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Full Length Research Article

PARASEQUENCE SET ANALYSIS OF THE MAASTRICHTIAN TO PALEOCENE STRATIGRAPHIC SUCCESSION IN THE SOKOTO SECTOR OF IULLEMMEDEN BASIN, NORTHWESTERN NIGERIA

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ABSTRACT
Detailed geological field mapping of Maastrichtian - Paleocene sedimentary deposits exposed at the Sokoto sector of Iullemmeden Basin was carried out in this study. The principle of sequence stratigraphy was applied on the exposed outcrops for a better understanding of their depositional history. Results of the sequence stratigraphic analyses reveal three (3) parasequence types, Two (2) system tracts and one (1) condensed section. The parasequence of the lower and upper portion of Taloka and Wurno formations are made up of aggradational and progradational stacking patterns – which all belong to the Lowstand system tracts. Retrogradational stacking pattern was observed within the Dukamaje, Dange and Kalambaina formations which consist of fossiliferous limestone and shales. The retrogradational stacking pattern belongs to the Transgressive system tracts. The condensed section which was observed at the transitional boundary between Wurno and Dange formations near Gada village is represented by a 7 cm thick phosphate bed fused with glauconite and fossil bones. This indicate a strata associated with the maximum flooding surfaces, represented by sedimentary intervals deposited during the maximum marine transgression.

Keywords: Parasequence; stacking pattern; System tracts; Condensed section; Transitional boundary

BACKGROUND

Earlier geological works on Sokoto Basin were mostly centred on fossils (e.g., Bather, 1904; Newton, 1904, 1905; Nopsca, 1925; Swinton, 1930); while others described the water resources of the basin (e.g., Raeburn and Tattam. 1930; Anderson and Ogilbee 1973; Oteze, 1976, 1991; Adelana *et. al*. 2003 and Alagbe 2006). Works on the geology and geography of the basin were done by Falconer (1911) and Parker (1964). Some authors carried out geochemical studies for trace elements and mineral potential of the basin (e.g., Okosun and Alkali (2013); Bassey and Eminu (2014).Works on paleoenvironment was also done within the basin (e.g., Adekeye *et al* (2013) and Toyin *et al*. (2016), The first stratigraphic study of the basin was carried out by Tattam (1944) and Jones (1948) where they reported occurrence of cyclic sedimentation. Kogbe *et al.,* (1972) and Kogbe (1973; 1979); (1981) and Adetunji and Kogbe (1986) carried out geological mapping and biostratigraphical evaluation of the basin and reported paucity of outcrops. He produced a map of the basin in where the sediments were delineated into Rima and Sokoto Groups leaving out respective formations.Obiosio *et al.* (1998) and Okosun (1999**)** studied the biostratigraphy and Paleoecology of Foraminifera and Ostracoda from boreholes in the basin.Several studies on the petroleum potential of the basin have also been done (e.g., Obaje *et. al*., 2013; Obaje et al. 2020and Bonde *et al*. 2014). Theses earlier works led to the erection of the Cretaceous and Tertiary stratigraphy of the Sokoto Basin.

However, work on sequence stratigraphy in the basin include Mutari et al (2023) who worked on sedimentary facies of Taloka Formation and Hamidu et al (2024) who worked on high resolution sequence stratigraphy of the basin. Thus, this study is tailored towards further application of sequence stratigraphic tools on outcrop exposures within the study area with the aim of discussing the types of parasequence and parasequence sets present therein.Sequence stratigraphic approach has led to improved understanding of how stratigraphic units, facies tracts and depositional elements relate to each other in time and space within sedimentary basins (Sloss, 1988). Application of sequence stratigraphy to surface and subsurface outcrops has been the area of growing interest (Sloss, 1988; **Loutit,** et al., **1988;** Posamentier, et al., 1988; Wangoner et al., 1990; Ye and Kerr, 2000; Embry,2009;Catuneanu, 2019; Catuneanu, *et al*., 2011;Abdulganiyu, 2021; Hamidu, et al., 2013; 2024). Stratigraphic surfaces, strata architecture, reservoir facies associations and structural features within system tracts are easily identified and visualized on outcrops (Nwajide and Reijers, 1997).

STUDY AREA

The study area lies within the Sokoto sector of the Iullemmeden Basin and covered by three topographic sheets; Gada Sheet 4, Sokoto Sheet 10, and Rabah Sheet 11. The study area covers a total area of nine thousand two hundred and forty square kilometres (9.240 km^2) (see inset on Fig. 1). It is located in the northeastern part of the study area and accessible through a network of roads such as Sokoto-Kalambaina, Sokoto-Wurno, Sokoto-Goronyo-Isa, and Sokoto-Gada-Wauru-Illela, with several untarred roads and footpaths. Major communities in the study area include Gada, Baredi, Dukamaje, Dogondaji, Gilbedi, Goronyo, Taloka, and Gadon Mata; Katanga, Gidan Bauchi, Derbabiya, Kerenjia, Gidan Hashimu, Wurno, Kalambaina, and Sokoto Metropolis. The study area is covered by prominent outcrops (Fig. 1) that are well exposed and hence, serves as a laboratory for sequence stratigraphic studies.

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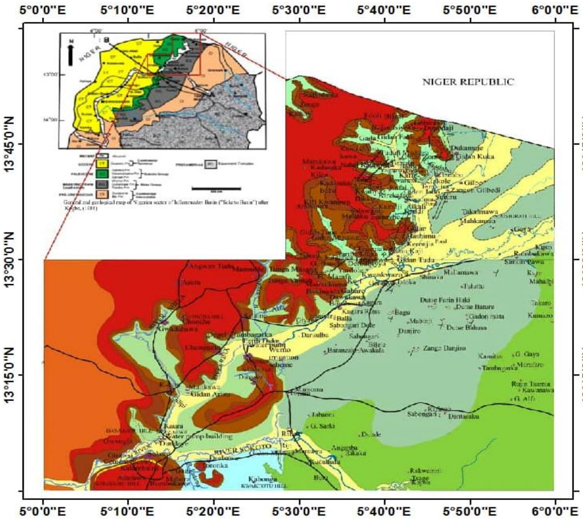

Figure 1: Showing the study area in the Sokoto basin (Inset) and the geological map of study area with several exposed outcrops (Abdulganiyu, 2021).

STRATIGRAPHY

Kogbe (1979) harmonised the stratigraphic works reported by earlier workers (see Table 1); and further stated that the sediments were deposited during four main phases:

i. Pre-Maastrichtian during which Illo and Gundumi formations were deposited. They are mainly made-up of grits and clays, and were deposited unconformably on the Pre-Cambrian basement. These formations are lateral equivalents.

ii. Maastrichtian Rima Group rests unconformably on Illo and Gundumi formations. The Taloka and Wurno formations of the Group consist of mudstones and friable sandstones while the Dukamaje Formation is composed entirely of fossiliferous shale.

iii. Paleocene Sokoto Group consists of Dange and Gamba formations (mainly shales) and separated by the calcareous Kalambaina Formation.

iv. Post-Paleocene Continental-Terminal which is the Gwandu Formation occurs as tabular hills or low hummocks over the dip slope of the Paleocene Formation.

Table 1: Lithostratigraphy of Sokoto Basin (after Jones, 1948 and Kogbe, 1979).

AGE	FORMATION	DESCRIPTION	GROUP	ENVIRONMENT
EOCENE-MIOCENE	GWANDU	Red mottled massive clays with sandstone intercalation and ironstone.	CONTINENTAL TERMINALE	Continental (Kogbe, 1972)
PALEOCENE Montian-Landenian	GAMBA	Grey laminated shales with abundant fossil.	SOKOTO GROUP (Jones, 1948)	Marine (Kogbe, 1979)
	KALAMBINA Calcareous Group (Jones, 1948)	White clayey limestones and shales with abundant fossil. Forams, Ostracods, Mollusks, Bivalves and Echinoids		
	DANGE (Parker, 1964) Clay-shale Group (Jones, 1948)	Slightly indurated bluish-grey shales interbedded with thin layers of yellowish- brown limestone with bands of fibrous gypsum and irregular phosphatic nodules.		
MAASTRICHTIAN Upper Senonian, (Jones, 1948)	WURNO Upper Sandstones and Mudstones (Jones, 1948)	Pale friable fine-grained sandstone and siltstone with thin intercalated mudstone and carbonaceous mudstone with iron sulphides.	RIMA GROUP (Jones, 1948)	Continental (Kogbe, 1979).
	DUKAMAJE (Parker, 1964) Mosasaurus shales (Jones, 1948)	Shales with some limestone, mudstone and gypsiferous shales with a bone bed which is an excellent marker horizon. It is highly fossiliferous.		Marine (Kogbe, 1979).
	TALOKA Lower Sandstones and Mudstones (Jones, 1948)	White fine grained friable sandstone and siltstone with thin intercalated mudstone and carbonaceous mudstone or shales with gypsum and ferruginous material.		Continental (Kogbe, 1979).
PRE-MAASTRICHTIAN	GUNDUMI	Basal conglomerates, gravel, sand, Pisolitic and nodular clays. Poorly fossiliferous.	CONTINENTAL INTERCALAIRE	Fluviatile and Lacustrine (Jones, 1948; Kogbe, 1979)
	ILLO	Upper Grits Pisolitic and Nodular Clays Lower Grits		
PRECAMBRIAN	BASEMENT COMPLEX			

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MATERIALS AND METHODS

A detailed field mapping was carried out within the study area where outcrops were identified and studied. Basic lithological characteristics including bed thicknesses, textural features, sedimentary structures, biogenic structures, and structural features in terms of dip and strike were recorded. Lithologic logs were produced from the well exposed outcrops along road cuts, river valleys, footpaths and field photographs of outcrops were also taken. Using the outcrops alongside the lithologic logs, parasequence stacking patterns were identified and used to define system tract, stratal surfaces and sequences according to the methods of Van Wagoner et al. (1990).

RESULTS AND DISCUSSION

Lithologies in the study area comprised of sandstone, siltstone, silty shale (Taloka and Wurno formations), shale (Dukamaje and Dange formations), and limestone (Kalambaina Formation) formations respectively. All these formations and their respective environments of deposition based on previous works are highlighted in Table 1. Lithostratigraphic sections produced from well-marked outcrops in the study area are presented in Figure 2a and 2b below.

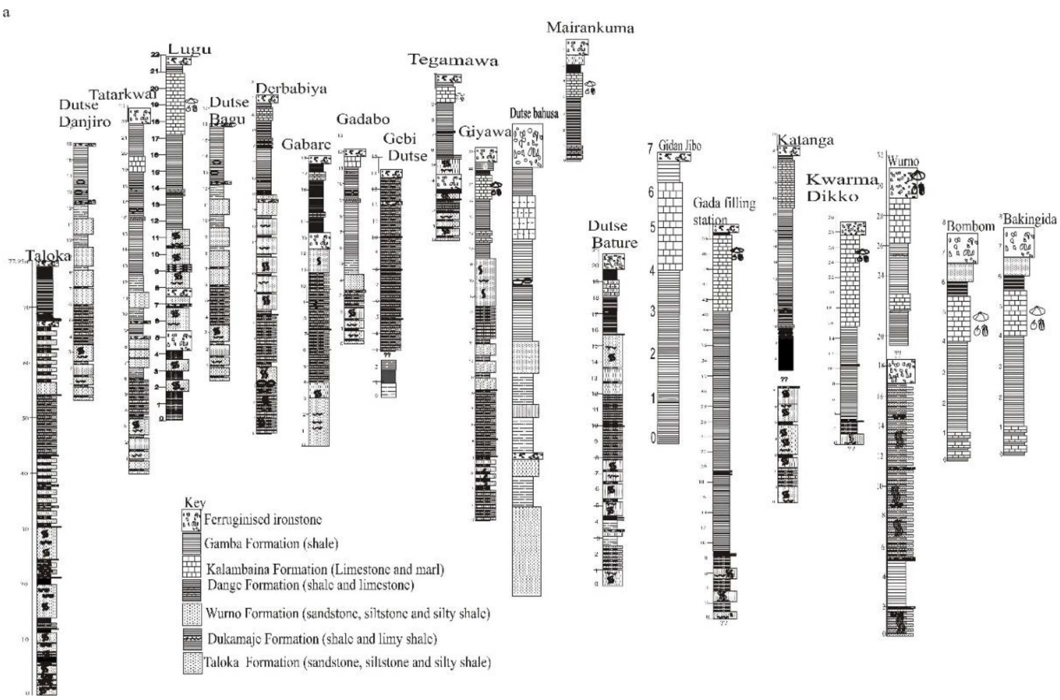

Figure 2a. Lithostratigraphic sections of exposures in the study area. Locality names are written on top of the individual logs.

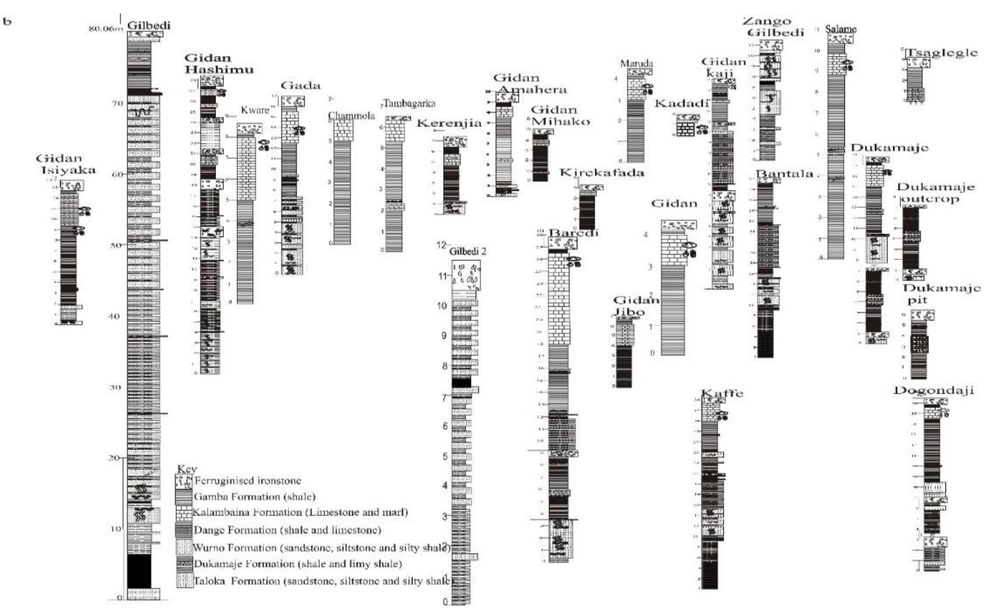

Figure 2: b Lithostratigraphic sections of exposures in the study area. Locality names are written on top of the individual logs.

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SEQUENCE STRATIGRAPHIC ANALYSIS

The study area clearly display good exposures with excellent cyclic pattern in the various formations. Careful application of sequence stratigraphic principles is only limited to outcrop with sequence stratigraphic features. These includes exposures of Taloka and Dukamaje formations on a hill near Taloka, Bagu, Gilbedi, Gidan Hashimu villages and outcrop of Dukamaje along Tsaglegle. Other outcrops include: Wurno Formation near Wurno village and the exposures of Wurno, Dange and Kalambaina formations near Gada village were selected for this purpose as they display features that are relevant to sequence stratigraphic analysis.

Parasequence sets

Three types of parasequence sets were interprèted which includes aggradational, progradational and retrogradational types.

(i) Aggradational parasequence sets

This type of parasequence set occurs in the lower part of Taloka Formation. their upper parts are made up of thickly, bedded, varicoloured sandstones of 30 cm - 10 m thick having lignitic and carbonaceous shale, While the lower parts of the parasequences commonly show 2 mm - 5 m thick intercalations(Fig. 3 ; 4 a and b) displaying flaser and lenticular bedding, parallel lamination, low angle cross lamination and hummocky cross stratification. The sandstones represents the shallow marine part while the deeper marine part is represented by the silty shale and gypsiferous carbonaceous shale while lignitic shale represent a deposition in a freshwater swamps in a deltaic plain. This type of parasequence is capped by ferruginised ironstone indicating subaerial exposures. This succession typified the basal part of Taloka Formation (Figure 3) exposed near Taloka, Kaffe, Gidan Hashimu and Gilbedi villages (Fig. 4 a and b). The individual sets observed from both outcrop and photo show no overall shallowing or deepening and the facies proportion was relatively constant and indicating that the rate of sediment supply balanced the accommodation created.

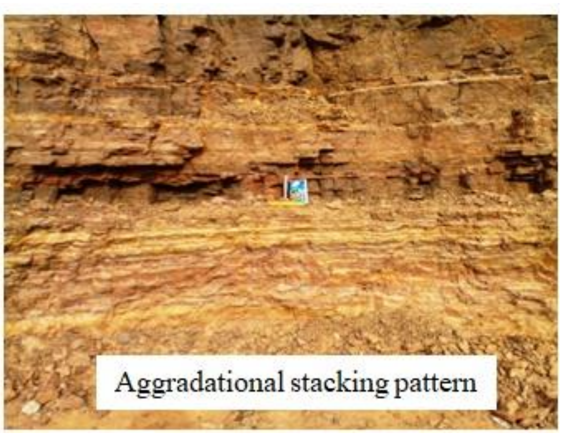

Figure 3: Outcrop of the lower portion of Taloka Formation displaying varicoloured sandstone 30 cm - 10 m with lignitic and/or carbonaceous shale near Taloka village (N 13˚ 27' 00" and E 5° 41' 20.1").

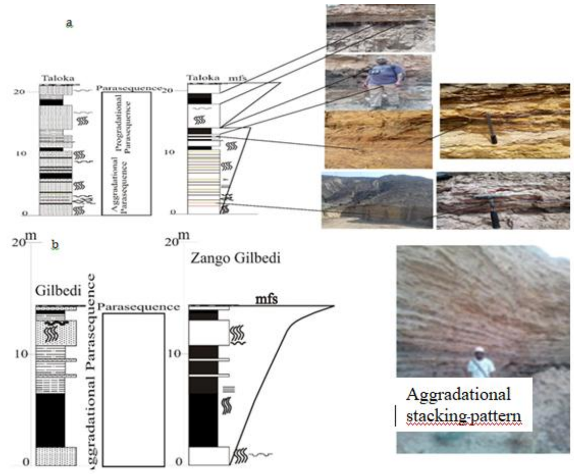

Figure 4: (a) Lithostratigraphic section of lower part of Taloka Formation exposed on a hill near Taloka village (N 13˚ 27' 00" and E 5° 41' 20.1") (b)Lower part of Taloka Formation exposed on a hill near Gilbedi village (N 13° 38' 35.9" and E 5° 48' 19.4") displaying the parasequences.

(ii) Progradational parasequence sets

Parasequence comprising of rapidly alternating sequence of bioturbated sandstone 50 cm –1.55 m and silty shale 30 cm -1 m which gradually reduce in thickness upward measuring about (80-95 cm) bioturbated sandstone and silty shale 8-10 cm Fig. 5 a and b. The succession display structures like hummocky cross-stratification, low angle cross stratification and intra formational unconformity(Fig.5a). Localized tectonic structures like, growth fault, listric fault and silicification surface were also identified within the parasequence.

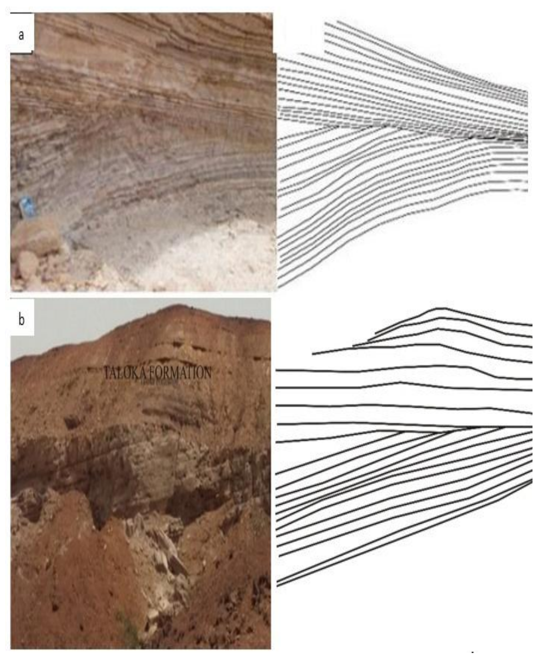

***Figure 5*a:** a Bi-directional low angle cross-stratification near Gidan Hashimu (N 13˚ 45' 35.9" and E 5° 45' 48.7"). b. Intra

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formational unconformity observed on Taloka Formation near Gilbedi.

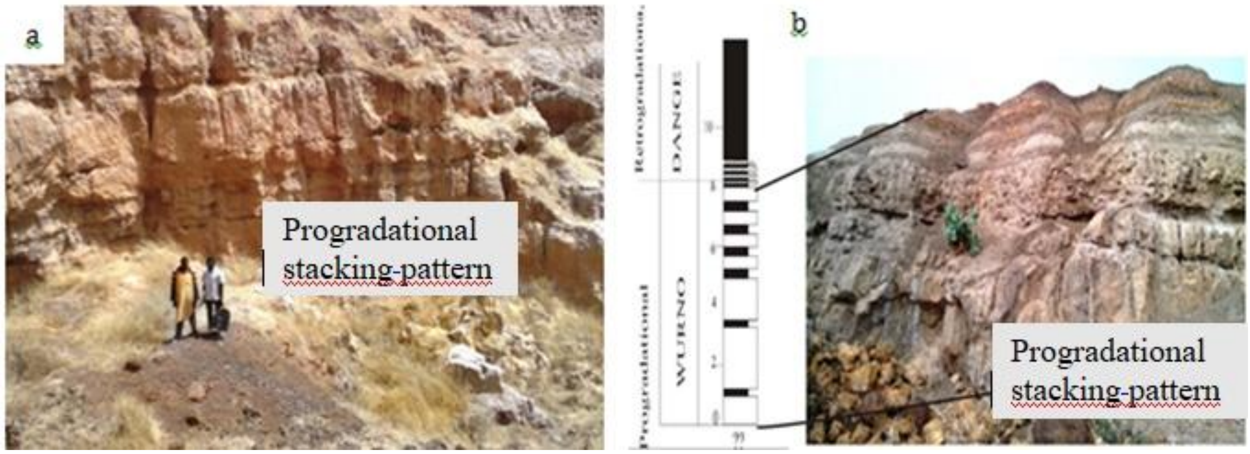

Figure 5b: (a) Upper part of Taloka Formation exposed on a hill near Bagu village. (b) Sequence stratigraphic interpretation of upper part of Wurno Formation exposed on a hill near behind market in Gada village displaying progradational parasequence sets (N 13° 31' 5.4" and E 5° 41' 43.7")

The parasequence is capped by ferruginised ironstone separating Taloka Formation from the overlying Dukamaje Formation with the basal part of the ironstone variably bioturbated and depicting reduction in water volume – hence infestation by burrowing worms. The sandstone represents the shallow marine while the silty shale represents the deeper marine with the ironstone capping (Figs. 6ai, aii, aiii; 7; 8 and 9). Each successive parasequence going up through the set, displays shallower water facies, indicating an overall shallowing-up trend. This indicates that the rate of sediment supply exceed accommodation created. Generally, sediments of both Taloka (Mutari et al., 2023) and Wurno formations display both aggradational to progradational trends. Thus, belong to the early part of Highstand system tract based on parasequence types observed on the field.

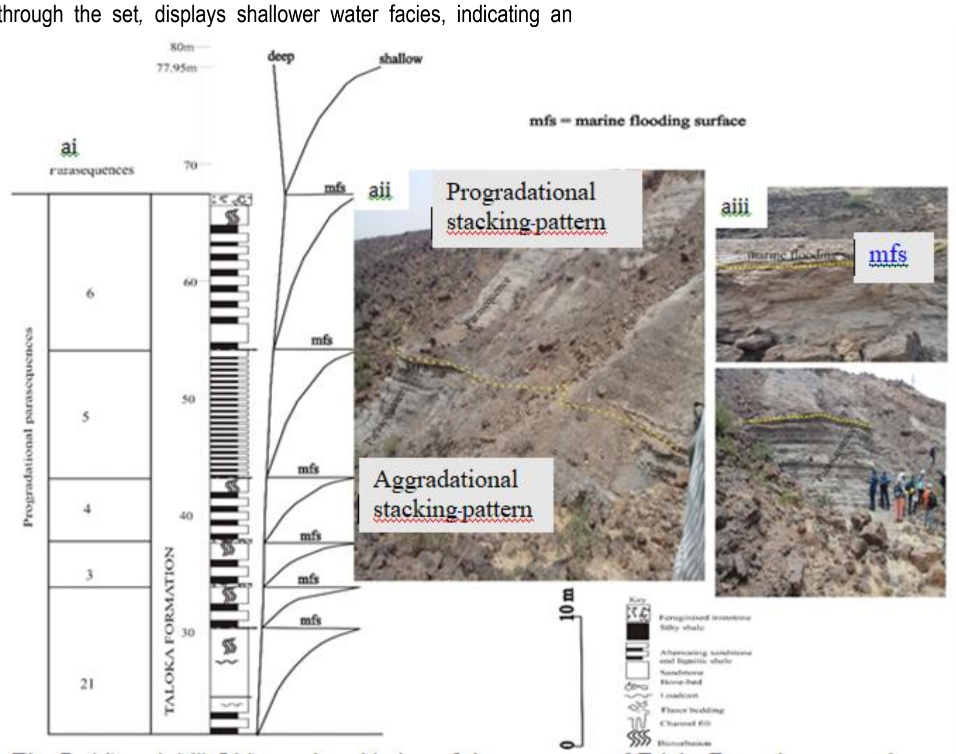

Figure 6: (ai) and (aii) Lithostratigraphic log of the upper part of Taloka Formation exposed on a hill near Taloka village showing parasequence (aiii) flooding surface (mfs) (N 13˚ 27' 00" and E 5° 41' 20.1").

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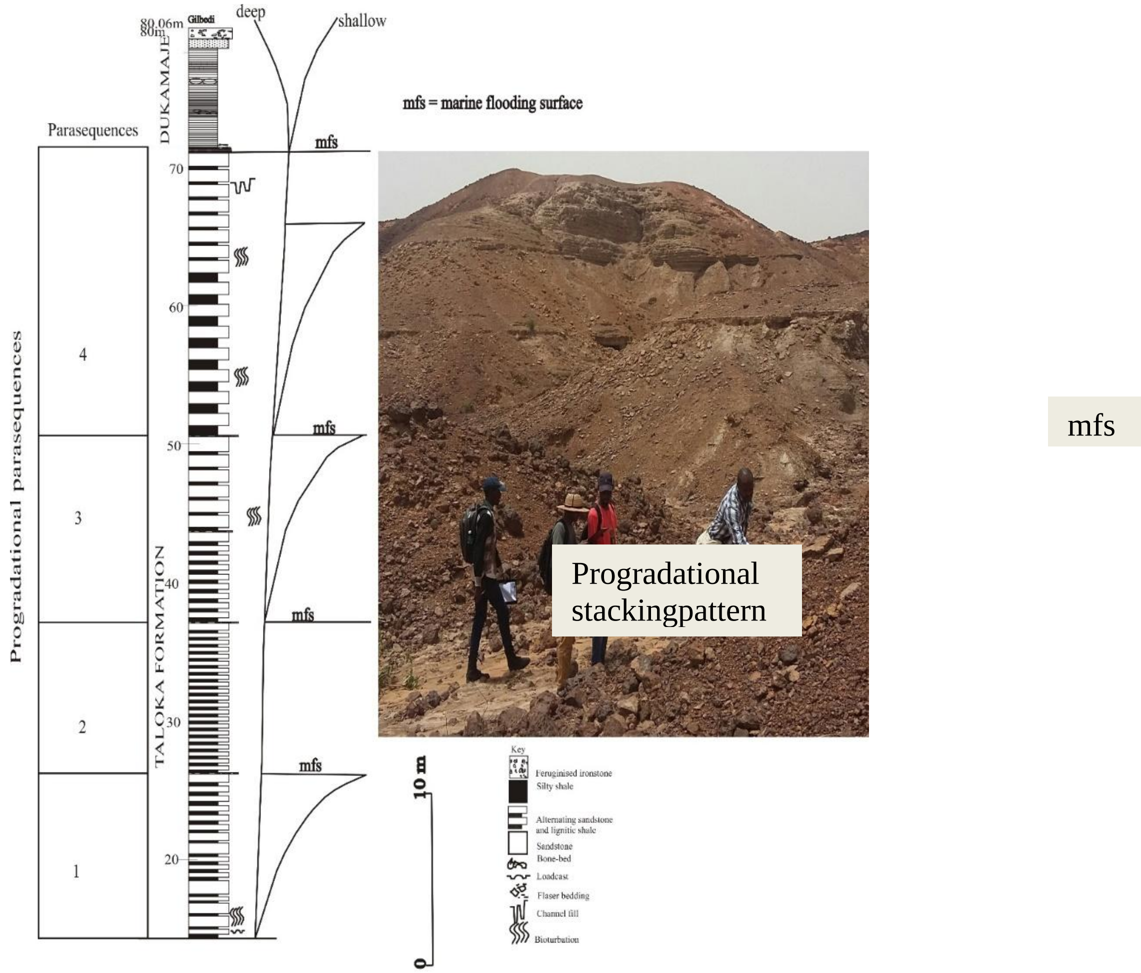

Figure **7: Lithostratigraphic section of the upper part of Taloka Formation exposed on a hill near Zango Gilbedi showing progradational parasequence(N 13° 38' 35.9" and E 5° 48' 19.4").**

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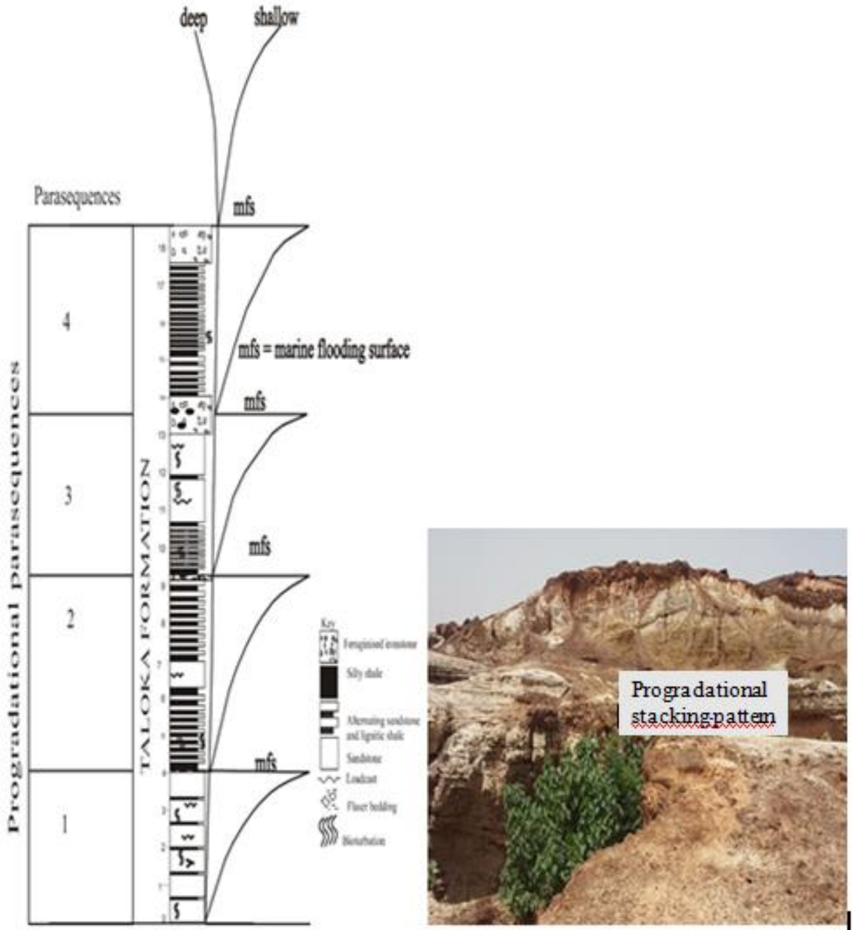

Figure **8: Lithostratigraphic section of the upper part of Taloka Formation exposed on a hill near Gidan Hashimu village showing the parasequence (N 13˚ 33' 55" and E 5° 44' 25")**

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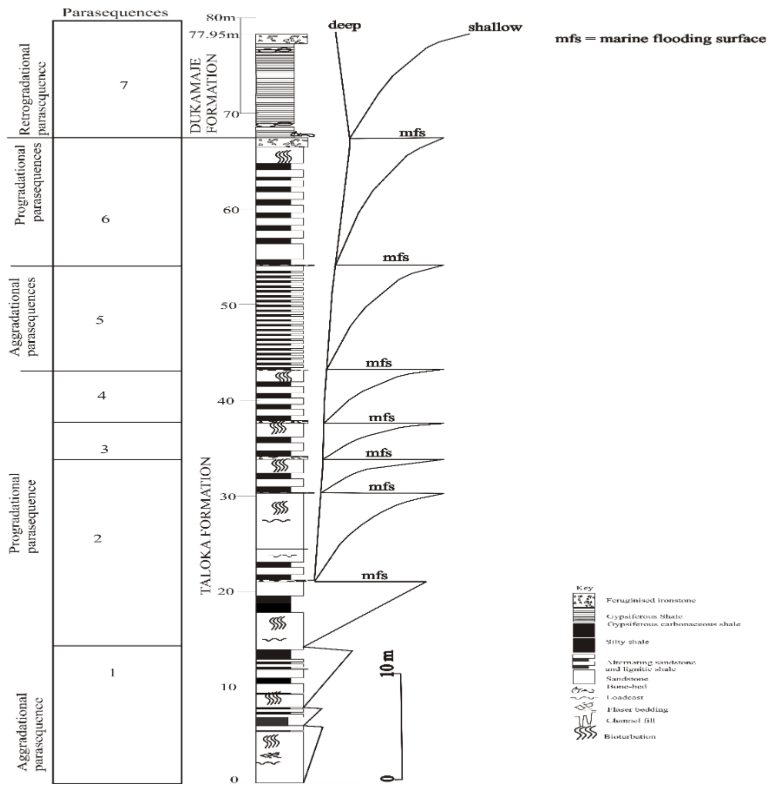

Figure 9: Generalized sequence stratigraphic interpretation of Taloka Formation exposed on a hill near Taloka village displaying the 3 types of parasequence (N 13˚ 27' 00" and E 5° 41' 20.1")

(iii) Retrogradational parasequence sets

Parasequence comprising of entirely shales and limestones exclusively of marine origin. In some cases, they have sandstone interbeds which display fining upward grain size profile with trough cross-lamination (Fig. 10). This parasequence sets show increased deepening trend up through the succession, indicating the fossiliferous (Bivalve) shale and the limestone with fossils like bivalve, Echinoderm and Molluscs are of deeper water facies.

The parasequence set usually have interbeds of non-fossiliferous limestone beds which could be one (1), two (2) or three (3) beds (Fig. 11). But within Dukamaje Formation, the beds are thin (3 cm) and made up of gypsiferous non-fossiliferous limestone alternating with shale (limy shale). However, both the fossiliferous limestone and shale indicate deepening upward succession – producing a retrogradational trend (Fig. 12). In essence, a considerable decrease in sand content suggests a deepening facies trend and an environment which promotes organic activity (Loutit et al., 1988; Vail et al., 1991). Thus, Dukamaje, Dange and Kalambaina formations are characterized by retrogradational parasequence sets which are indicative of Transgressive systems tract.

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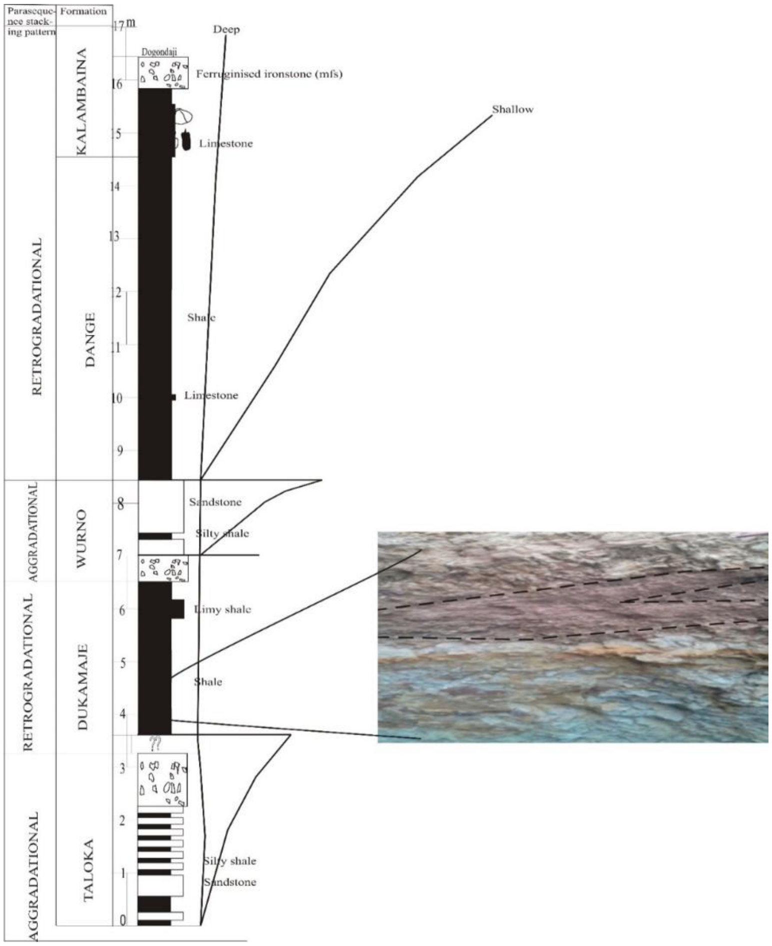

Figure 10: Sequence stratigraphic interpretation of Taloka, Dukamaje, Wurno, Dange and Kalambaina formations exposed on a hill near Dogondaji village with sandstone intercalation within the Dukamaje Formation (N 13˚ 45' 35.9" and E 5° 45' 48.7")

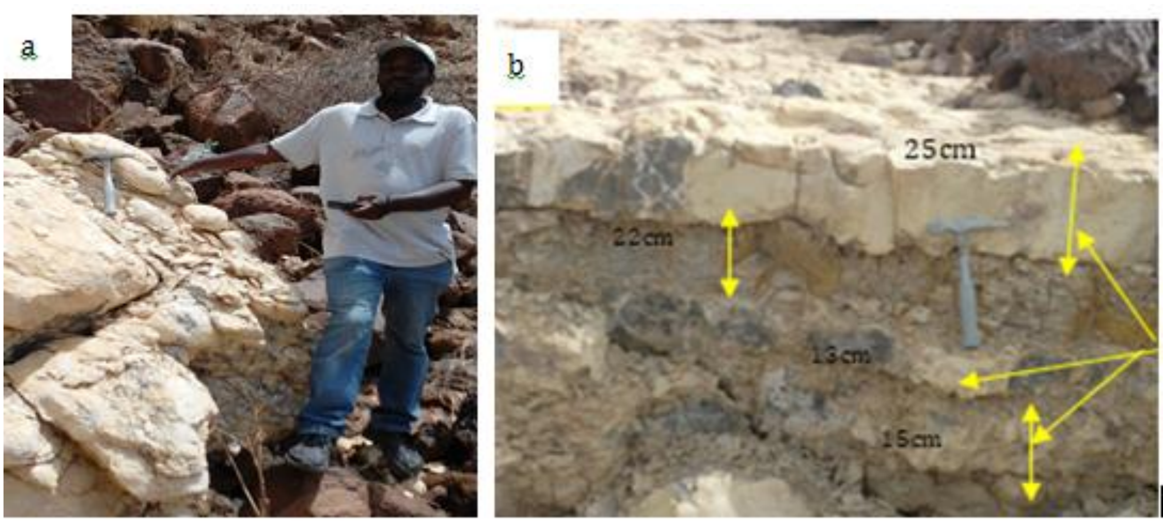

Fig. 11:(a) Bivalves and Echinoderm fossils from Limestone (Kalambaina Formation) behind Dutse Gidan Isiyaka 0.7km north of Gada (Excellent place for fossil collection) (N 13° 46' 35.3" and E 5° 39' 47").(b) Three limestone beds within Dange Formation shale along a stream channel near Mairankuma (N 13° 26' 9.4" and E 5° 33' 33.9").

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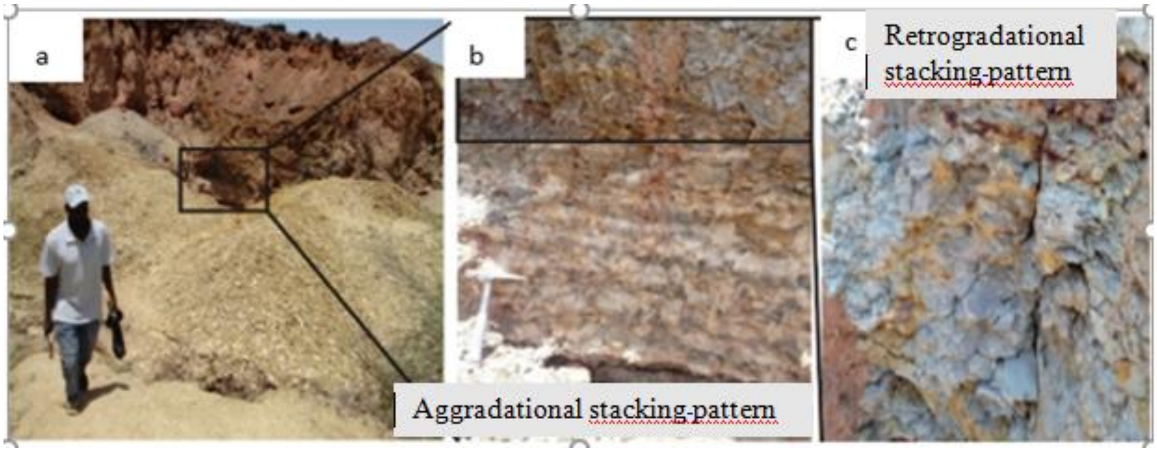

Figure 12: **a**. Outcrop of Dukamaje Formation **b**. Gypsiferous bluish-green shale with ironoxide patches underlain by limy shale (alternating limestone and grey shale) **c.** Close-up view of bluish green shale of Dukamaje Formation exposed 1.5km from Tsaglegle along Tsaglegle-Dukamaje Road (N 13° 44' 57.9" and E 5° 46' 10.2")

Condensed section

The condensed section has been observed to lie at the boundary between Wurno and Dange formations (Fig. 14). At this boundary, there is a significant facie change with different lithological characteristic (Fig. 13 a, ai aii and aiii). At the base, arealternating gypsiferous sandstone (15 cm) followed by gypsiferous shale (10 cm) with ferruginous concretions. This in turn is overlain by laminated glauconitic shale and above the shale is sandstone with 7 cm phosphate bed fused along with glauconite and fossil bones. The succession is capped by purple laminated gypsiferous shale with ironoxide partings (Fig. 14).This assemblage represents a condensed horizon which is a s*ection of fine-grained sedimentary rocks that accumulated slowly*, and represent physical stratigraphic link between shallow and deep-water sections.

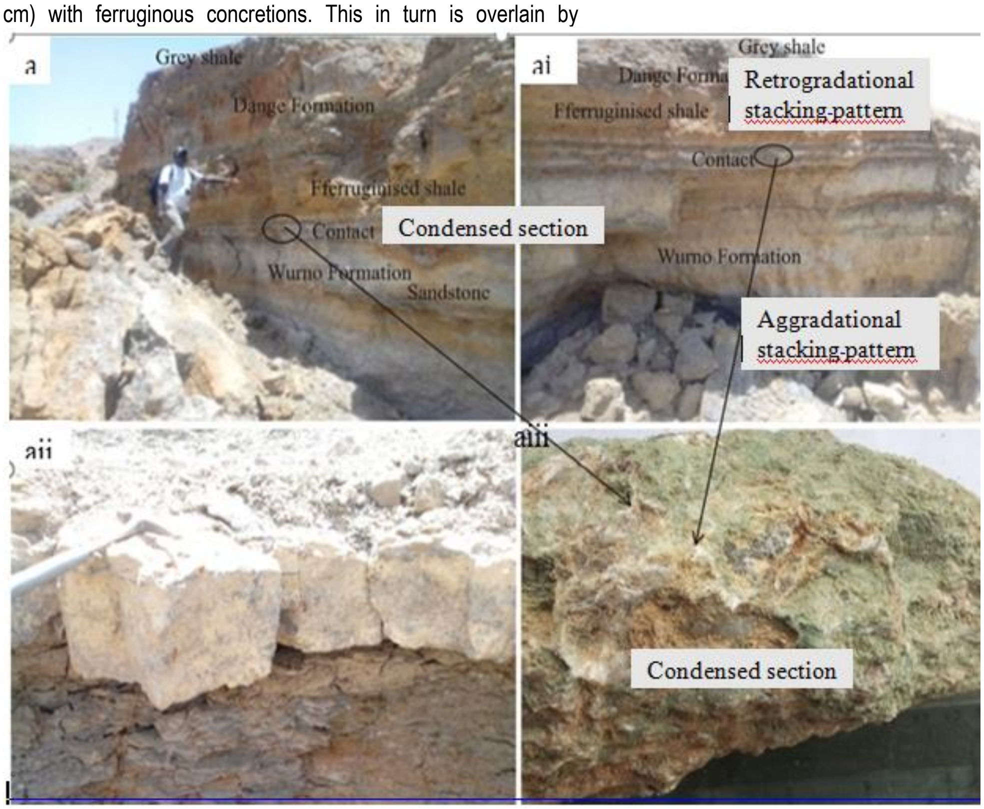

Figure 13: (a) and (ai) photograph showing contact between Wurno and Dange formations (aii) Photograph of brown non fossiliferous limestone with no erosional panel base but shale. (aiii) Hand specimen of the contact exposed behind the filling station near Gada (N 13° 44' 41.1" and E 5° 39' 51.2").

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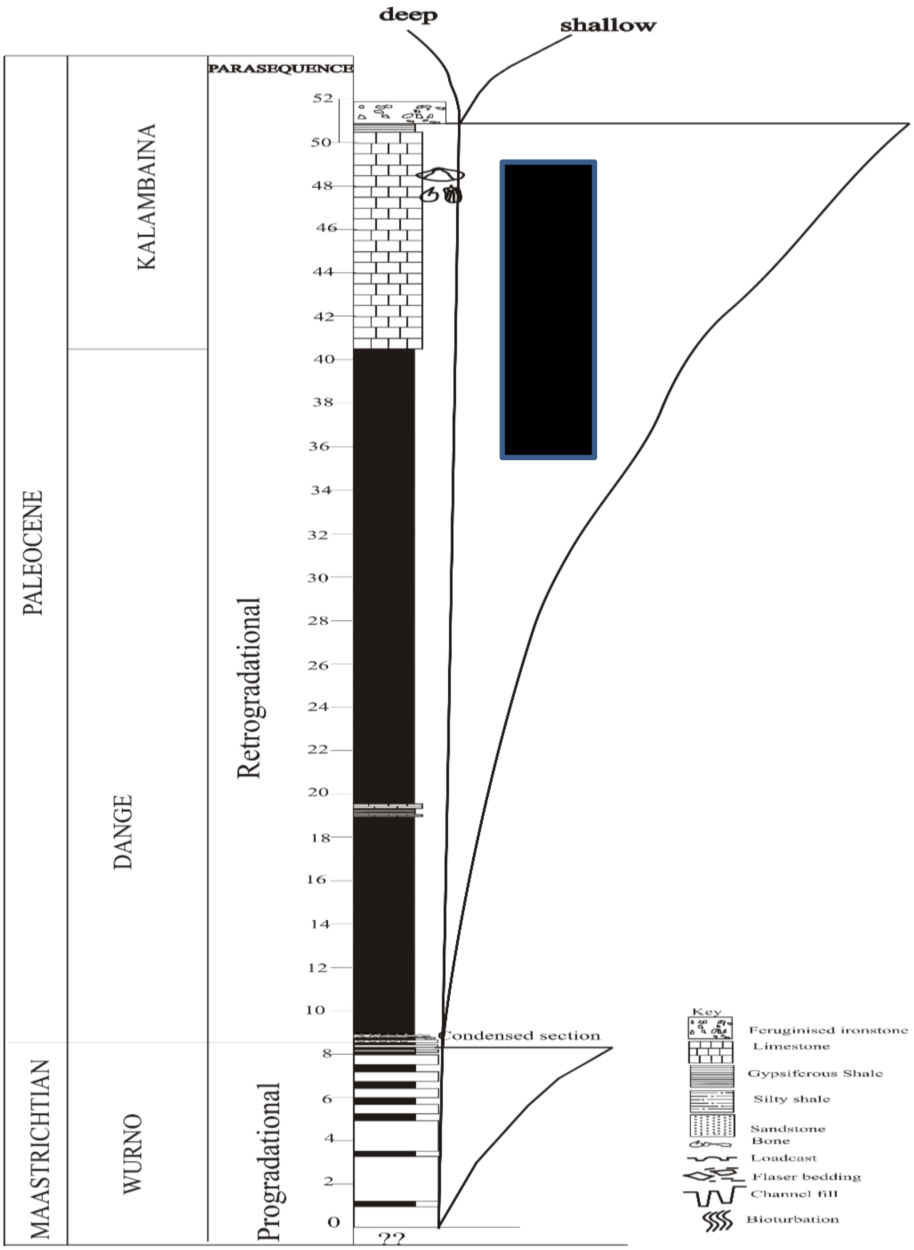

Figure 14: Generalized sequence stratigraphic interpretation of Wurno, Dange and Kalambaina formations exposed on a hill near Gada village displaying the parasequence and condensed section at the boundary between Wurno and Dange formations (N 13° 44' 41.1" and E 5° 39' 51.2").

Conclusion

Our study shows that the sediment of the Taloka and Wurno formations, which consists of sandstone, siltstone, and silty shales, displays aggradational and progradational stacking patterns that belong to the early part of the Highstand system tract.

While Dukamaje, Dange, and Kalambaina formations are composed of fossiliferous shale and limestone, which display a retrogradational stacking pattern thus, belong to the transgressive system tracts.

A condensed section occurring between the Wurno and Dange formations is reported in this study for the very first time. This is a strata surface associated with the maximum flooding surfaces, represented by sedimentary intervals deposited during the maximum marine transgression. It is coincident with marine flooding surfaces and, in particular, maximum flooding surface.

In essence, application of sequence stratigraphic analysis revealed three (3) parasequence types, two (2) system tracts, and one (1) condensed section.

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