and Xie 2000; Bai et al. 2015; He et al. 2022; Johnson et al. 2024). The index indicates the prevailing redox environmental conditions during sediment deposition. The ash content was calculated using the equation:

$$\text{Ash content} = \left[(Fe_2O_3 + CaO + MgO) / (SiO_2 + Al_2O_3)\right] \quad (3)$$

3.5.4 | Bioproductivity

The bioproductivity can be accurately quantified using the biological source Ba_{bio} (Dymond, Suess, and Lyle 1992; Tribovillard et al. 2006; He et al. 2022; Huang et al. 2023). The Ba_{bio} is calculated from the formula:

$$Ba_{bio} = Ba_s - Al_s \times (Ba/Al)_{PAAS} \quad (4)$$

where Ba_s represents the Ba content of the measured samples, Al_s is the Al value of the measured samples determined from the Al_2O_3 content in the Owan-1 and Ubiaja wells, and $(Ba/Al)_{PAAS}$ is the ratio of Ba and Al contents in Post-Archean Australian Shales (PAAS), which is 0.0075 (Dymond, Suess, and Lyle 1992; Ross and Bustin 2009). Therefore, the Ba_{bio} equation is:

$$Ba_{bio} = \left(Ba_s - Al_s\right) \times 0.0075 \quad (5)$$

3.5.5 | Palaeobathymetry

Geochemical data has been successfully used to reconstruct palaeobathymetric variations internationally (Fu 2023; Merenkova et al. 2020; Miao et al. 2023; Yang et al. 2024). Previous research has shown notable discrepancies in specific major and trace elements as the distance from the coastline increases. These findings provide a valuable understanding of changes in water depth during the process of sediment accumulation. In the present investigation, we used the formula proposed by Yang, Fu, et al. (2022) to deduce ancient water depths in the Anambra Basin.

$$F = (Rb \times Al) / (Zr \times K) \quad (6)$$

3.5.6 | Enrichment Factor

The enrichment factor (EF) is a standard method for evaluating the extent of metal enrichment (Omietimi et al. 2022). It is determined by computing the ratio of the contents of an element in the measured samples to that in the upper continental crust (UCC) and chondrite levels (Boynton 1984; Taylor and McLennan 1985).

4 | Results

4.1 | Palynofacies

Phytoclasts, palynomorphs and AOM were identified in the samples from the Owan-1 well (Table 1; Figure 6). In general, the preservation is very good, and all samples yielded rich palynofacies assemblages. In contrast, most of the samples from the Ubiaja well are characterised by low amounts of sedimentary organic matter comprising AOM and phytoclasts and only poorly preserved palynomorphs. Sandstones contain reworked palynomorphs and high numbers of equidimensional phytoclasts.

The Owan-1 well mudrocks are dominated by phytoclasts of different sizes and shapes, which are opaque or translucent (Figure 6); translucent phytoclasts comprise plant tissues, cuticles and woody fragments (cf. Li, Wang, and Vajda 2021). Opaque phytoclasts include woody material that was oxidised during extended transport or post-depositional modification; partly opaque material was interpreted as charcoal, which may indicate the existence of wildfires during the time of deposition (Ma et al. 2022). Opaque phytoclasts represent 7.0% to 92.6% of the palynofacies, and translucent particles range from 2.1% to 78.3%. Cuticles and larger plant debris comprise up to 8.3% of the palynofacies, with sample OW36 showing the highest amounts.

Palynomorphs include terrigenous particles such as pollen grains and spores, together with freshwater algae such as *Botryococcus* sp. and marine particles such as dinoflagellate cysts, acritarchs and prasinophytes. The percentage of pollen grains ranges from 0.6% to 10.9%, with the highest amounts occurring in sample OW34. Spores are rare (up to 1.96%). Within the marine fraction, dinoflagellate cysts range between 0.6% and 10.5%, with the maximum occurring in sample OW15. Both prasinophytes and acritarchs reach up to 0.6% of the palynofacies. Foraminiferal test linings are also present (up to 0.6%). AOM and degraded organic matter (DOM) are represented by semi-transparent to structureless particles derived from bacterial degradation of dinoflagellates and acritarchs (AOM) and biodegradation of higher plant materials (DOM), respectively (Figure 6). The percentage of DOM ranges from 0.9% to 42%, with sample OW29 showing the highest content. The highest AOM value (4.2%) was recorded in sample OW31.

Two palynofacies associations (PFA1 and PFA2) (Figures 4 and 7) were distinguished. PFA1 was identified in the Mamu Formation and the lower Imo Formation, dominated by translucent and opaque phytoclasts. Terrigenous palynomorphs appear light brown under the microscope and are dominated by pollen grains, which show a maximum abundance in sample OW34; fern spores are rare elements throughout the succession. *Botryococcus* sp., fungal remains and resins occur in samples from the lower part of the Mamu Formation (samples OW30-OW36). The relative abundance of marine dinoflagellate cysts increases up-section in the Mamu Formation, while acritarchs are rare. AOM is characteristic of the lower part of the Mamu Formation. Both AOM and DOM are most abundant in sample OW31.

PFA2 was found in samples from shallower depths in the Imo Formation from the Owan-1 well (Figure 4). Opaque phytoclasts dominate throughout the succession, with marine dinoflagellate cysts peaking in sample OW15. AOM was found in only one sample from the lower part of the Imo Formation. The upper part of the formation is characterised by a higher number of pollen grains, large cuticles and a peak abundance of translucent phytoclasts. *Botryococcus* sp., fungal remains and resin are present in samples OW1 and OW9. The terrigenous palynomorphs range in colour from light brown to yellow.

4.2 | Maceral Analysis

Maceral analysis shows that the three studied formations contain relatively low amounts of macerals (i.e., $<10\%$) and a high percentage of mineral matter (MM) (i.e., 90% or more). The majority of the observed macerals are small homogeneous organic matter fragments, which could be classified as solid bitumen (pyrobitumen) and vitrinite particles (Figure 8).

4.3 | Organic Geochemistry

The results of the TOC analysis (i.e., TOC ≥ 0.1) of the studied samples from the two wells are shown in Figures 4 and 5, and Data S1.

The TOC content of the studied mudrocks varies from 0.2 to 21 wt% (mean 1.6 wt%) in samples from the Owan-1 well and 0.1 to 4 wt% (mean 1.4 wt%) in samples from the Ubiaja well. In

TABLE 1 | Palynofacies data of the Owan-1 well, western Anambra Basin.

Well	Sample no	Depth (m)	Formation	Phytoclasts (%)	Palynomorphs (%)	AOM (%)	Palynofacies type
Owan-1	OW1	93	Imo	87.9	12.1	0	PFA2
	OW9	99	Imo	93.5	6.5	0	
	OW11	107	Imo	92.3	7.7	0	
	OW12	122	Imo	92.0	8.0	0	
	OW14	139	Imo	94.8	5.2	0	
	OW15	147	Imo	86.4	13.6	0	
	OW16	153	Imo	91.4	8.6	0	
	OW18	172	Imo	88.9	11.1	0	
	OW19	182	Imo	92.5	7.5	0	
	OW20	187	Imo	98.5	1.5	0	
	OW22	194	Imo	89.4	10.0	0.6	
	OW24	199	Imo	95.1	4.9	0	
Owan-1	OW25	210		90.0	10.0	0	PFA1
	OW26	246	Mamu	98.5	1.5	0	
	OW27	256	Mamu	95.0	4.0	1.0	
	OW28	275	Mamu	95.3	4.0	0.7	
	OW29	300	Mamu	93.9	6.1	0	
	OW30	353	Mamu	92.7	5.3	2.0	
	OW31	367	Mamu	84.0	11.7	4.3	
	OW34	443	Mamu	83.7	14.3	2.0	
	OW36	540	Mamu	93.6	4.1	2.3	

general, samples from greater depths record higher TOC values (Figures 4 and 5). The highest TOC content in the Owan-1 well was measured in sample OW22 (Figure 4). The organic geochemistry values become more variable upsection in the stratigraphy (Figures 4 and 5).

4.4 | Sedimentary Bulk-Rock Elemental Chemistry

The major element concentrations of the Owan-1 well and Ubiaja well are expressed as weight percentages of oxides (Data S1). The oxides of SiO_2, Al_2O_3 and Fe_2O_3 are the most abundant in the Upper Cretaceous to Palaeocene formations. SiO_2 values range from 7.08% to 72.87% (average of 47.52 wt%) in the Owan-1 well, while in the Ubiaja well, SiO_2 ranges from 56.07% to 85.22% (average of 68.56 wt%). Al_2O_3 ranges from 2.65 to 22.63 wt% (average of 14.99 wt%) in the Owan-1 well, while in the Ubiaja well, it ranges from 4.13 to 27.42 wt% (average of 15.53 wt%). Fe_2O_3 ranges from 1.70 to 23.85 wt% with an average of 5.98 wt% in the Owan-1 well, while in the Ubiaja well, it ranges from 0.57 to 10.77 wt% with an average of 3.31 wt%. MgO varies between 0.18 and 8.09 wt% (average of 2.73 wt%) in the Owan-1 well and 0.04 to 0.54 wt% (average of 0.21 wt%) in the Ubiaja well. CaO ranges between 0.13 and 47.37 wt% (average of 5.63 wt%) in the Owan-1 well and 0.04 to 3.14 wt% (average of 0.52 wt%) in the Ubiaja well. In contrast, the concentrations of TiO_2, K_2O, P_2O_5, MnO and Na_2O are relatively low.

The trace elements and REE concentrations of the Owan-1 and Ubiaja wells are expressed in parts per million (ppm) (Data S1). The abundant trace elements were Ba, Rb, Sr, Co and Cu. The Ba values range from 70.24 to 136 (average of 94.20) in the Owan-1 well. In the Ubiaja well, they range from 79 to 588.37 (average 227.31). The Rb values were from 7.90 to 54.15 (average of 28.94) in the Owan-1. In contrast, the Ubiaja well records values ranging from 2.98 to 46.10 (average of 16.08). The Sr values in the Owan-1 range from 42.37 to 652.33, with an average of 184.27. The Ubiaja well records values ranging from 22.72 to 116.64, with an average of 58.74.

5 | Discussion

Palaeoclimatic conditions, palaeotemperatures, palaeobathymetry, sedimentation rate, basin retention and palaeo-sedimentary environments are vital parameters that influence ocean anoxic events (OAE) and organic matter deposition in sedimentary

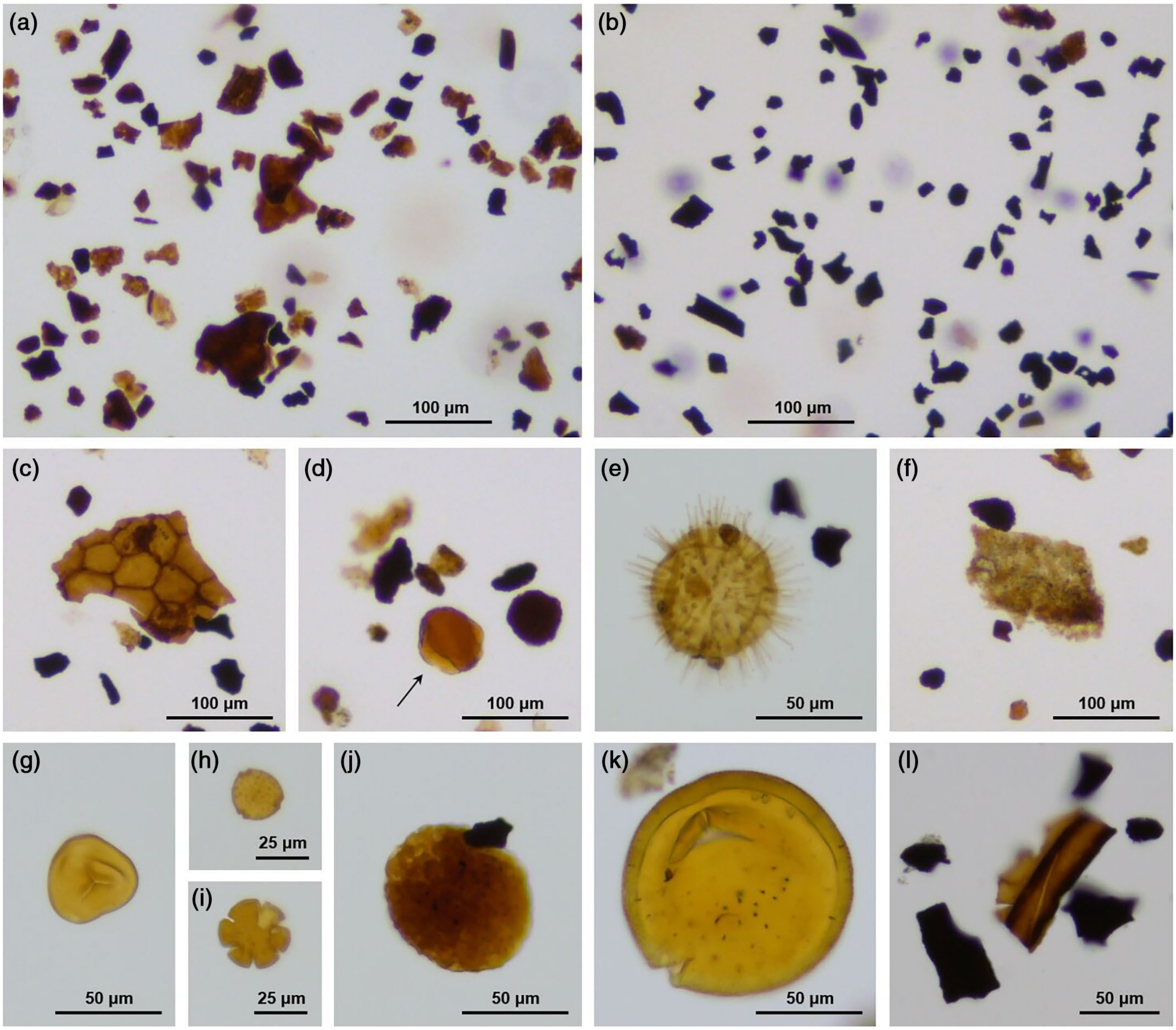

FIGURE 6 | Palynofacies of the Mamu and Imo formations intersected in the Owan-1 well is characterised by the general high amount of terrestrial phytoclasts. (a) high amount of equidimensional and blade-shaped, translucent phytoclasts within the early transgressive and late highstand phase (OW9); (b) opaque, mainly equidimensional phytoclasts characteristic of the maximum flooding and early highstand phase (OW12); (c) well-preserved cuticles characteristic of the early transgressive phase with "fresh" plant debris (OW36); (d) resin (highlighted by arrow) pointing to high terrestrial influx and DOM during the early transgressive phase (OW34); (e) peak abundance of marine phytoplankton (dinoflagellate cysts) and opaque, equidimensional phytoclasts during maximum flooding (OW15) in the Imo Formation; (f) low amount of AOM in the lower Mamu Formation (OW31); (g) trilete fern spores and pollen grains (h, i) documenting high terrestrial influx (OW1, OW34); (j) freshwater algae (*Botryococcus* sp.) pointing to periodic freshwater influx (OW30); (k) prasinophytes (*Tasmanites* sp.) indicating fluctuation in salinity (OW36); (l) terrestrial phytoclasts of different size and shape revealing a short distance from the source area (OW1).

basins (Lv et al. 2021). Additionally, these parameters impact the number of palynomorphs, macerals and elemental concentrations in marginal to deep marine settings. Furthermore, sedimentary organic matter preservation may likely have a relationship with elemental geochemical indicators (Chen, Huang, and Heng 2018; Fu et al. 2018; Chen et al. 2021; Chukwuma et al. 2022; Huang et al. 2023; Nie, Fu, Liang, et al. 2023; Nie, Fu, Wei, et al. 2023; Qiao et al. 2023; Xiao et al. 2023; Yang et al. 2024). In this study, we used organic petrography data, major oxides, trace elements and rare earth elements to provide new insights into the factors controlling sedimentary organic matter preservation in the Anambra Basin.

5.1 | Palynofacies and Sea-Level Changes

Palynofacies analysis has been used on a global scale to reconstruct palaeoclimatic fluctuations, palaeoenvironments, transgressive/regressive trends, as well as oxygenation conditions and the transport of organic particles from potential source areas into the basin (Götz, Feist-Burkhardt, and Ruckwied 2008; Carvalho et al. 2013; El Beialy, Zobaa, and Taha 2016; Mahmoud et al. 2017; Achaegakwo and Atta-Peters 2021; Li, Wang, and Vajda 2021).

The APP ternary plot (Tyson 1989, 1993, 1995) is a well-established graphical tool for interpreting depositional

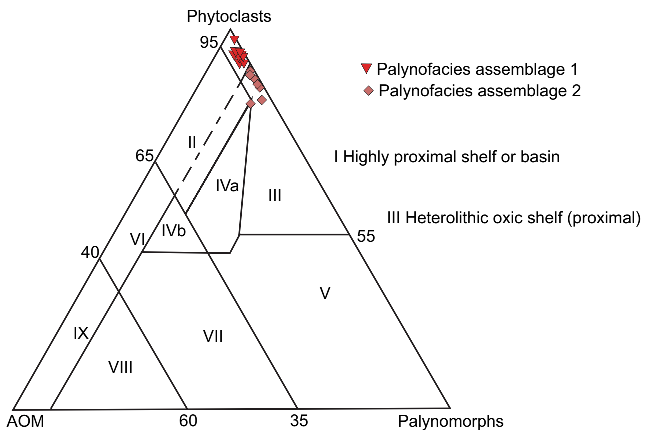

FIGURE 7 | Palynofacies data of the Owan-1 well plot in fields I and III of the APP ternary diagram introduced by Tyson (1989). AOM = amorphous organic matter.

environments. The studied samples of the Owan-1 well fall into fields I (highly proximal shelf or basin) and III (heterolithic oxic shelf). Both fields are characterised by the dominance of phytoclasts (Figures 6 and 7). These shallow or marginal marine environments frequently have a high level of terrestrial input (mainly phytoclasts; additionally, pollen grains, spores, freshwater algae and cuticles). Our findings support the interpretations by Edegbai, Schwark, and Oboh-Ikuenobe (2020) based on outcrop data from the western margin of the Anambra Basin. Palynofacies assemblage PFA1 plotting into field I suggests a deltaic, shallow-marine environment with high terrestrial input under oxidising conditions (Li, Wang, and Vajda 2021).

Palynofacies assemblage PFA2 plotting in field III suggests a marginal-marine and oxic shelf depositional setting (Tyson 1993; Li, Wang, and Vajda 2021). The preservation of sedimentary organic matter is limited in marginal to shallow-marine environments due to continuous reworking and oxidation, which

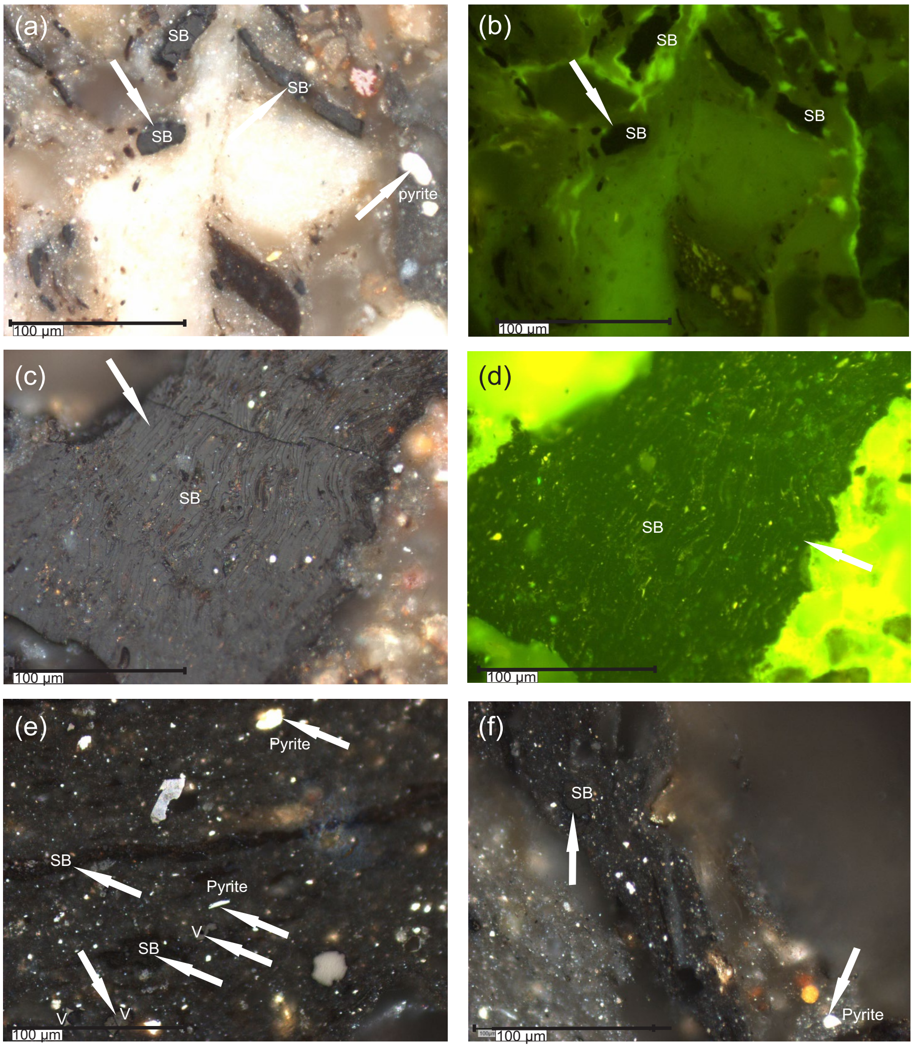

FIGURE 8 | Photomicrographs of macerals and mineral matter in reflected white light (a, c, e and f) and reflected fluorescence light (b and d) within the Owan-1 and Ubiaja wells: (a and b) made up of solid bitumen (SB) at depth 623 m (UB39); (c and d) showing solid bitumen at depth 625 m (UB40); (e) homogeneous organic matter fragments composed of vitrinite (V), solid bitumen particles at depth 353 m (OW30); (f) mudrock composed of solid bitumen at 353 m depth (OW 30).

may be the main cause of the poor preservation of sedimentary organic matter in the Ubiaja well (Götz, Feist-Burkhardt, and Ruckwied 2008; Omietimi et al. 2022).

Stratigraphic variations in the composition of palynofacies reflect changes in the coastline's position as a result of sea-level changes (Götz, Feist-Burkhardt, and Ruckwied 2008; Carvalho et al. 2013). In the studied Owan-1 well, we detected increasing amounts of marine phytoplankton (dinoflagellate cysts) in the Mamu Formation, with a peak abundance in sample OW15 (which also contains foraminiferal test linings). Higher percentages of dinoflagellate cysts and the dominance of equidimensional, opaque phytoclasts in samples OW14 to OW19 are interpreted to document the maximum flooding phase (Figures 4 and 6). Cuticles, translucent phytoclasts and a high amount of DOM in the lower Mamu Formation within the interval covered by samples OW30 to OW36 indicate an early transgressive phase, followed by a continuous transgressive trend up-section as reflected by an increase of marine phytoplankton within the Imo Formation (samples OW20 to OW29). The lower part of the Mamu Formation, representing the early transgressive phase, was also affected by a periodic freshwater influx, as indicated by the occurrence of the freshwater algae *Botryococcus* sp. and fungal remains. The palynofacies of the upper Imo Formation document the early highstand phase with an increase in translucent phytoclasts covered by samples OW11 and OW12. The late highstand phase is marked by a striking input of translucent phytoclasts, large cuticles and spores, as documented by samples OW1 and OW9 (Figures 5 and 6).

5.2 | Reconstruction of Campanian-Maastrichtian to Early Palaeocene Palaeoclimate

5.2.1 | Palaeoclimatic Conditions

Palaeoclimate investigations often rely on distinctive rock indicators, ice cores, palynofacies present in sedimentary sequences and geological techniques such as oxygen, carbon and hydrogen isotopes and palaeomagnetism (Hay and Floegel 2012; Boboye and Egbeola 2017; Pickering et al. 2019; Chen et al. 2021; Ding et al. 2022; Venu et al. 2022; Wang et al. 2022; Wu et al. 2022; Qureshi et al. 2023; Ribeiro et al. 2023; Yang et al. 2024). In the context of the Nigerian Anambra Basin, this study used palynomorphs, maceral data and the elemental ratio method to assess the Upper Cretaceous palaeoclimate (Figures 4, 6, 8 and 9). The evolution of the palaeoclimate is intricately linked to variations in palynomorph amounts, elemental content, changes in elemental ratios and palaeosalinity. The distribution of elements in mudrocks and other siliciclastic sedimentary rocks is, to some extent, influenced by palaeoenvironmental factors such as palaeoclimate and palaeosalinity. Alterations in palaeoclimate lead to fluctuations in palaeowater depth, subsequently inducing changes in the palaeoenvironment, influencing the distribution of elements and impacting alterations in elemental ratios.

Palynofacies data show a high abundance of trilete fern spores and pollen grains, cuticles, prasinophytes and higher plant materials that thrive in warm, humid conditions (Figures 4 and 6) and they contribute substantial organic material to the Cretaceous formations in the Anambra Basin (Carvalho et al. 2013; Mahmoud et al. 2017; Ojo et al. 2020). Over geological time, with the suitable conditions and available hydrocarbon system elements, these carbonaceous materials would likely transform into shale gas (Li, Wang, and Vajda 2021). There was coastal vegetation that was predominated by araucarian conifers (*Classopollis* spp.), and the presence of spores, particularly fern spores such as *Deltoidospora* spp., further supports humid and warm tropical climates. Furthermore, the morphology and distribution of vitrinite macerals within sedimentary sequences can also shed light on past environmental conditions (Figure 8). The presence of vitrinite macerals in the Owan-1 and Ubiaja wells likely indicates moist rainforest environments.

The palaeoclimate plays a significant role in defining the palaeoenvironment, which subsequently influences the formation of carbonaceous source rocks. Since the Cu/Sr proportion is susceptible to variations in climatic conditions, their ratio is commonly applied in reconstructing palaeoclimates (Wang et al. 2017; Xu et al. 2021; Yang, Fu, et al. 2022). A Cu/Sr ratio >0.05 implies a humid climate, while a ratio lower than 0.05 reflects a dry climate (Wang et al. 2017; Yang, Fu, et al. 2022). The Cu/Sr ratios observed in the Campano-Maastrichtian to Palaeocene deposits of the Nkporo, Mamu and Imo formations varied between 0.001 and 0.29, with an average value of 0.12 in the Owan-1 well (Figures 4, 5 and 9a). The Ubiaja well exhibited Cu/Sr ratios from 0.14 to 0.56, with an average of 0.29 (Figures 3, 4 and 9a). These ratios show an increasing trend up-section. Based on the shifting pattern, the palaeoclimate during the formation of the Ubiaja well samples had a higher level of moisture compared with the Owan-1 data, which experienced an intermittent arid phase. The Anambra Basin experienced a prevailing moist and warm climate during the Campano-Maastrichtian period, on the western border of the basin.

Similar to the Cu/Sr proxy, the ratios Ga/Rb versus K_2O/Al_2O_3 can provide insight into variations in palaeoclimate (Ratcliffe et al. 2010; Roy and Roser 2013; Nie, Fu, Liang, et al. 2023). Typically, high Ga/Rb and low K_2O/Al_2O_3 ratios indicate a warm and humid climate. In contrast, high K_2O/Al_2O_3 and low Ga/Rb values are characteristic of terrigenous sediments deposited under cold, arid climates (Roy and Roser 2013; Nie, Fu, Liang, et al. 2023). The Ga/Rb ratios of the samples from the Owan-1 and Ubiaja cores are high (0.41–4.78, i.e., >0.2), while the K_2O/Al_2O_3 ratios are low (0.01–0.15, i.e., <0.2), indicating a dominance of kaolinite formed through intense chemical weathering in warm and humid climatic conditions (Figure 9c). Vertical plots of Ga/Rb and Cu/Sr ratios reveal consistency, further supporting predominantly moist and warm climatic conditions (Figures 4 and 5).

Furthermore, the $CaO/(MgO \times Al_2O_3)$ ratio can detect the calcium carbonate amounts in siliciclastic rocks and provides insights into temperature variations (Yang et al. 2024). A ratio exceeding 0.01 indicates a warm period, whereas a ratio below 0.01 suggests relatively colder conditions (Fu et al. 2018; Venu et al. 2022; Yang, Fu, et al. 2022; Yang et al. 2024).

In the Upper Cretaceous Nkporo and Mamu formations and early Palaeocene Imo Formation samples, $CaO/(MgO \times Al_2O_3)$ ratios range from 0.01 to 12.50, averaging 1.27 in the Owan-1 well (Figure 4). For the Ubiaja well, ratios range from 0.01 to

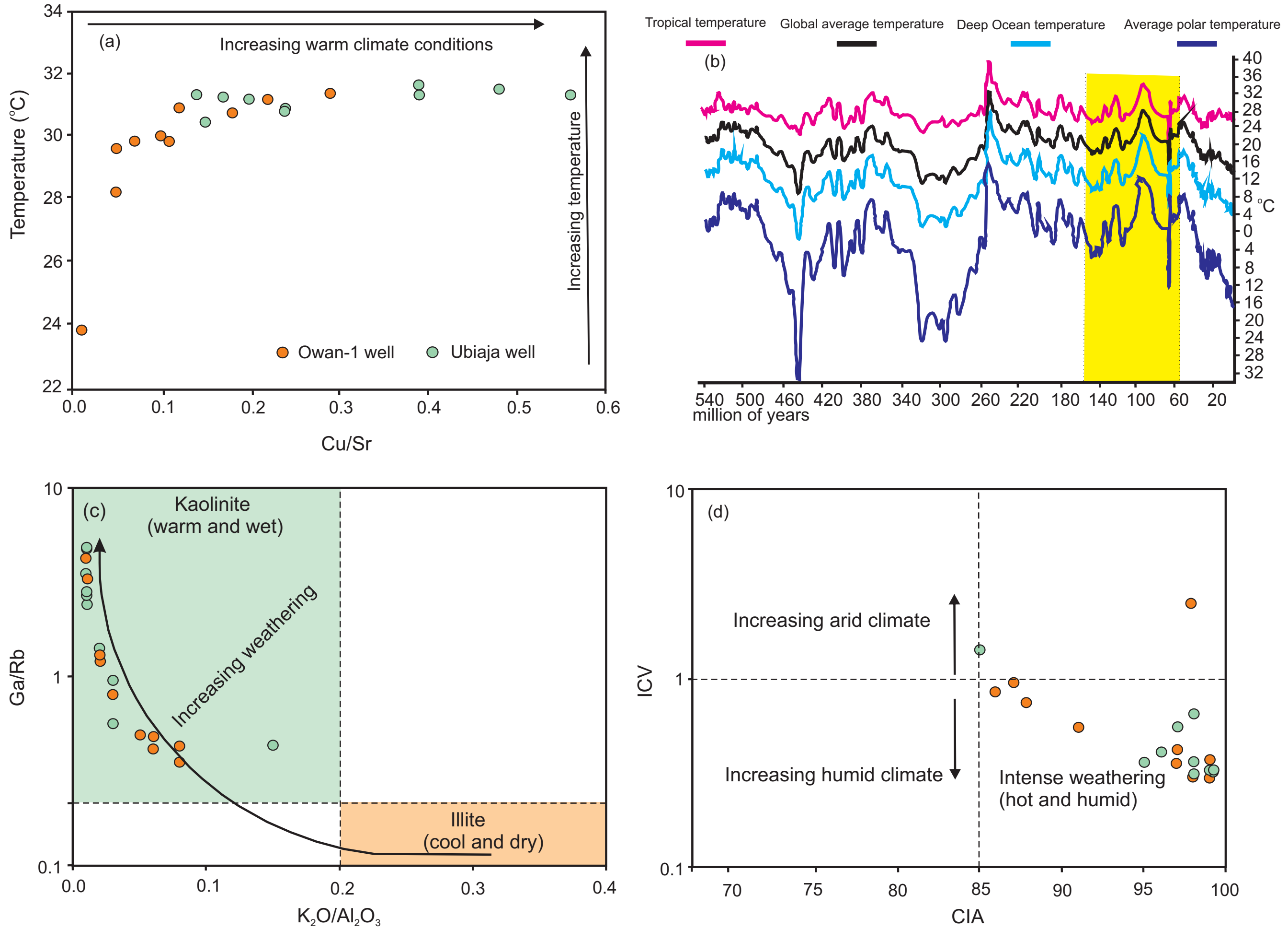

FIGURE 9 | (a) Diagram showing palaeotemperature interpretation of the Upper Cretaceous to Palaeocene sequences. (b) Scotese et al. (2021) global average temperature model: Magenta line = tropical temperature, black line = global average temperature, cyan line = deep ocean temperatures, blue line = polar temperature. The Cretaceous-Palaeocene period is highlighted in yellow. (c) Ga/Rb versus K_2O/Al_2O_3 palaeoclimate discrimination cross-plot (after Roy and Roser 2013). (d) CIA versus ICV palaeoclimate cross-plot (after Long et al. 2012; Johnson et al. 2024).

3.83, averaging 0.52 (Figure 5). Notably, the basal Nkporo and Mamu formations of the Owan and Ubiaja wells exhibited ratios consistently above 0.01, indicating warm climatic conditions (Figures 4 and 5). Conversely, the upper Imo Formation showed higher values, suggesting warmer conditions and a possible slight temperature increase. The temperature variations suggest relatively warm localised periods. Additionally, the chemical index of alteration (CIA) data from Omietimi et al. (2022) show relatively high values (> 85) in the Owan-1 and Ubiaja wells, suggesting deposition under hot-humid tropical climatic conditions (Nie, Fu, Liang, et al. 2023). In addition, the index of compositional variability (ICV) versus CIA cross-plot (Figure 9d) shows intense chemical weathering under a hot, humid palaeoclimate (van de Kamp and Leake 1985; Long et al. 2012; Johnson et al. 2024).

Overall, the Upper Cretaceous units in the Anambra Basin experienced a predominantly warm and humid climate during deposition, which is consistent with the palynofacies, maceral analysis and trace element proxies interpretation above.

During the Cretaceous period, high temperatures were prevalent (Barron et al. 1995; Hay 2017; Bolarinwa, Idakwo, and Bish 2019). Global temperature records spanning the Early to Late Cretaceous epochs indicate prolonged periods of high temperatures, followed by a cooling trend toward the end of the Cretaceous (Barron et al. 1995; Ladant et al. 2020). West Africa experienced high precipitation throughout the Cretaceous period, fostering robust chemical weathering processes (Chumakov et al. 1995; Omietimi 2022). In Chad, analysed palynofacies data from the Cretaceous Bongor Basin reveals a diverse flora, including plants of the family Lygodiaceae, which thrive in humid climates, and parent plants of *Afropollis*, indicating a humid tropical coastal environment (Hu et al. 2023). During the deposition of the Maastrichtian Yogou Formation in the Termit Basin in Niger, there was a prevailing hot-humid climatic environment (Lai et al. 2018). In Nigeria, Bolarinwa, Idakwo, and Bish (2019) identified warm and humid tropical climates during the Maastrichtian in the Benue Trough. In addition, subsurface data from the Maastrichtian Patti Formation in the adjacent Bida Basin (Nigeria) showed moist coastal swamp forests to marshland in a primarily warm, humid tropical environment (Ojo et al. 2020). Furthermore, Oretade, Adepehin, and Ola (2024) investigated subsurface data from the Gaibu-1 well, which penetrated the Upper Cretaceous Bima, Yolde, Gongila, Fika and Gombe formations in the Bornu Basin (i.e., the Nigerian sector of the Chad Basin). The authors revealed dominantly tropical to subtropical humid climates, corroborated by the findings of the present study.

5.2.2 | Palaeotemperatures

In recent times, trace element concentrations have been internationally used to reconstruct palaeotemperatures from the sedimentary rock record (He et al. 2022; Liu et al. 2022; Wang et al. 2022; Wu et al. 2022; Yang, Fu, et al. 2022; Johnson et al. 2024). In this study, the strontium concentration was used to determine the palaeotemperatures prevalent in the Anambra Basin during the formation of the Campano-Maastrichtian Nkporo and Mamu formations and the Palaeocene Imo Formation. The computed palaeotemperatures from subsurface data from the Owan-1 well range from 24°C to 31°C with an average of 30°C (Figure 4). In contrast, the Ubiaja well palaeotemperatures varied from 31°C to 32°C (with an average of 32°C) (Figures 5 and 9a; Liu et al. 2022). The empirical equation overlooks the influence of trace amounts of strontium in atmospheric moisture, resulting in a reduced Sr concentration and an elevated calculated palaeotemperature (Liu et al. 2022). Nevertheless, the study area exhibited warm tropical climatic conditions during this period. The Upper Cretaceous sequences show that warm and humid tropical climatic environments characterised the region, supported by other palaeoclimatic proxies employed in this study (Figures 4, 5 and 9a). These conclusions are consistent with relatively warm and humid tropical climates during the Upper Cretaceous period in West Africa (Hay 2017; Bolarinwa, Idakwo, and Bish 2019; Scotese et al. 2021; Johnson et al. 2024; Oretade, Adepehin, and Ola 2024). In addition, the Campano-Maastrichtian palaeoclimate of West Africa was generally characterised as warm and tropical (Chumakov et al. 1995; Pearson et al. 2024). Furthermore, Scotese et al. (2021) determined that tropical temperatures observed during the Cretaceous period ranged from 23°C to 32°C, which supports palaeotemperature data from this study (Figure 9b).

5.3 | Campano-Maastrichtian to Early Palaeocene Depositional Environment

5.3.1 | Palaeoredox Conditions

The preservation of sedimentary organic matter in mudrocks is intricately linked to the redox conditions of bottom water (Zhang, Liu, and Liu 2021; Yang et al. 2024). The presence of anoxic conditions is crucial for the preservation and concentration of organic matter, which significantly influences the formation of deposition models primarily driven by preservation processes (Zhao et al. 2016; Lai et al. 2018; Huang et al. 2020; Chukwuma et al. 2022; Ma et al. 2022; Yang et al. 2024). The assessment of redox conditions during deposition is essential in palaeoenvironmental studies. A key indicator used for this purpose is palaeoredox, which is classified according to the level of dissolved oxygen present in the bottom water. The classification scheme encompasses four distinct categories: oxic conditions, characterised by oxygen levels >2 (ppm); dysoxic conditions, characterised by oxygen levels between 0.2 and 2 (ppm); anoxic conditions, characterised by oxygen levels below 0.2 (ppm); and euxinic conditions, characterised by oxygen levels below 0.2 with the presence of hydrogen sulphide (Chukwuma et al. 2022). Recent advancements in sedimentary geochemistry studies have proven to be reliable approaches for classifying palaeoredox conditions.

The levels of authigenic uranium (Uau) concentration during deposition have been used to discern redox conditions (Bai et al. 2015; Costa et al. 2018; Liang et al. 2020; Zhou and McManus 2023). Uau values below 5 indicate an oxic depositional environment, while values above 5 suggest anoxic conditions (Wignall and Myers 1988; Bai et al. 2015; Zhou and McManus 2023). In the present study, most samples from the Upper Cretaceous to Palaeocene formations in the Owan-1 and Ubiaja wells recorded relatively low Uau concentrations (with averages of 1.60 and 1.39), indicating deposition in an oxic environment (Figures 5 and 10). Only one sample from the Owan-1 well (e.g., OW 30) displayed slightly anoxic conditions (Uau of 8.86).

Palynofacies data of the present study indicate deposition in an oxic environment (Figure 7), thus corroborating the geochemical interpretations. Furthermore, the observed salinity concentrations in this investigation support predominantly oxic redox conditions with occasional minor anoxic intervals. Marine environments typically demonstrate more reducing bottom water conditions due to their greater water depth. Conversely, continental, marginal marine and shallow-marine environments are characterised by high oxygen levels, aligning with the largely oxic depositional environment identified in the Cretaceous deposits of the Anambra Basin (see Figures 5 and 10).

In addition, the redox environmental conditions that prevailed during sediment deposition are revealed by the ash index content (Hao, Ge, and Xie 2000; Bai et al. 2015; He et al. 2022; Johnson et al. 2024). An ash content index range of 0.03–0.22 denotes poor reducing conditions, whereas a range of 0.23–1.23 denotes strongly reducing bottom water conditions (Bai et al. 2015; He et al. 2022; Johnson et al. 2024). In the mudrocks of the Mamu and Imo formations, the ash content index values range between 0.02 and 5.14, with an average of 0.67 for the Owan-1 well (Figure 10), reflecting a poorly to moderately reducing water environment during deposition and diagenesis (Bai et al. 2015; He et al. 2022) (see Figure 12a). In contrast, the Nkporo, Mamu and Imo formations in the Ubiaja well reveal ash content index values ranging from 0.01 to 0.16, with a mean of 0.05, indicating poorly reducing conditions during deposition (Figure 5). Finally, the presence of diagenetic pyrite in the Upper Cretaceous sequences and Palaeocene unit is likely indicative of bacterial sulphate reduction (Figure 8), suggesting suboxic conditions (Edegbai, Schwark, and Oboh-Ikuenobe 2020).

5.3.2 | Water Salinity

Water salinity provides information on palaeosedimentary environments by identifying different water types and reflecting the water depth during sedimentation (Yang et al. 2024).

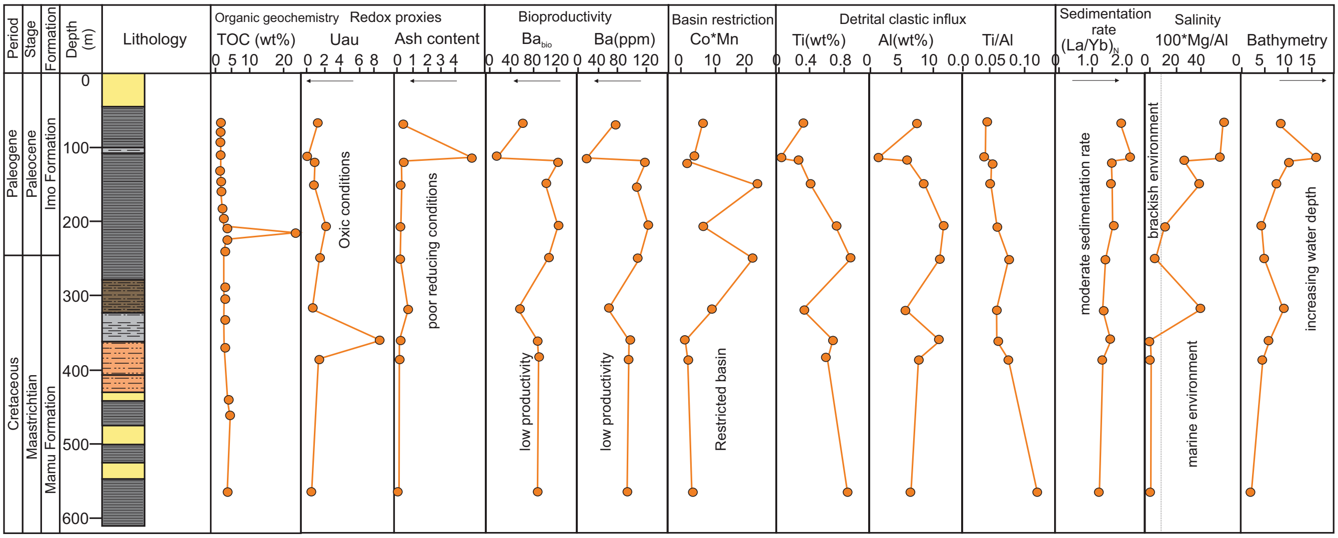

FIGURE 10 | Stratigraphy and geochemical data from the Owan-1 well. For legend, see Figure 5.

The variability in salinity impacts not only the evolution of biotic productivity but also influences redox conditions (Lv et al. 2021; Omietimi et al. 2022; Xu et al. 2022). Therefore, reconstructing the water salinity is important in understanding organic matter enrichment and preservation. In calm environments, when low-salinity water is injected into a basin, it has a tendency to separate into layers based on density. This stratification can create and intensify oxygen-depleted conditions in the lower part of the water, making it easier for organic matter to be preserved (Huang et al. 2023). Palaeosalinity conditions can be inferred by analysing elemental ratios of Mg and Al within sedimentary rocks. The Mg/Al ratios have been established as effective proxies for reconstructing variations in palaeosalinity levels within sedimentary formations (Lei, Que, and Hu 2002; Stanistreet et al. 2020; Zhang et al. 2020; Xu et al. 2021, 2022; Johnson et al. 2024). In this study, we used the equation $100 \times Mg/Al$ to detect the palaeosalinity conditions during the deposition of the Upper Cretaceous units on the western border of the Anambra Basin. Typically, low $100 \times Mg/Al$ ratios suggest lower saline levels during deposition, indicative of a freshwater palaeosedimentary environment devoid of marine influence, while ratios between 1 and 10 represent a brackish environment. Higher values (i.e., > 10) suggest marine conditions (Lei, Que, and Hu 2002; Xu et al. 2022; Zhang et al. 2020; Johnson et al. 2024).

The $100 \times Mg/Al$ values in the Owan-1 well, ranging from 1.21 to 56.38 (mean of 23.79; Figure 10), indicate that the deposition of the basal Mamu Formation occurred in a brackish to freshwater environment, whereas the upper Imo Formation was deposited in a marine environment (Figure 10). The Ubiaja well, in contrast, has significantly lower $100 \times Mg/Al$ concentrations ranging from 0.44 to 3.39 wt% (with a mean of 1.52 wt%; Figure 5), suggesting fluvial to marginal marine conditions.

The stratigraphic trend of $100 \times Mg/Al$ exhibits high values predominantly in the upper parts of the Imo Formation, while relatively low values are observed in the basal Nkporo and Mamu formations in the Owan-1 and Ubiaja wells (Figures 5 and 10). The low values recorded in the basal units may be related to increased rainfall in humid climates and terrigenous influx, which caused a pulsed decrease in the water salinity. Our palynofacies results support the detected salinity levels. High percentages of marine palynomorphs were recorded in the upper Imo Formation, with fewer terrestrial palynomorphs. In the basal Mamu Formation, we observed increased amounts of terrestrial palynomorphs, AOM and only a low number of marine palynomorphs, suggesting a marginal marine depositional environment in the Owan-1 well deposits (Figures 3 and 10). The geochemical salinity interpretation shows a similar vertical trend as the palynofacies data (Figures 3 and 10). We hypothesise that the Owan-1 well sediments were likely deposited in a proximal marginal marine environment, whereas the Ubiaja sediments were formed in a proximal shallow freshwater to marginal marine setting.

5.3.3 | Bioproductivity

Palaeoproductivity (i.e., bioproductivity) measures organic material generated by organisms and stored as energy during the energy cycle in sedimentary environments (Tribovillard et al. 2006; Harris et al. 2018; Chen et al. 2021; Xu et al. 2021; Yang, Fu, et al. 2022; Huang et al. 2023; Qiao et al. 2023; Zeng et al. 2024). The formation of organic source rocks is influenced by palaeoenvironmental factors, such as palaeoproductivity and conditions that affect the preservation of organic matter in the basin (Harris et al. 2018). The palaeoproductivity of the studied basin was reconstructed using the TOC, major and trace elements and palynofacies data.

The palaeoproductivity was quantified using the biological source Ba_{bio} from equation 5 (Dymond, Suess, and Lyle 1992; He et al. 2022; Yang, Liu, et al. 2022; Huang et al. 2023). The measured Ba_{bio} values range from 17.20 to 126.64 (Figure 10), with an average of 86.24 for the Owan-1 well. The samples from the Ubiaja well recorded Ba_{bio} values from 53.71 to 581.56, averaging 235.25 (Figure 5).

The Ba (ppm) concentration showed a consistent trend with the computed Ba_{bio} (Figures 5 and 10), suggesting that the Ba present in the mudrocks of the Upper Cretaceous Nkporo and Mamu formations and Palaeocene Imo Formation within the Ubiaja and Owan-1 wells in the Anambra Basin primarily originates from biological sources (Dymond, Suess, and Lyle 1992; Tribovillard et al. 2006; He et al. 2022; Yang, Liu, et al. 2022). Overall, the palaeoproductivity in the western part of the Anambra Basin was mainly low to moderate. The basal Nkporo Formation in the Ubiaja well showed moderate palaeoproductivity. In the Ubiaja well, the bioproductivity was relatively higher than in the Owan-1 sediments (Figures 5 and 10), likely due to more humid conditions that resulted in an enhanced fluvial detrital input and nutrient supply (Xu et al. 2018).

Furthermore, the variation of the TOC (Figures 4 and 5) and palynofacies data (Figure 4) supports low to moderate palaeoproductivity during the deposition of the studied formations.

5.3.4 | Water Retention and Hydrogeography

Water retention in hydrographically confined basins influences nutrient cycles in brackish and marine settings (Algeo and Lyons 2006; Tribovillard et al. 2006; Harris et al. 2018; Huang et al. 2023; Xiao et al. 2023). Continental margin upwelling results in the accumulation of sedimentary organic material and the formation of oxygen-depleted water bodies (Algeo and Lyons 2006; Harris et al. 2018; Huang et al. 2023). Variations in the levels of elements such as phosphorus (P), cadmium (Cd), cobalt (Co), molybdenum (Mo) and manganese (Mn) can be used to differentiate these hydrographic characteristics (Algeo and Lyons 2006; Harris et al. 2018; Huang et al. 2023; Xiao et al. 2023). Deep marine environments typically have lower concentrations of Mn and Co. Upwelling conveys bottom sea water into the basin, resulting in a lower Mn and Co ratio in sediments (Sweere et al. 2016; Huang et al. 2023). Therefore, $Co \times Mn$ is often used to differentiate various hydrographic characteristics and to determine the degree of water retention (Sweere et al. 2016; Harris et al. 2018; Jin et al. 2021; Huang et al. 2023; Xiao et al. 2023). In this study, we used the $Co \times Mn$ value to determine basin restriction and hydrogeography of the Upper Cretaceous to Palaeocene formations on the western border of the Anambra Basin. In general, $Co \times Mn > 0.4$ suggests confined basins, whereas $Co \times Mn < 0.4$ represents continental margin upwelling (Sweere et al. 2016; Jin et al. 2021; Huang et al. 2023).

The $Co \times Mn$ values in the Nkporo, Mamu and Imo formations were considerably higher than 0.4 in the Owan-1 and Ubiaja wells. This indicates sedimentation occurred in a restricted environment during the Cretaceous period (Jin et al. 2021) (refer to Figures 10 and 11). The $Co \times Mn$ versus Al cross-plot in Figure 12b (Sweere et al. 2016; Huang et al. 2023) shows that all data points fall inside the restricted region, suggesting that hydrographically restricted environments were the prevailing conditions on the western margin of the Anambra Basin. Furthermore, palynofacies data of the present study show a significant abundance of terrestrial palynomorphs and phytoclasts, indicating that deposition occurred in a shallow marine or marginal marine environment with minor interaction with materials from the open ocean (Figures 3, 10, 11 and 12b).

5.3.5 | Clastic Influx and Sedimentation Rate

The detrital clastic input and sedimentation rate exert dual effects on accumulating and preserving organic matter in sedimentary rocks (Zhang, Liu, and Liu 2021; Chukwuma et al. 2022; Zeng et al. 2024). The influx of terrestrial material introduces increased plant debris and nutrients into the basin. However, it also diminishes the biological supply and absorbs organic materials during the deposition of sediments (Chukwuma et al. 2022; Zeng et al. 2024). Consequently, it is an important factor that controls organic matter accumulation and preservation. This study uses aluminium (Al) and titanium (Ti) concentrations to assess variations in the clastic input during sedimentation of the Nkporo, Mamu and Imo formations in the Upper Cretaceous. Al is common in fine-grained rocks with high amounts of silicate minerals and primarily originates from clastic material that enters the basin. On the other hand, titanium is found inside heavy mineral phases like rutile and ilmenite (Tribovillard et al. 2006; Chen et al. 2023). Because Al and Ti remain inert in geochemical conditions during sedimentation and diagenesis, they offer reliable proxies for evaluating clastic influx (Tribovillard et al. 2006; Ross and Bustin 2009; Chukwuma et al. 2022; Xu et al. 2022; Chen et al. 2023; Zeng et al. 2024). The Al_2O_3 concentrations show significant covariance with TiO_2 values ($R^2 = 0.77$, Figure 12c), suggesting that Ti was primarily sourced from terrestrial material through fluvial transport (Ross and Bustin 2009; Chukwuma et al. 2022; Zeng et al. 2024). The Ti and Al concentrations show similar stratigraphic trends in the Owan-1 and Ubiaja wells (Figures 10 and 11). We observed that the Ti/Al ratios and SiO_2 concentrations in the Ubiaja well are similar and tend to be slightly elevated compared with those in the Owan-1 well (see Figures 10 and 11 and Section 4.4). This suggests a modest increase in the contribution of terrigenous clastic material during the deposition of the Nkporo, Mamu and Imo formations in the Ubiaja well. We hypothesise that the enhanced terrestrial influx documented in the Ubiaja well may likely be linked to high precipitation and strong chemical weathering conditions, favouring a high terrestrial clastic influx. Conversely, intermediate chemical weathering conditions possibly controlled the lower terrestrial clastic influx recorded in the Owan-1 well. Furthermore, the Si/Al, Ti/Al and Zr/Al ratios were used to differentiate between detrital fluxes from fluvial and aeolian transport (Calvert and Pedersen 2007; Reolid et al. 2012; Nie, Fu, Wei, et al. 2023). The proxies suggest a predominant contribution from fluvial sources (Data S1). Additionally, palynofacies data and other geochemical proxies support palaeoenvironments ranging from fluvial to marginal marine and shallow marine.

Rare earth elements (REE) can provide insights into the sedimentation rate of terrestrial materials. An increased rate of sediment deposition can accelerate the burial of organic materials, protecting them from oxic conditions and enhancing their preservation. Nevertheless, it may also result in dilution, which is disruptive to preservation (Wang et al. 2021; Chukwuma et al. 2022; Yang, Liu, et al. 2022). Hence, understanding sedimentation rates in specific areas requires detailed analysis. The fractionation of REE primarily indicates the duration sediments are retained in the water column (Wang et al. 2021). A slow sedimentation rate leads to substantial differentiation between heavy rare earth elements (HREEs) and light rare earth elements (LREEs), indicating prolonged retention (Wang et al. 2021). In

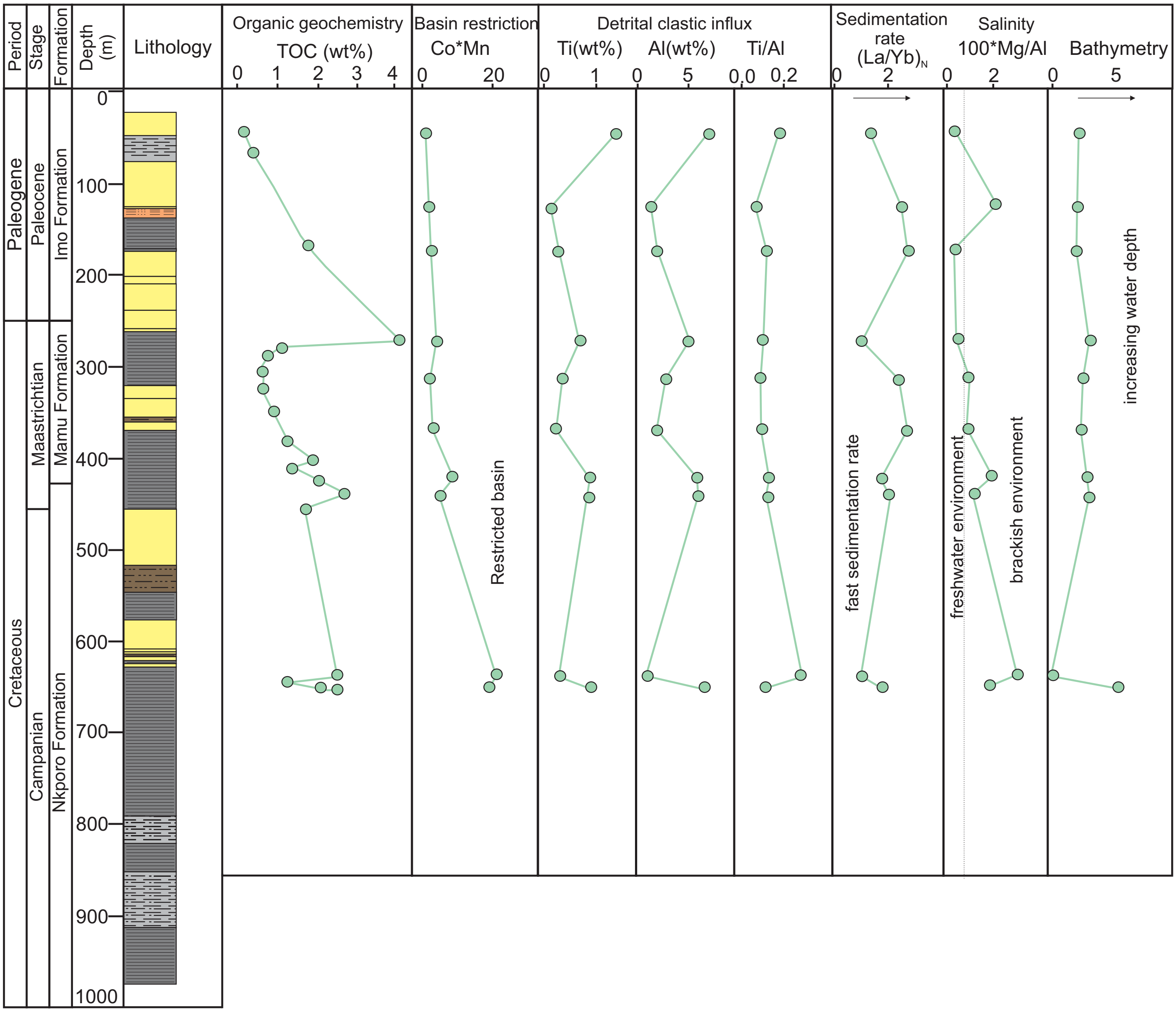

FIGURE 11 | Stratigraphy and geochemical data from the Ubiaja well. For legend, see Figure 5.

contrast, when sedimentation occurs rapidly and sediments do not stay in the water column for long, there is a weak separation between HREEs and LREEs, indicating short retention (Wang et al. 2021). A $(La/Yb)_N$ ratio normalised to UCC is commonly used to detect the sedimentation rate in sedimentary rocks (Tenger et al. 2006; Wang et al. 2021; Chukwuma et al. 2022; Yang, Liu, et al. 2022; Miao et al. 2023; Xiao et al. 2023). A $(La/Yb)_N$ ratio close to 1 implies a high rate of sediment deposition (i.e., weak REE separation). In contrast, a ratio away from 1 suggests a slow rate of sediment deposition (Tenger et al. 2006; Wang et al. 2021). The computed $(La/Yb)_N$ ratios obtained for sediments of the Owan-1 well vary from 1.20 to 1.78, indicating a relatively consistent sedimentation rate or depositional environment, with an average of 1.56 (Figure 10). In contrast, the samples of the Ubiaja well exhibit a broader range of $(La/Yb)_N$ ratios, from 1.02 to 2.73 and a higher average of 1.94 (Figure 11). This variability suggests fluctuations in sedimentation rates or varying depositional conditions, most likely reflecting different environments or processes recorded in the sediments of the Ubiaja well compared with those recorded by the Owan-1 well. The sedimentation rate in the basin part documented by the Owan-1 well can be interpreted as moderate, suggesting relatively stable sedimentation conditions over time. The higher average ratio of 1.94 recorded in the sediments of the Ubiaja well indicates potentially faster sedimentation rates or more dynamic depositional conditions compared to the area documented by the Owan-1 well (Figure 12d) (Wang et al. 2021).

5.4 | Palaeobathymetry

Palaeobathymetry refers to the study of ancient water depths in oceans, seas or lakes based on geological and geochemical indicators found in sedimentary formations, providing valuable insights into palaeoenvironmental conditions, ocean circulation patterns and tectonics (Herkat and Ladjal 2013; Merenkova et al. 2020; Fu 2023; Miao et al. 2023; Yang et al. 2024). The distribution and composition of siliciclastic rocks are influenced by palaeobathymetry (Liang et al. 2020; Yang, Fu, et al. 2022; Yang et al. 2024). Commonly, when the water depth transitions

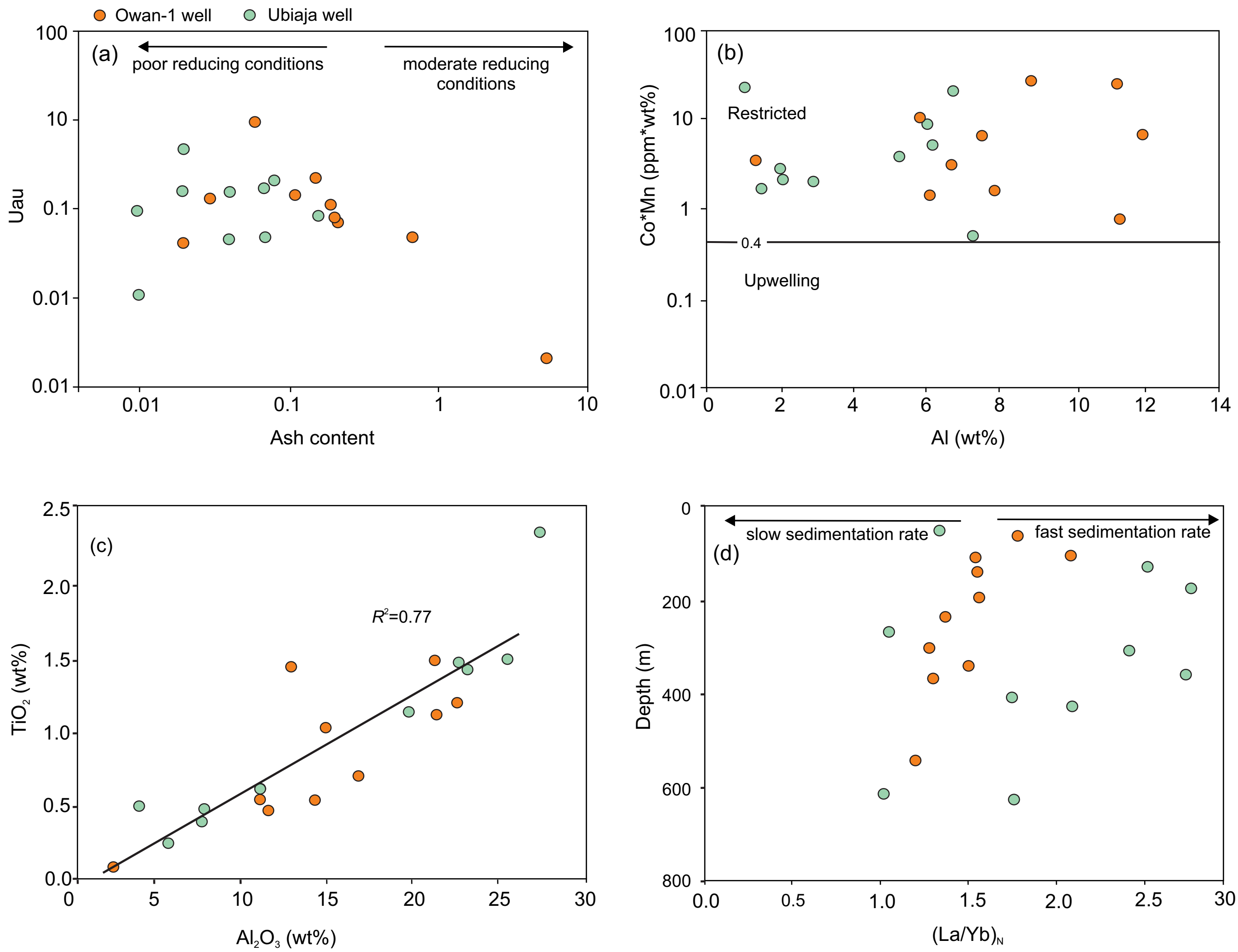

FIGURE 12 | Cross graphs related to redox conditions, basin restriction and hydrogeography, detrital supply and sedimentation rate. (a) Ash content (ppm) versus Uau (ppm); (b) Co × Mn (ppm × wt%) versus Al (wt%); (c) Al_2O_3 (wt%) versus TiO_2 (wt%); (d) $(La/Yb)_N$ versus Depth (m).

from shallow to deep, the proportion of sand in the sediment will progressively reduce while the contents of fine-grained clastics (i.e., clay) will correspondingly increase (Yang et al. 2024). Palynomorphs, sedimentary structures and geochemical data can serve as reliable markers of ancient water depth and hydroenergy circulation. The Owan-1 and Ubiaja wells samples exhibit grey to dark grey carbonaceous mudrocks with wavy parallel laminations and thin sandstone lenses. They contain high quartz and clay mineral contents and plant and trace fossils in specific intervals, indicating deposition across varying water depths. Additionally, the presence of marine indicators such as dinoflagellate cysts, forams and acritarchs in the basal Mamu and upper Imo formations suggests seawater incursions (Figures 4 and 6), with the maximum flooding surface recorded in OW 30. In addition, we observed freshwater indicators such as *Botryococcus*, fungal remains and continental phytoclasts implying varying palaeobathymetry (Figures 4 and 6). This aligns with the fluctuations in sea level during the Upper Cretaceous to Palaeogene periods (Edegbai, Schwark, and Oboh-Ikuenobe 2019) (Figure 2).

Sedimentary geochemistry provides a reliable means to infer palaeobathymetry. Prior studies indicate significant variations in certain major and trace elements with distance from the shore, providing insights into changes in water depth during sedimentation (Merenkova et al. 2020). The Zr/Al and Rb/K proxies are commonly used to detect water depth and infer palaeobathymetry in sedimentary basins (Herkat and Ladjal 2013; Zheng et al. 2015; Müller et al. 2018; Zhang, Xuanjun, et al. 2018; Merenkova et al. 2020; Fu 2023; Miao et al. 2023).

Zirconium (Zr) is a common trace element in terrestrial environments, and its concentration decreases as the distance from the land increases. Nevertheless, the presence of Zr in clastic rocks is primarily influenced by Al (Chen, Huang, and Heng 2018; Müller et al. 2018; Miao et al. 2023). Therefore, the Zr/Al ratio reflects terrigenous input over small spatial scales and palaeobathymetric shifts (Chen, Huang, and Heng 2018; Miao et al. 2023). Lower Zr/Al values correspond to increased distances from the shore and deeper depths. The concentration of rubidium (Rb) and potassium (K) in water is directly related to the amount of clay present, with clay having a greater affinity for Rb than K. The Rb/K ratio is a reliable indicator of palaeobathymetric variations, with elevated values corresponding to greater water depths. Consequently, Equation (6) provided a palaeobathymetry curve of the Cretaceous Nkporo and Mamu formations and the Palaeocene Imo Formation during sedimentation and diagenesis, with higher values indicating deeper water bodies. The computed palaeobathymetric values of the sediments of the Owan-1 well range from 2.13 to 16.73, with an average of 7.62 (Figure 10). The Ubiaja well samples showed lower values, ranging from 0.43 to 5.52, with an average of 2.87 (Figure 11). Our geochemical indicators revealed greater water depths in the Owan-1 well and relatively lower water depths in the Ubiaja well. According to our palaeobathymetric ratios, transgression occurred in the basal Mamu units during the Maastrichtian, followed by regression. During the sedimentation of the upper Imo Formation, the basin experienced a transgression in the Palaeocene. The water mass gradually increased in depth and deposited the Imo Formation with a regression toward the end of the Palaeocene. We observed that the intervals with higher salinity correspond to greater depths (Figures 10 and 11). Consequently, this supports the conclusion that the Owan-1 well deposits formed in a proximal coastal marine environment. Furthermore, the geochemical interpretations are consistent with the palynofacies interpretation.

5.5 | Organic Matter Enrichment Model

As outlined in Section 4.3, the TOC content of mudrocks ranges from 0.2 to 21 wt% (mean 1.6 wt%) in samples from the Owan-1 well and from 0.1 to 4 wt% (mean 1.4 wt%) in samples from the Ubiaja well. However, the key factors controlling the accumulation, enrichment and preservation of organic matter in the basin remain unclear. Based on trace and major element geochemistry, organic petrography data (i.e., macerals and palynofacies) and organic geochemical (i.e., TOC) investigations of subsurface data from the Owan-1 and Ubiaja wells, we reconstructed the palaeoclimate, basin restriction, sedimentation rate, sea-level fluctuations and bioproductivity of the Upper Cretaceous to Palaeocene formations in the Anambra Basin. Analysing the interplay between various factors such as palaeoclimate, palaeosalinity, redox conditions, organic matter source, bioproductivity and terrigenous clastic input, along with TOC values, presents a direct method for assessing the predominant factors influencing organic matter enrichment.

In this study, the covariance values suggest that climate has a relatively stronger influence on TOC enrichment compared with redox conditions, sedimentation rate and basin restriction (Figure 13). Climate variations, water salinity levels and biological productivity play significant roles in organic matter enrichment. These factors likely contribute to the availability and preservation of organic material in a specific sedimentary environment. The palaeoclimate is an important parameter that affects the accumulation of organic matter and the formation of carbonaceous source rocks (Harris et al. 2018; Lv et al. 2021; Wang et al. 2021; Zhang, Liu, and Liu 2021; Chen et al. 2023; Yang et al. 2024; Zeng et al. 2024). It influences the chemical alteration of source rocks and affects detrital influx, bioproductivity and salinity (Harris et al. 2018; Xu et al. 2022; Chen et al. 2023; Yang et al. 2024; Zeng et al. 2024). These factors subsequently control organic matter production, accumulation and dilution. The investigation revealed a direct relationship (i.e., moderate to strong covariance) between climate indicators and TOC values (Figure 13a), suggesting that warm and humid tropical climates favour organic matter enrichment and accumulation. The bioproductivity proxies (Ba_{bio} and Ba) used in the present study showed that the primary productivity in the Ubiaja well was low to moderate, with high TOC values. In contrast, the Owan-1 well showed low primary productivity with lower TOC contents. Higher bioproductivity can lead to increased organic matter production and subsequent deposition. Therefore, the primary productivity probably enhanced the higher TOC values in the Cretaceous formations intersected by the Ubiaja well. We observed a low covariance between TOC and bioproductivity proxies Ba_{bio} ($R^2 = 0.18$) and B (ppm) ($R^2 = 0.17$) for the sedimentary formations (Figure 13b,c). A moderate to low negative correlation was observed between $100 \times Mg/Al$ and TOC ($R^2 = 0.20$; Figure 13d), indicating that the presence of stable brackish to marine conditions was possibly beneficial for organic matter accumulation. Similarly, we noted a moderate negative covariance for Rb/K versus TOC ($R^2 = 0.23$), suggesting that palaeowater depth and palaeobathymetry were probably beneficial for organic matter accumulation (Figure 13e). Additionally, detrital supply exhibited a low positive relationship with TOC (Figure 13f).

Conversely, a weak negative correlation was found between $CO \times Mn$ and TOC ($R^2 = 0.0009$; Figure 14a), ash content versus TOC ($R^2 = 0.04$; Figure 14c), authigenic uranium versus TOC ($R^2 = 0.02$; Figure 14d) and $(La/Yb)_N$ versus TOC ($R^2 = 0.02$; Figure 14b), suggesting that basin restriction, dominantly oxic bottom water conditions and moderate to slow sedimentation rates had little effect on organic matter (OM) accumulation. Overall, the results suggest climate as the main environmental factor contributing to organic matter enrichment in the Upper Cretaceous sequences (Figure 15).

5.6 | Implications on Cretaceous West and Central African Rift Intervals

The Cretaceous period witnessed high temperatures, humid tropical conditions, the breakup of Gondwana and the widespread formation of organic-rich mudrocks and development of the Tethys Sea and the South Atlantic Ocean (Nwajide 1990; Morakinyo, Mohamed, and Bowden 2021; Omietimi 2022; Dou et al. 2024). Passive margin rift basins emerged on the African continent and other parts of the world, featuring sedimentary sequences comprising various clastic sediments deposited across fluvial, deltaic and marine environments. Advances in sedimentary archive interpretation, geochemistry and palynology have enriched our understanding of these sequences and their formative processes.

The Cretaceous transitional and marine mudrocks are largely recognised as the primary source rocks in the West African rift basins (WARS) (Lai et al. 2018). Nevertheless, there is a lack of geochemical investigations and regional correlation. In this study, we compared geochemical and palynological interpretations with similar Cretaceous basins sharing a common tectonic history, aiming to detect the main drivers controlling organic matter accumulation and preservation in the Cretaceous. The Anambra Basin, formed in a passive rift setting, often exhibits sedimentary and tectonic characteristics akin to the Termit Basin in Niger, the Chad Basin in Chad, the Muglad Basin in Sudan and the Benue Trough in Nigeria. The late Cenomanian

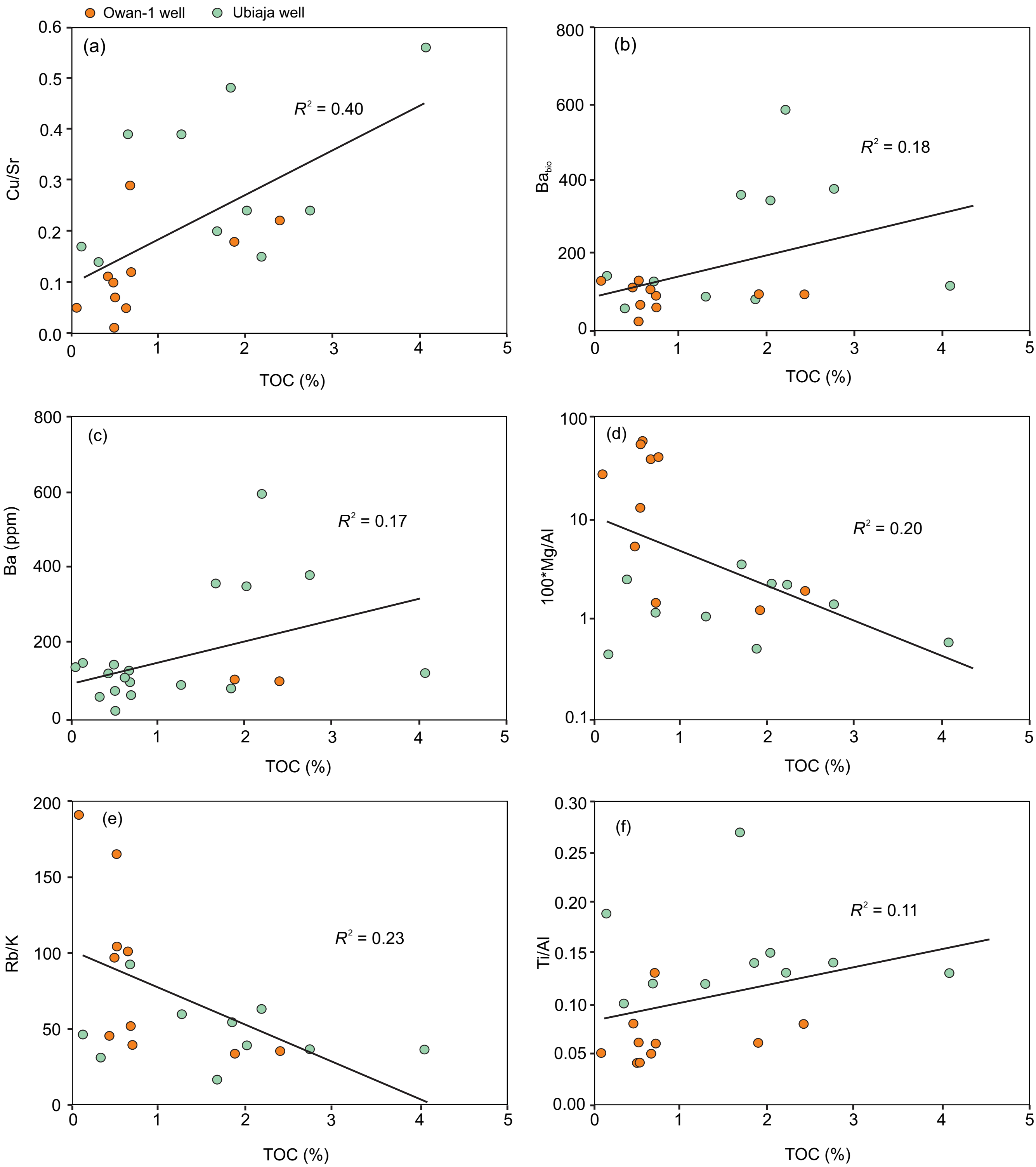

FIGURE 13 | Covariance graphs between TOC contents and various geochemical indicators. (a) Cu/Sr versus TOC; (b) Ba_{bio} versus TOC; (c) Ba versus TOC; (d) 100 × Mg/Al versus TOC; (e) Rb/K versus TOC; (f) Ti/Al versus TOC.

to early Turonian Cretaceous Trans-Saharan seaway connected the Tethys in the north through Chad, Niger and Nigeria to the South Atlantic Ocean, undergoing a re-establishment during the late Campanian to early Maastrichtian periods (Nwajide 1990; Edegbai, Schwark, and Oboh-Ikuenobe 2019; Usman et al. 2021). This development led to the regional deposition of marine sedimentary facies in Nigeria, Niger, Sudan and Chad. As a result, this study identified a sedimentary history, palaeoclimatic conditions, hydrodynamics, basin restriction and palaeotectonics similar to those of the Benue Trough and the Termit and Muglad basins.

In the Termit Basin, during the deposition of the Campano-Maastrichtian Yoguo Formation, a prevailing hot, humid and tropical climate was observed. Geochemical investigations of subsurface cores from the Yoguo Formation by Lai et al. (2018)

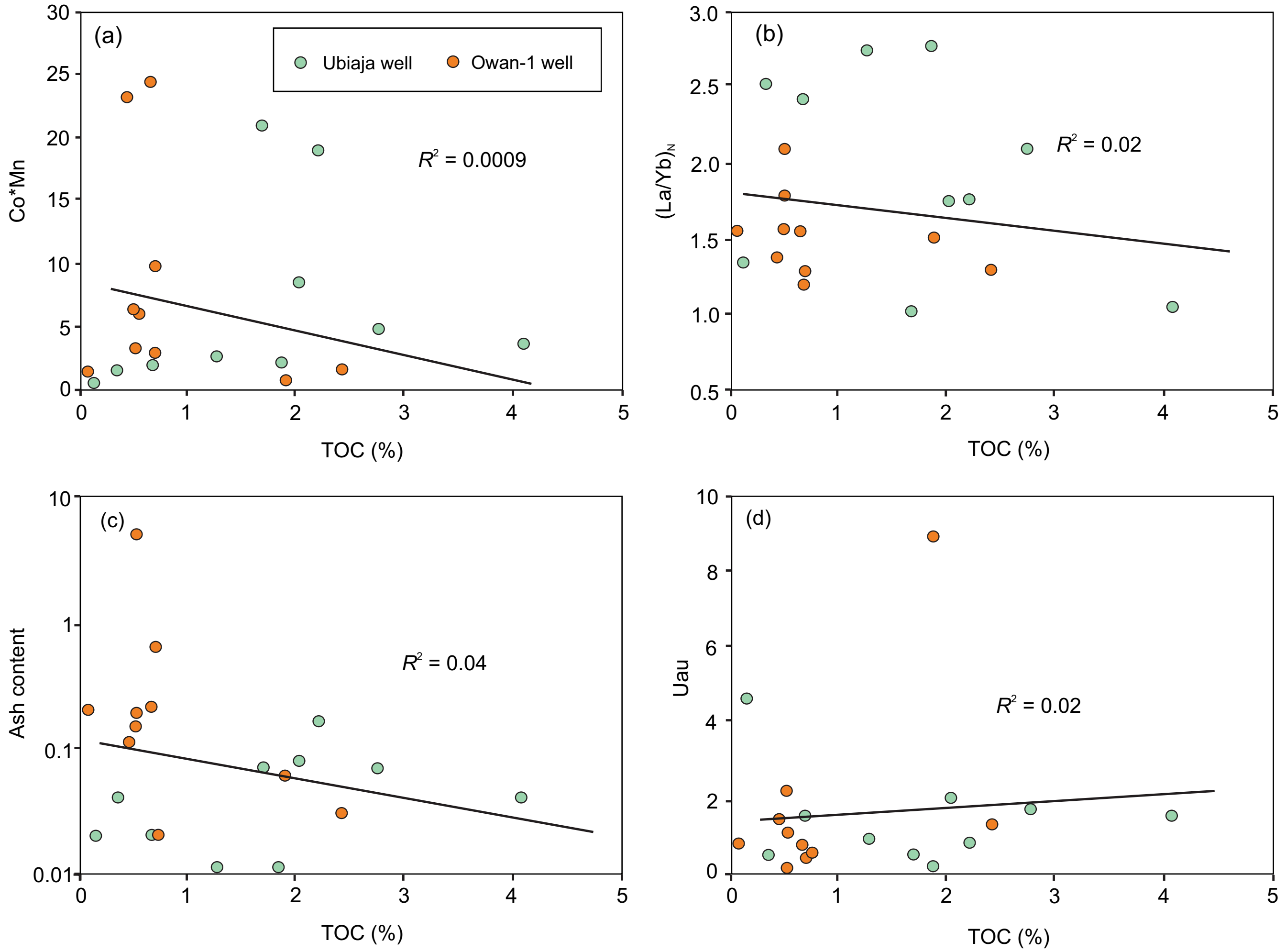

FIGURE 14 | Covariance graphs between TOC contents and various geochemical indicators. (a) Co × Mn versus TOC; (b) $(La/Yb)_N$ versus TOC; (c) Ash content versus TOC; (d) Uau versus TOC.

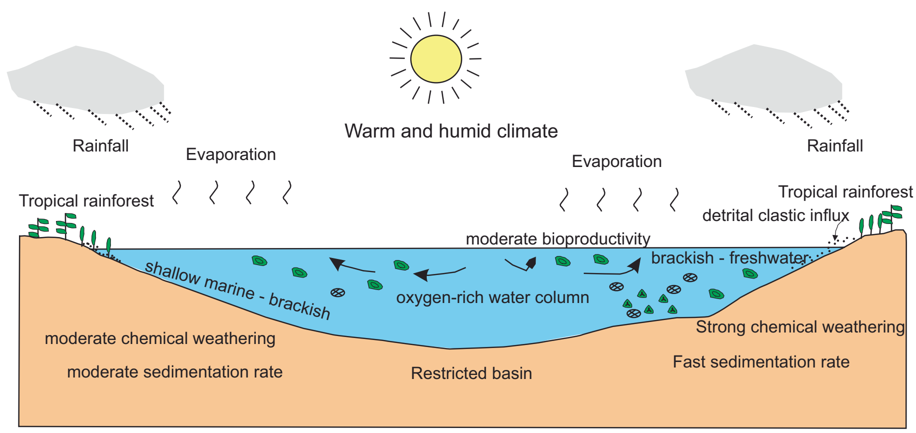

FIGURE 15 | Conceptual organic matter accumulation model of the Upper Cretaceous to Palaeocene formations in the western margin of the Anambra Basin.

revealed elevated ω(MgO)/ω(CaO) values and a high chemical index of alteration values (CIA). Deposition mainly occurred in a shallow-marine environment, with minor to intermediate contributions from freshwater and brackish environments. TOC values of this formation range from 1.04 to 8.51 wt%, suggesting a favourable preservation potential for sedimentary organic matter (Lai et al. 2018). The organic matter accumulation shows that the primary factors influencing the origins, depositional conditions and preservation of organic matter in the Termit Basin were changes in global sea level, patterns of seawater circulation and humid climatic conditions. In the Muglad Basin, the TOC values range from 1 to 7.2 wt%

(Makeen et al. 2015). Geochemical and palynofacies analyses indicate deposition in a lacustrine environment with marine incursions under suboxic conditions and warm, humid climates with ephemeral arid pulses (Makeen et al. 2015). Predominantly humid climatic conditions and enhanced bioproductivity are suggested to be the primary controlling factors of organic matter enrichment and preservation (Makeen et al. 2015). Furthermore, low oxygen levels (i.e., suboxic to anoxic conditions) and fine-grained particles influenced organic matter accumulation. The presence of clay particles at the top most likely protected organic matter, leading to sediments rich in organic material (Kennedy, Pevear, and Hill 2002; Ross and Bustin 2009; Makeen et al. 2015).

In the Nigerian Benue Trough, analysed inorganic and organic geochemical data revealed pristane/phytane (Pr/Ph) ratios ranging from 1.0 to 1.9, suggesting deposition under sub-oxic to relatively anoxic conditions in a humid climatic environment (Yandoka et al. 2015, 2021). Deposition occurred in a low-salinity environment, and the accumulation and enrichment of organic matter in the Northern Benue Trough were mainly influenced by the climate, salinity, suboxic to anoxic conditions, a stratified water column and fine-grained particles (Yandoka et al. 2015).

In conclusion, the primary factors that led to the buildup and preservation of organic matter in the WCARS basins throughout the Cretaceous period were primarily warm and humid climate conditions, fluctuations in sea levels, high biological productivity and fine-grained particles.

6 | Conclusions

In this study, a multi-proxy approach involving organic petrography, palynofacies, major element oxides, trace elements and REEs was applied to the western margin of the Nigerian Anambra and Niger Delta basins to characterise its subsurface deposits. In addition, it is the first detailed study on the factors controlling organic matter deposition in the Campanian to Palaeocene Nkporo, Mamu and Imo formations from the Owan-1 and Ubiaja wells. The organic matter richness varies within the analysed samples from fair to good in all three studied formations. These values compare favourably to those of other Cretaceous WCARS basins with similar depositional conditions. The palaeotemperature values, Cu/Sr ratios, Ga/Rb versus K_2O/Al_2O_3, ICV versus CIA and $CaO/(MgO \times Al_2O_3)$ suggest that the palaeoclimate in the study area was warm and humid during the Late Cretaceous period. The palynofacies of the upper Imo Formation document the early highstand phase. Higher percentages of dinoflagellate cysts and the dominance of equidimensional, opaque phytoclasts represent the maximum flooding phase, accompanied by warmer conditions. Additionally, the high abundance of terrestrial phytoclasts, *Deltoidospora* spp., *Classopollis* spp. and geochemical proxies collectively indicates warm tropical climatic conditions, consistent with geochemical interpretations.

Through the investigation of geochemical data, we outlined and defined the curves representing palaeosalinity and palaeobathymetry within the Upper Cretaceous to Palaeocene sequences in the southwestern part of the Anambra Basin.

Author Contributions

Erepamo J. Omietimi: conceptualization, investigation, data curation, writing – original draft. **Nils Lenhardt:** conceptualization, funding acquisition, project administration, supervision, writing – review and editing. **Renchao Yang:** funding acquisition, supervision, writing – review and editing. **Annette E. Götz:** palynologicalanalysis, methodology, writing – review and editing. **Aitalokhai J. Edegbai:** writing – review and editing. **Adam J. Bumby:** supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.