



# High-resolution sequence stratigraphy of the Maastrichtian-Paleocene succession in the Sokoto Basin

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## Abstract

An outcrop sequence stratigraphic interpretation of the Maastrichtian-Paleocene succession in the southwestern part of the Iullemeden Basin (here referred to as Sokoto Basin, northwestern Nigeria) is carried out. The methods involved analysis and interpretation of the successions regarding their stratal stacking patterns, transgression and regression trends, and identification of critical surfaces that characterize sequences and sequence boundaries. The results obtained are as follows: All the formations in the basin are made up of four sequences marked by unconformities which occur at the tops of the pre-Maastrichtian Illo/Gundumi formations, the Dukamaje Formation, the Gamba Formation, and the Gwandu Formation. The maximum flooding surfaces occur within the Dukamaje and Dange formations, which match the 73.5 Ma and 68.7 Ma peaks of eustatic change at sea level, respectively. The reworking surface corresponds with the transgressive surface occurring at the base of the Dange Formation, and condensed horizons or hard grounds towards the top. The Maastrichtian lower Taloka Formation belongs to a transgressive systems tract displaying a retrogradational parasequence stacking pattern; the middle and upper parts are high-stand systems tracts displaying an aggradational to progradational stacking pattern. The Dukamaje Formation belongs to a transgressive system tract displaying a retrogradational parasequence stacking pattern and a maximum flooding surface. The Wurno Formation belongs to a high-stand system tract displaying a progradational parasequence stacking pattern. The Dange Formation belongs to a transgressive systems tract displaying an aggradational parasequence stacking pattern with condensed horizons towards the top marked by glauconitic/phosphate/hardgrounds and shales displaying a retrogradational stacking pattern. The Kalambaina Formation belongs to the high-stand systems tract displaying retrogradational to progradational parasequence stacking pattern. The Gamba Formation has been largely removed by prolonged erosion and unconformity, marking the upper sequence boundary. The Gwandu Formation is a low-stand system tract marked by incision and channel-filling geometries displaying an aggradational to progradational parasequence stacking pattern.

**Keywords** Sokoto Basin · Maastrichtian · Paleocene · Sequence · Systems tract · Parasequences

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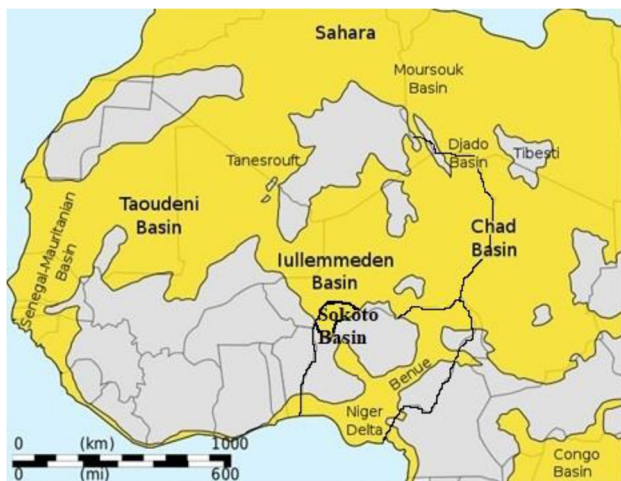
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## Introduction

The southwestern sector of the Iullemeden Basin in Nigeria is also known as the “Sokoto Basin.” The Iullemeden Basin is an intracratonic interior sag basin that covers an area of approximately 800,000 km<sup>2</sup>, encompassing parts of Algeria, Mali, Niger, and the Benin Republic, as well as northwestern Nigeria. The basin is bounded to the west by basement outcrops of the Adrar des Iforas and Leo uplifts. To the north, it is bounded by basement outcrops of the Ahaggar or Hoggar Massif, which form part of the central Saharan Massif; to the south, by crystalline and metamorphic rocks of northern Nigeria and the Upper Volta Arch; and to the east, by the Chad Basin (Fig. 1). Oil exploration activities started in Nigerian sedimentary basins, in the early part of the nineteenth century when the whole acreages in Nigeria were concessioned to the then Shell D’arcy and the Sokoto sector of the Iullemeden Basin was part of this. As with all exploration activities, initial efforts in the Sokoto sector included the reconnaissance geophysical survey which showed the poor thickness of the sedimentary cover in this sector of the Iullemeden Basin. Efforts to have a second look at the Sokoto sector were rekindled in the 1990s during the Deep Offshore Niger Delta bid round which was tied to exploration in the inland basins.



**Fig. 1** Generalized map of West African basins with the Iullemeden Basin (Sokoto Basin) terminating southwest into Nigeria (after Obaje et al. 2020)

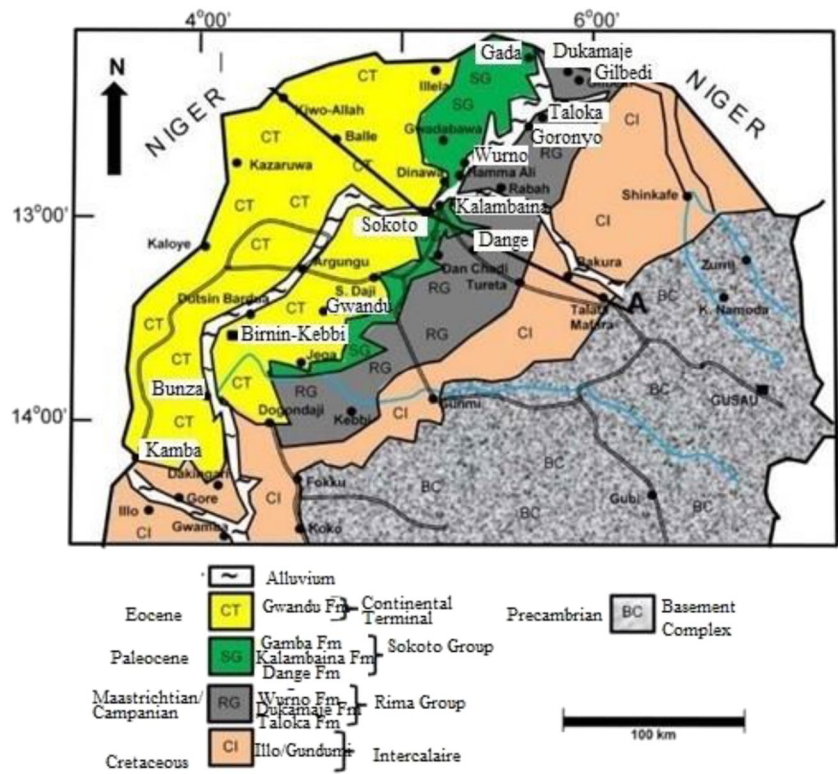
These companies finally moved out of the Sokoto sector to the Niger Delta which is a very well-known and prolific oil province. Following the exit of the major oil companies and their initial activities, the academic community took over essentially with fieldwork, preliminary geochemical studies, and integrating petroleum systems studies. Recent work that concerns fieldwork and preliminary geochemical studies was done by (Obaje et al. 2020) and work on the sequence stratigraphy of the Gada Stream section by (Yunusa 2021); however, he was able to interpret two parasequences and a condensed section for the first time related to sequence stratigraphy in the Sokoto Basin. The previous studies in the basin are on geological mapping, stratigraphy, biostratigraphy, some aspects of petroleum potential, and sedimentary thickness of the basin by (Falconer 1911; Obaje 2009; Kogbe 1981; Kogbe 1979; Obaje et al. 2013). The stratigraphy of the basin was presented by (Kogbe 1981; Kogbe 1979) that the Maastrichtian to Paleocene succession is overlain unconformably by the pre-Maastrichtian continental Intercalaire. It is made up of the Rima Group, consisting of mudstones and friable sandstones (Taloka and Wurno formations), separated unconformably by the fossiliferous, calcareous, and shaley Dukamaje Formation. The Paleocene Sokoto Group consists of the Dange and Gamba formations (mainly shales) separated by the calcareous Kalambaina Formation. The Gwandu Formation (Eocene Continental Terminal) unconformably overlies the Shaley Gamba Formation (Fig. 2).

The previous studies have not taken into consideration the importance of sequence stratigraphy in hydrocarbon exploration. The Maastrichtian to post-Paleocene succession of the Sokoto Basin has received little attention in terms of sequence stratigraphy; the present article concerns the sequence stratigraphic interpretation of the succession in the Sokoto Basin, to objectively unveil the various systems tracts so that knowledge of elements of petroleum systems such as the potential reservoir rocks, effective seals, and the age of formations they occur will be appraised.

## Methodology

At the preliminary stage, interpretation of high-resolution satellite imagery was conducted aided by Global Mapper software, which was imported into Avenza

**Fig. 2** Generalized geological map of Sokoto Basin; the highlighted are outcrop areas and type localities (after Obaje et al. 2013)



Mapper and used during the fieldwork. Detailed field mapping was conducted, involving descriptions of exposed sections mainly along river channels and road cuts, outcrop sample collection, photography of relevant features, and coordinates obtained using the Global Positioning System (GPS). The successions that make type sections or reference sections were analyzed and interpreted based on their stratal stacking patterns, depositional architectures, transgression and regression trends, and identification of critical surfaces that characterize sequences and sequence boundaries. Sequence stratigraphic logs were produced using sedlog software and annotated using Corel Photo-Paint and finally GIMP 2.10.34 software was used to enhance the pictures and logs to higher resolutions.

## Results/discussion

### Sequence stratigraphic interpretation

An outcrop sequence stratigraphic interpretation of selected sections was compiled based on the vertical relationship of strata, analysis of sedimentological features

within units or lithofacies, and identification of critical surfaces. Stratigraphic data were synthesized into composite sequence stratigraphic sections. Parasequences, surfaces, and units were defined by the stratigraphic arrangement. Parasequence stacking patterns were used to define system tracts and sequences according to the methods of (Mitchum Jr. 1977; Van Wagoner et al. 1988; Vail et al. 1977; Hunt and Tucker 1992; Posamentier and Allen 1999; Embry 2001; Shanley and McCabe 1993; Catuneanu 2003; Galloway 2001). Large-scale geometrical relationships such as onlap and downlap were not identifiable in this study.

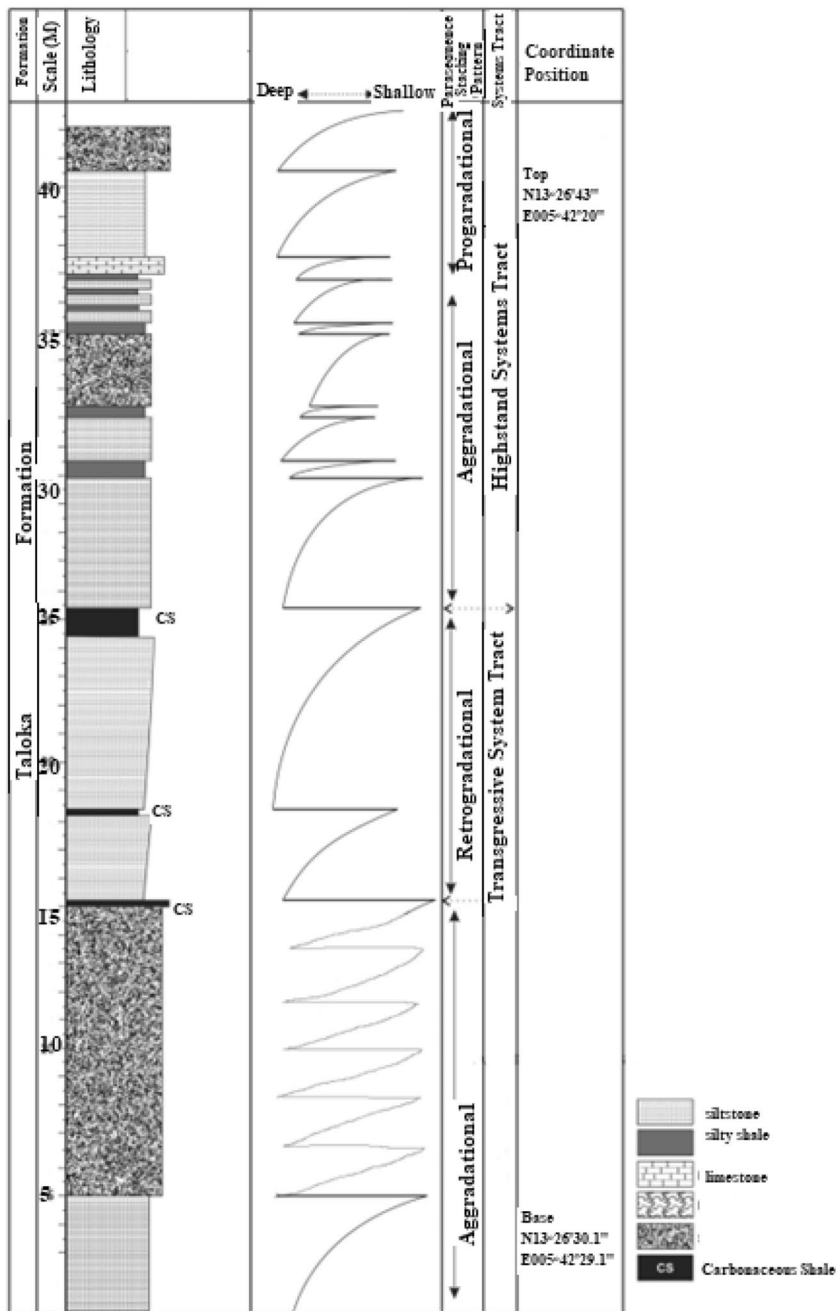
### Sequence

This study has identified four sequences that occur in the late Cretaceous to post-Paleocene succession of the southwestern part of the Iullemeden Basin. Based on (Obaje et al. 2020; Kogbe 1979), at its type section, the Maastrichtian Taloka Formation unconformably overlies the Early Cretaceous to Late Jurassic Gundumi Formation; this represents the lower sequence boundary of the first sequence. The top of the Upper Campanian Dukamaje Formation is an unconformity that marks the upper

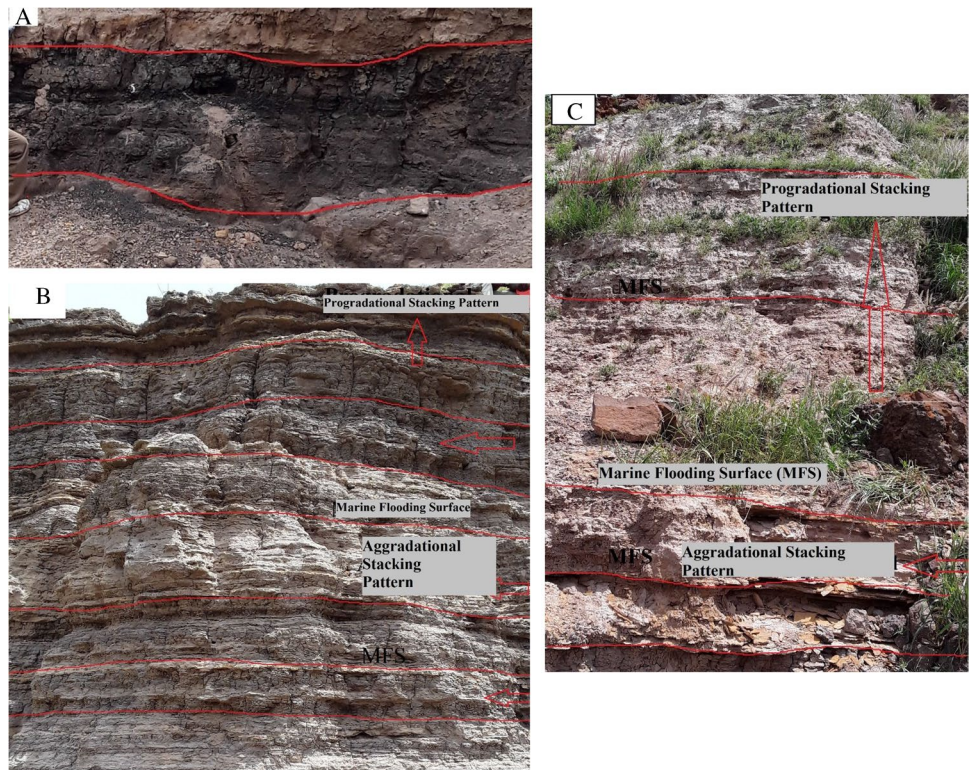
sequence boundary; the top of the Paleocene Gamba Formation is an unconformity that represents the third sequence boundary; and the top of the post-Paleocene Gwandu Formation is an unconformity that represents the upper boundary of the fourth sequence. The base of the

Dange Formation is marked by a siltstone with reworked shale clasts, representing both the transgressive surface (ravinement surface) and probably the basal sequence boundary of a sequence comprising the Dange Formation and the subsequence formations.

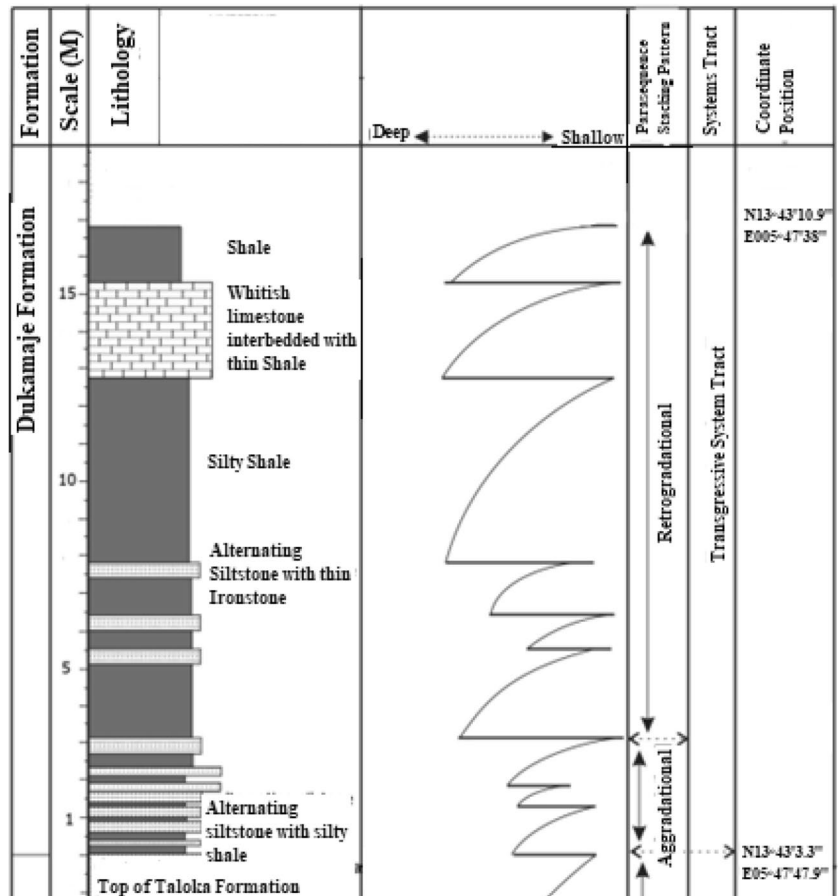
**Fig. 3** Sequence stratigraphic interpretation of Taloka Formation outcrop at Taloka Village (type section) N13° 26' 38.1" E005° 42' 29.9"



**Fig. 4** **A** Lower Taloka Formation: carbonaceous shale horizon indicating a condensed section, **B** middle Taloka Formation showing aggradational parasequence stacking pattern, and **C** upper Taloka Formation displaying Progradational Parasequence stacking pattern



**Fig. 5** Sequence stratigraphic interpretation of Dukamaje Formations outcrop at Dukamaje Hill (type section) N13° 43' 4.4" E005° 47' 47.6"



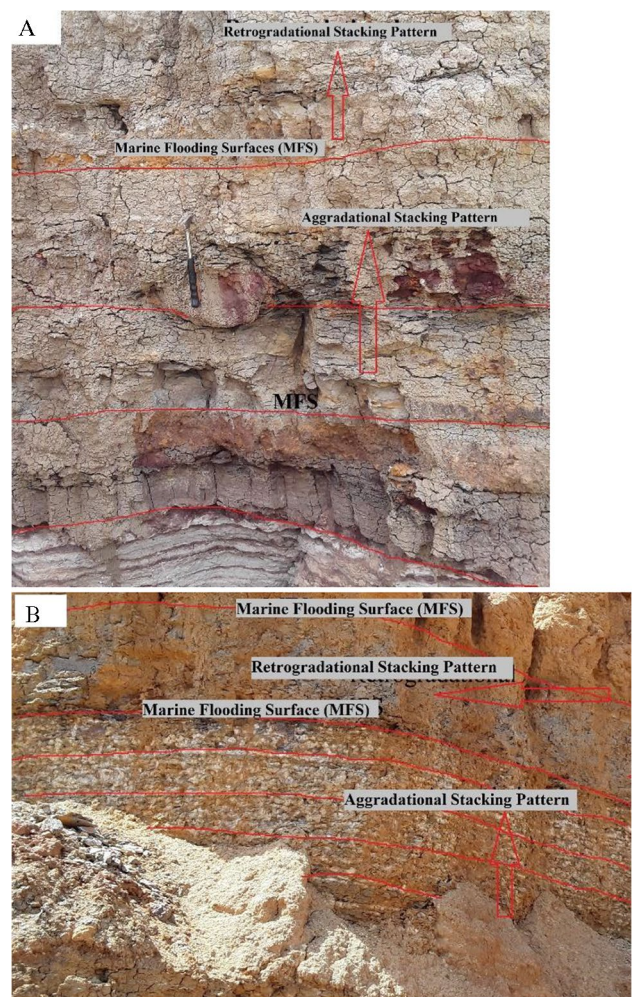
## Parasequence types

The various types of cycles in the Rima and Sokoto Group can also be interpreted and analyzed as parasequences in accordance with (Van Wagoner 1995). Therefore, nine basic parasequence types can be identified: (i) Parasequences comprising silty shale, siltstone showing hummocky cross stratification, and low-angle cross bedding interbedded with thin ironstone. The silty shales represent the deeper-water component. The upper surfaces of the ironstones represent the marine flooding surfaces and bioturbation occurring before the resumption of shale deposition. (ii) Parasequences comprising bioturbated gypsiferous siltstone, sulphur-rich silty shale, and black carbonaceous shale are overlain by faulted channel fillings (though the channel fillings are strictly not part of the parasequence). Parasequences i and ii characterize the lower Taloka Formation. The silty shales and the carbonaceous shale represent the deeper-water component. (iii) Parasequences comprising rapidly alternating siltstone, silty shale, and thin ironstones of equal proportions characterize the middle Taloka Formation. (iv) Parasequences comprise thicker sandstone, siltstone, and thin silty shale, towards the top; this characterizes the upper Taloka Formation. The shale-rich portions of the parasequences become progressively less important as they pass from the base to the top of the Taloka Formation, while the sandstone- and siltstone-dominated portions become increasingly dominant. (v). Parasequences consist of gypsiferous, phosphatic, sulphur-rich shale interbedded with silty shale and thicker limestones towards the top. This type of parasequence characterizes the Dukamaje Formation. (vi). Parasequences comprising siltstone and silty shale interbedded with thin ironstone, the proportion of siltstone being higher towards the top; this type of parasequence characterizes the Wurno Formation and is similar to iii above. (vii) Parasequences comprising equal proportions of siltstone and silty shale at the base are overlain by a thin (2–5 cm) glauconitic and phosphate-rich horizon, in turn overlain by 40 to 5 cm of grey gypsiferous shale and 20–45 cm of yellowish non-fossiliferous limestone. This type of parasequence characterizes the lower, middle, and upper parts of the Dange Formation. The glauconitic and phosphatic horizons represent the deepest water conditions found anywhere in the Sokoto Basin. (viii) Parasequences comprising 4–6 m of whitish fossiliferous calcareous shale are overlain by 2–8 m of whitish fossiliferous limestone. This type of parasequence characterizes the Kalambaina Formation. (ix) Parasequences comprising basal medium to coarse-grained tabular cross-bedded

sandstone overlain by fine-grained sandstone interbedded with thick mudstone, passing upwards into very coarse-grained tabular and trough cross-bedded sandstone with thin ironstone. The upper sandstone-dominated part represents shallow-water environments, with the ferruginized horizons indicating subaerial emergence. This type of parasequence characterizes the Gwandu Formation.

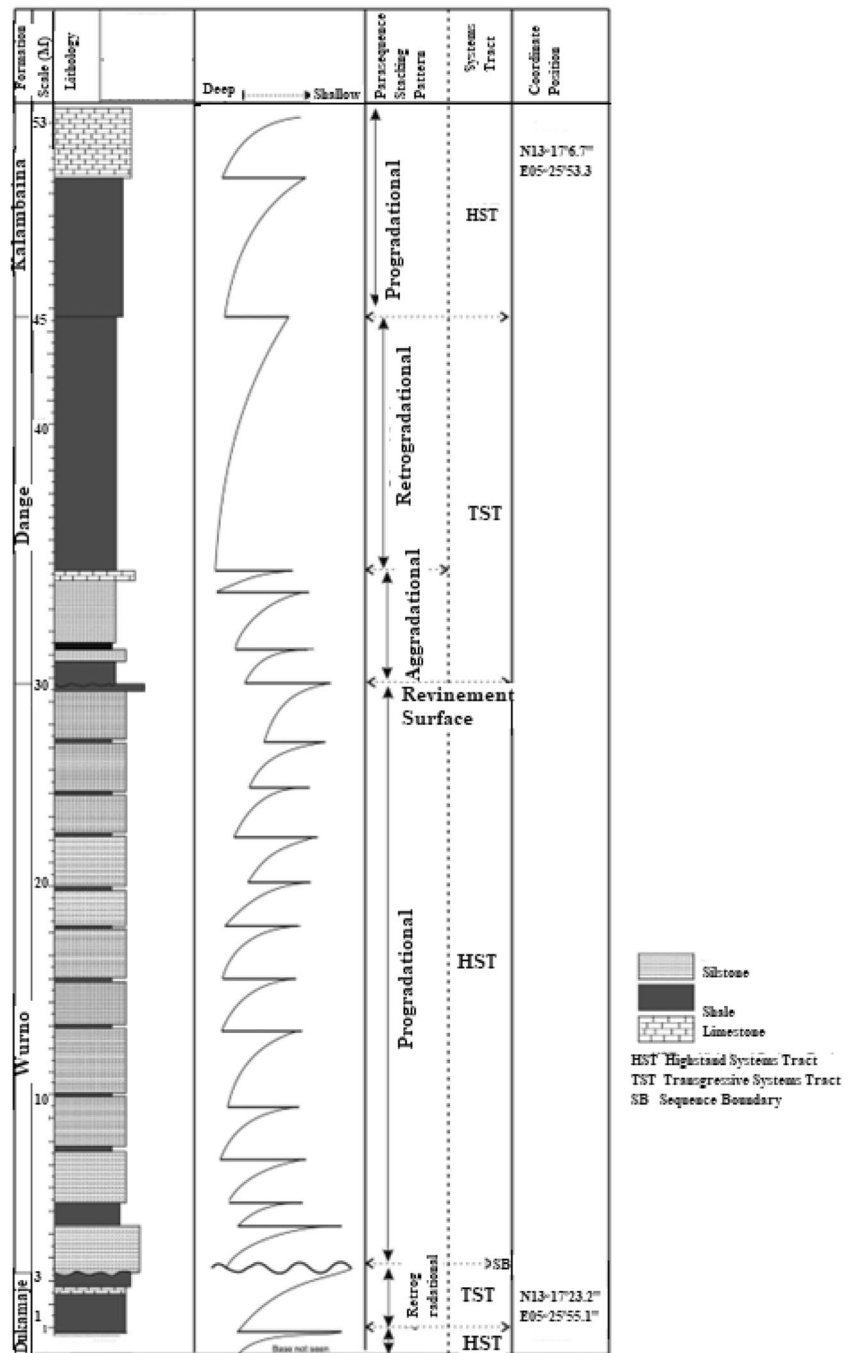
## Parasequence stacking patterns and systems tracts

The parasequence stacking pattern (in accordance with (Galloway 2001; Van Wagoner 1995; Posamentier et al. 1988)) of the Taloka Formation (Fig. 3) starts with aggradation at the base, grading to retrogradational



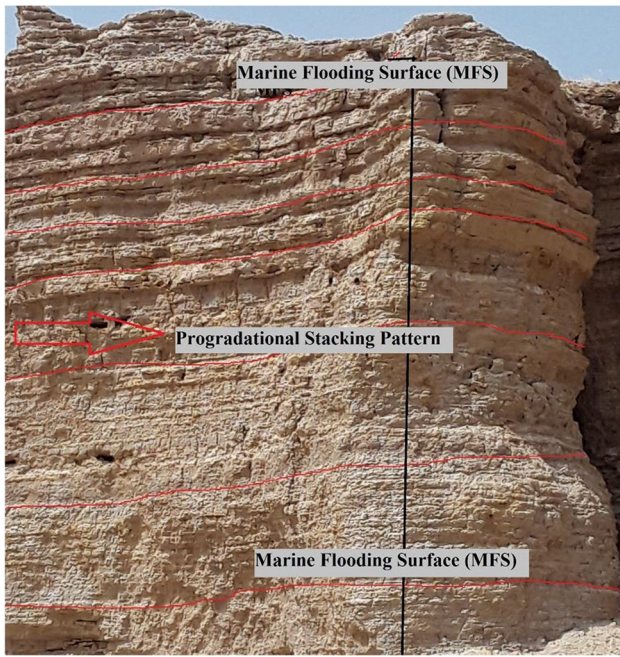
**Fig. 6** **A** Dukamaje Formation, aggradational parasequence stacking pattern to **B** retrogradational parasequence stacking pattern, thicker shale overlying thinly bedded whitish limestone. The sandstone above overlying the shale unconformably outcrop at Dukamaje Hill N13° 43' 3.3" E005° 47' 47.9"

**Fig. 7** Sequence stratigraphic interpretation of Wurno, Dange, and Kalambaina formations outcrop at Wurno Hill N13° 43' 4.4" E005° 47' 47.6"



where the carbonaceous shales occur (Fig. 4A). Aggradation resumes where the silty shale and very fine-grained sandstone are of equal proportion (Fig. 4B). Progradation occurs towards the top, where the proportion

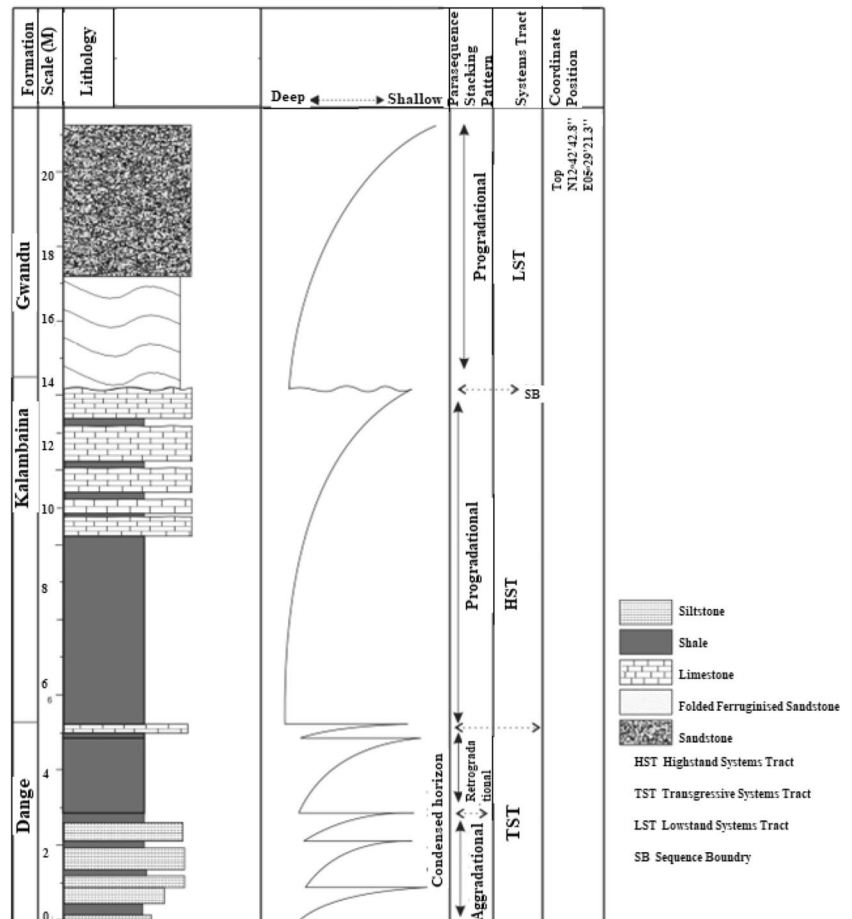
of the very fine-grained sandstone outpaces the silty shale (Fig. 4C). The progradational stacking pattern is well displayed by clinofolds at the top of the Taloka Formation, probably building into the sea in a NE



**Fig. 8** Wurno Formation, an progradational parasequence stacking pattern outcrop at Wurno Hill N13° 17' 11.3" E005° 25' 50.3"

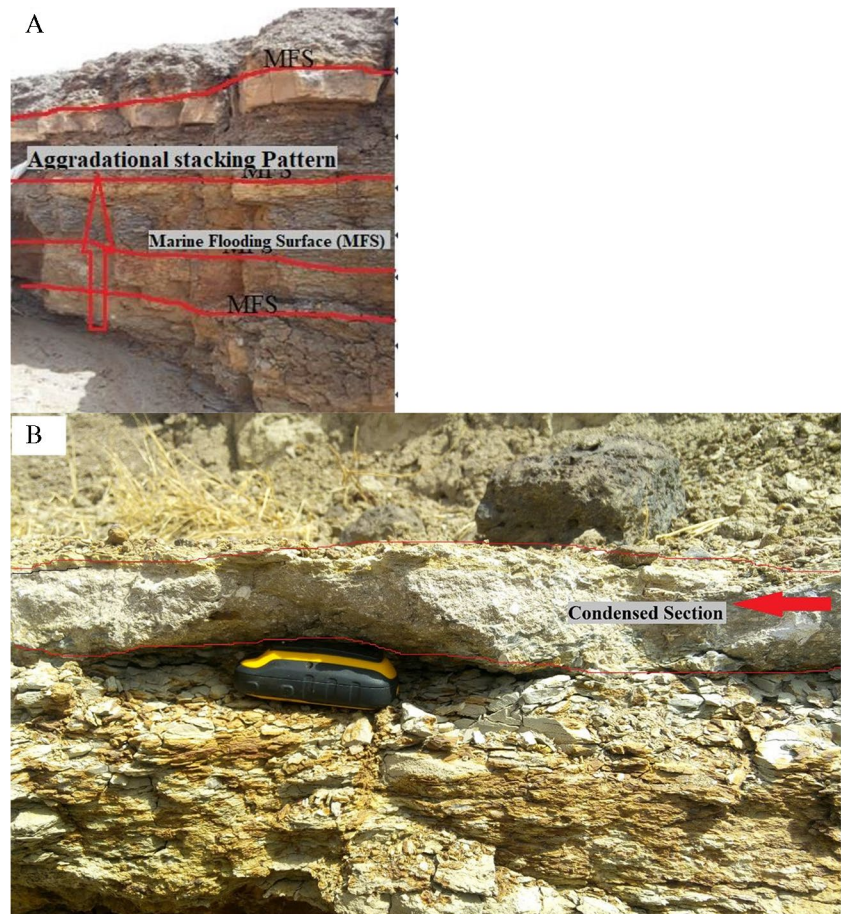
direction. These parasequence stacking patterns suggest a late transgressive to high-stand system tract. The parasequence stacking pattern of the Dukamaje Formation (Fig. 5) is made up of aggradational parasequences at the base where the siltstone and silty shale are vertically building up (Fig. 6A), and a retrogradational parasequence stacking pattern towards the top marked by two successions of thicker shale interbedded with very thin limestone (Fig. 6B). This parasequence stacking pattern suggests that the succession belongs to a transgressive system. The Wurno Formation (Fig. 7) is made up of a progradational parasequence stacking pattern shown by very fine-grained sandstone interbedded with silty shale grading upwards to well-bedded very fine-grained sandstone (Fig. 8). This parasequence stacking pattern suggests that the succession belongs to the high-stand systems tract. The parasequence stacking pattern of the Dange Formation was established at the Wurno Hill and Gada village stream sections (Fig. 9). It is marked by a revinement surface (in accordance with (Galloway 2001; Catuneanu et al. 2009; Moody and Sutcliffe 1991)), overlain by an aggradational parasequence stacking pattern (Fig. 10A) displayed by the siltstone and silty shale

**Fig. 9** Sequence stratigraphic interpretation of Dange and Kalambaina formations outcrop at Gada Stream N13° 44' 41.8" E005° 39' 27.9"





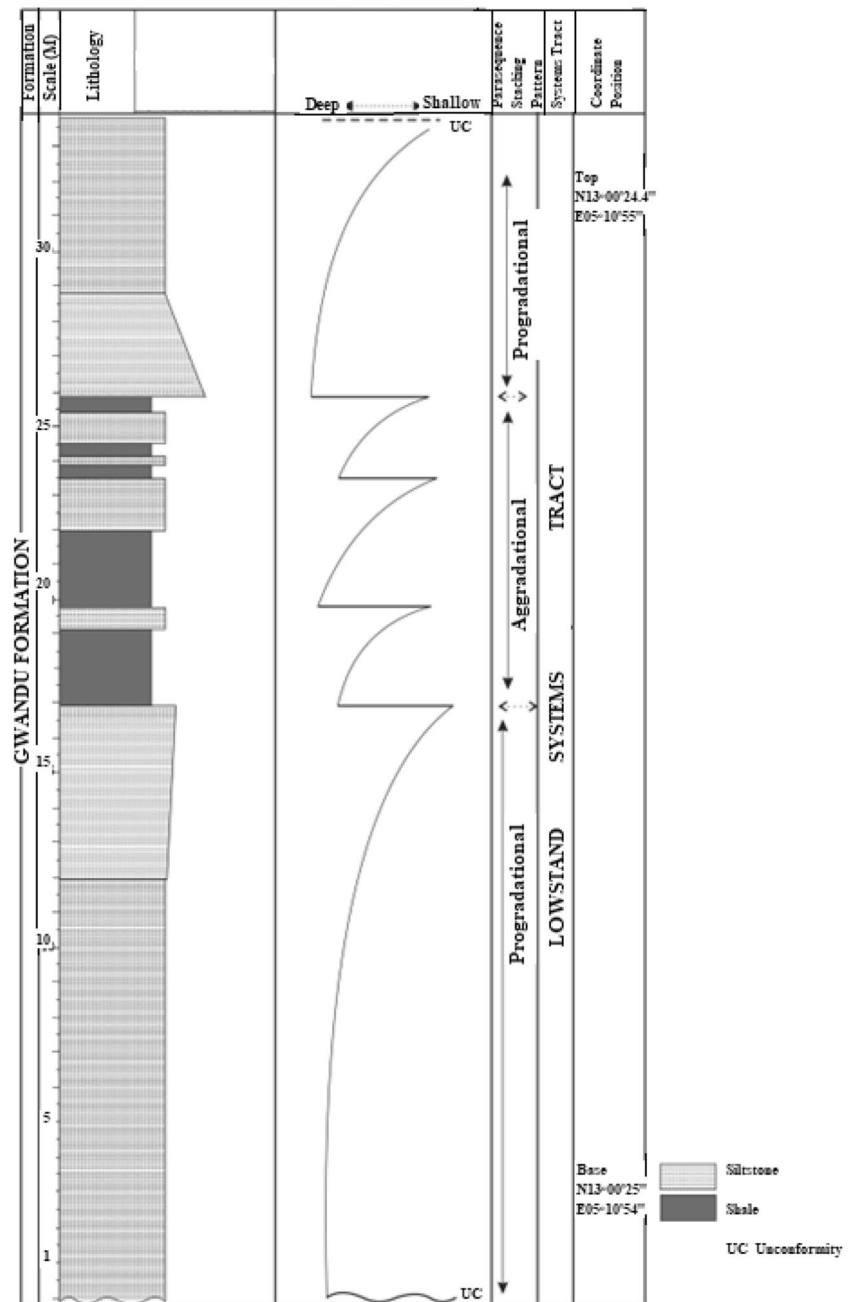
**Fig. 10** **A** Dange Formation, section displays an aggradational parasequence stacking pattern and **B** shows condensed horizon containing (phosphate and glauconite) outcrop at Gada village Stream N13° 44' 41.8" E005° 39' 27.9"



**Fig. 11** Kalambaina/Dange Formation, section displaying a retrogradational parasequence stacking pattern (lower is grey silty shale belonging to Dange Formation) and upper whitish calcareous shale belonging to Kalambaina Formation displaying an progradational parasequence stacking pattern, outcrop at Gada Stream N13° 44' 44.3" E005° 39' 25.6"

being of equal proportions and a retrogradational parasequence stacking pattern where thicker shale occurs. A condensed horizon (Loutit et al. 1988) is marked by silty shale, glauconitic, phosphate, and thin limestone (Fig. 10B). The maximum flooding surface may occur at the base of the condensed horizon, where the successions are most closely spaced. This formation characterizes the transgressive systems tract. In any event, the presence of condensed horizons indicates the deepest water environments identified. The Kalambaina Formation (Fig. 9) is made up of a retrogradational to progradational parasequence stacking pattern marked by limy shale overlain by thicker limestone (Fig. 11). This parasequence stacking pattern suggests that the succession belongs to a high-stand systems tract. The parasequence stacking pattern of the Gwandu Formation (Fig. 12) is made up of an aggradational to progradational stacking pattern marked by tabular cross-bedded coarse-grained sandstone overlain by whitish mudstone of equal proportions (Fig. 13A) and very thick tabular cross-bedded medium- to coarse-conglomeratic sandstone (Fig. 13B). Incised valley fills, amalgamated braided fluvial channels, and basin floor fans characterize this succession.

**Fig. 12** Sequence stratigraphic interpretation of Gwandu Formation outcrop at Arkilla Hill N13° 00'25" E005° 10' 54"



Based on the parasequence stacking pattern, this formation belongs to a low-stand system tract.

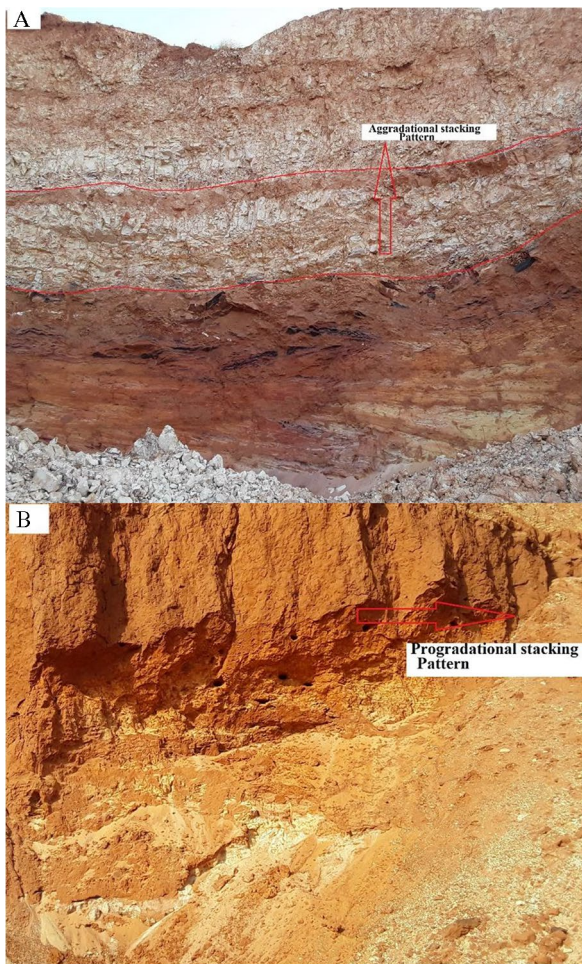
**Sequence boundary**

A sequence boundary occurs at the base of the Taloka Formation. A maximum flooding surface (in accordance with (Galloway 2001; Van Wagoner 1995; Posamentier et al. 1988)) occurs within the Dukamaje Formation. A reinvement surface (in accordance with (Catuneanu et al. 2009)) occurs at the base of the Dange Formation

with condensed horizons towards its top. Other sequence boundaries occur at the top of the Kalambaina and Gwandu Formations.

**Comparison with the Exxon curve**

The Exxon curve (Haq et al. 1987) shows two sequences (UZA-4.4 and UZA-4.5) in the Maastrichtian (Fig. 14) (Hancock 1989) matching transgressive peaks dated 73.5 Ma and 68.7 Ma, respectively (Fig. 15), identified from the British Isles (UZA-4.4 was believed to be misdated



**Fig. 13** Gwandu Formation: **A** tabular cross-bedded coarse-grained sandstone overlain by whitish mudstone that is interbedded with sandstone displaying an aggradational parasequence stacking pattern and **B** massively bedded coarse-grained sandstone displaying a progradational parasequence stacking pattern outcrop at Arkilla Hill N13° 00' 34.9" E005° 07' 26.8"

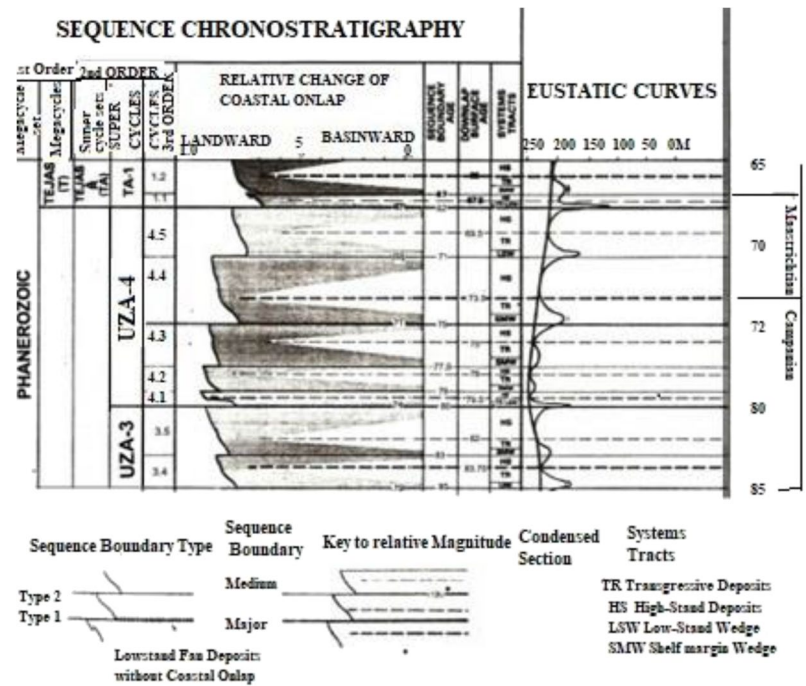
by (Haq et al. 1987) and should be largely Late Campanian in age). The Dukamaje Formation contains *Libycoceras crossense* (Zaborski), which also occurs in the Nkporo Formation of southeastern Nigeria, according to (Zaborski and Morris 1999), to date if the transgression that introduced it into the Sokoto Basin was Late Campanian, then the proposed maximum flooding surface in

the Dukamaje Formation would correspond best with the transgressive peak identified by (Haq et al. 1987) at 73.5 Ma (Fig. 15) and probably the maximum flooding surface within sequence UZA-4.4 on the Exxon curve (Fig. 14). However, it should be noted that a detailed biostratigraphical correlation of the Campano-Maastrichtian succession in the Sokoto Basin with other regions of the world is not currently possible. If matching the maximum flooding surface within the Dukamaje Formation with Hancock's peaks at 73.5 Ma (Fig. 15) is correct, then probably his 68.7 Ma peak is matched with the Dange Formation in the Sokoto Basin. Matching transgressive peaks and maximum flooding surfaces from widely separated areas makes the assumption that their control was an eustatic change in sea level.

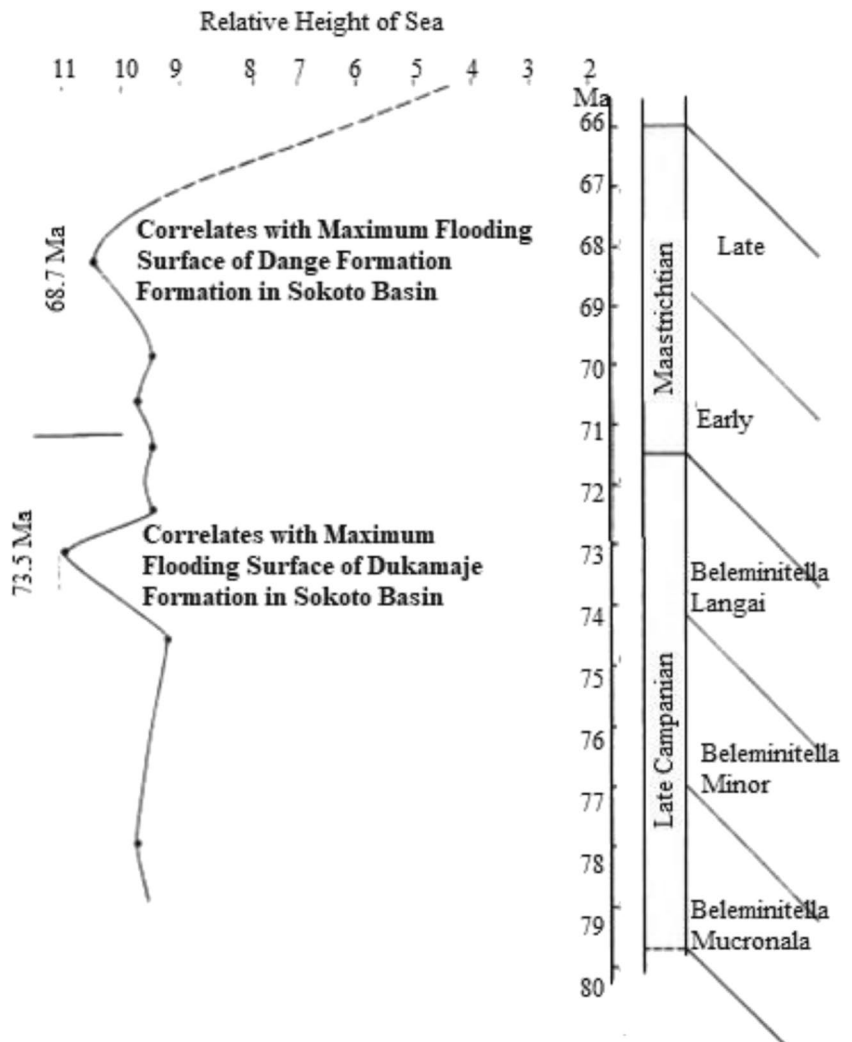
## Conclusion

An overall sequence stratigraphic interpretation of the Campano-Maastrichtian to Paleocene successions has been attempted. The lower sequence boundary is an unconformity between the Taloka and Illo/Gundumi formations; The Taloka and Dukamaje formations belong to a second sequence. The Wurno, Dange, Kalambaina, and Gamba formations belong to the third sequence. The Gwandu Formation belongs to the fourth sequence. The lower Taloka Formation displays retrogradational, the middle Taloka Formation displays aggradational, and the upper Taloka Formation displays progradational stacking patterns, marking the change from a late transgressive system tract to a high-stand systems tract. The Dukamaje Formation is interpreted to contain a diagnostic maximum flooding surface which displays a retrogradational stacking pattern, and characterizes a transgressive system tract. The Wurno Formation displays a progradational stacking pattern occurring within a high-stand system tract. The boundary between the Wurno and Dange formations is a ravinement surface, corresponding with the transgressive surface. The Dange Formation contains a condensed horizon towards the top marked by glauconitic and phosphatic hardgrounds and shales displaying a retrogradational stacking pattern within a transgressive

**Fig. 14** Cretaceous chronostratigraphic and eustatic-cycle chart for the Campanian to Maastrichtian (after Haq et al. 1987)



**Fig. 15** Graph of sea-level changes in British region from Late Campanian to Maastrichtian, showing possible correlation with the Campano-Maastrichtian succession in the Sokoto Basin (after Hancock 1989)



system tract. The Kalambaina Formation displays a progradational stacking pattern within a high-stand systems tract. The Gwandu Formation shows incised and channel-filling geometries with an aggradational to progradational stacking pattern, occurring within a low-stand systems tract. The potential reservoir rocks of the Sokoto sector include all the high-stand systems tract. The effective seals and source rocks are the shales of the transgressive system tract which according to (Obaje et al. 2020) has an average source rock thickness of 50 m, TOC of 7.5wt%, and HI of 212 mgHC/gTOC; charge modeling indicates 808.10 million barrels of oil equivalent extractable hydrocarbons in the Sokoto Basin. The low-stand systems tract contains aggradational to progradational stacking pattern made up of mudstone and coarse to medium sandstones of the Gwandu Formation may be good reservoir if the ironstones are proven to be good seals and, therefore, capable of retaining hydrocarbons.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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