STRATIGRAPHY AND SEDIMENTOLOGY OF ENAGI FORMATION, BIDA BASIN, NORTH WESTERN NIGERIA

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Abstract

Detailed facies and architectural element analyses of the sediments of Enagi Siltstone and part of the Jima Member of Bida Formation in the northern part of Bida basin reveal eight (8) lithofacies, five (5) architectural elements and three (3) large scale outcrop facies associations (OFA). The lithofacies include: conglomerate (F1); trough cross bedded sandstone (F2); planar cross bedded sandstone (F3); epsilon cross bedded sandstone (F4); tabular bedded sandstone (F5); heterolithic mudstones and siltstones (F6); erosive based siltstone (F7); and mudstone (F8) lithofacies. The identified architectural elements are: downstream macroforms (DA) recording downstream accretion within channels; sandy bedload macroforms (SB) suggesting gradual infilling of channels by normal regime bedflow sedimentation; lateral accretion macroforms (LA) suggesting deposition by high sinuosity channels; overbank element (OF) recording sedimentation outsides the confines of channels; and channel element (CH). The large scale outcrop facies associations (OFA) include: 1) OFA1, sand dominated with sands to mud interval ratio of approximately 70:30; 2) OFA2, 60:40 sand to mud/silt ratio; and 3) OFA3, mudstone/siltstone dominated. This study suggests the elevation of Enagi Siltstone to Enagi Formation status based on the heterogeneous nature of the sediment. Four reference sections were recommended to illustrate the typical features of the Enagi Formation.

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1. Introduction

Enagi Siltstone is one of the major lithostratigraphic units of the sedimentary fill of Bida basin which is a NW-SE trending inland basin in Nigeria (Fig. 1). The unit was first described and named Enagi Siltstone by Adeleye and Dessauvagies (1972). They described the unit as consisting mainly of siltstones with subsidiary sandstone and mudstone intervals; fossil leaf impressions and rootlets were also observed. They also correlated it with the Patti Formation in the southern part of the basin around Lokoja (Fig. 2). Even though the Patti Formation has been well studied (e.g. Ojo and Akande, 2006; Ojo and Akande, 2009), the Enagi Siltstone is yet to be studied in detail after the pioneering work. More recently Ojo (2012) studied some sections thought to belong to "Enagi Formation" around Abgona ridge located near Share and Shonga areas in Kwara state, Nigeria and interpreted them as transgressive shallow marine sediments that were intermittently influenced by fluvial events. This area however does not cover up to 10% of the Northern Bida Basin and so cannot be representative.

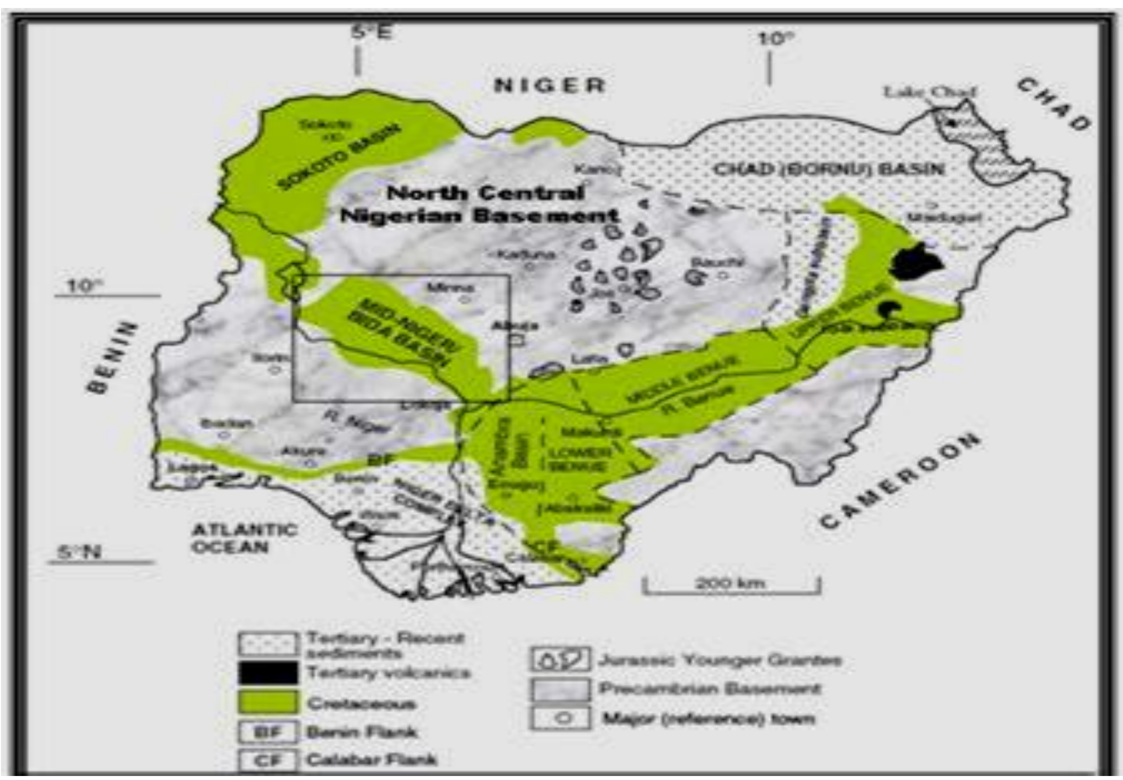


Figure 1: Simplified geological map of Nigeria showing the major geological components and location of Bida basin. (Modified from Obaje, 2009)

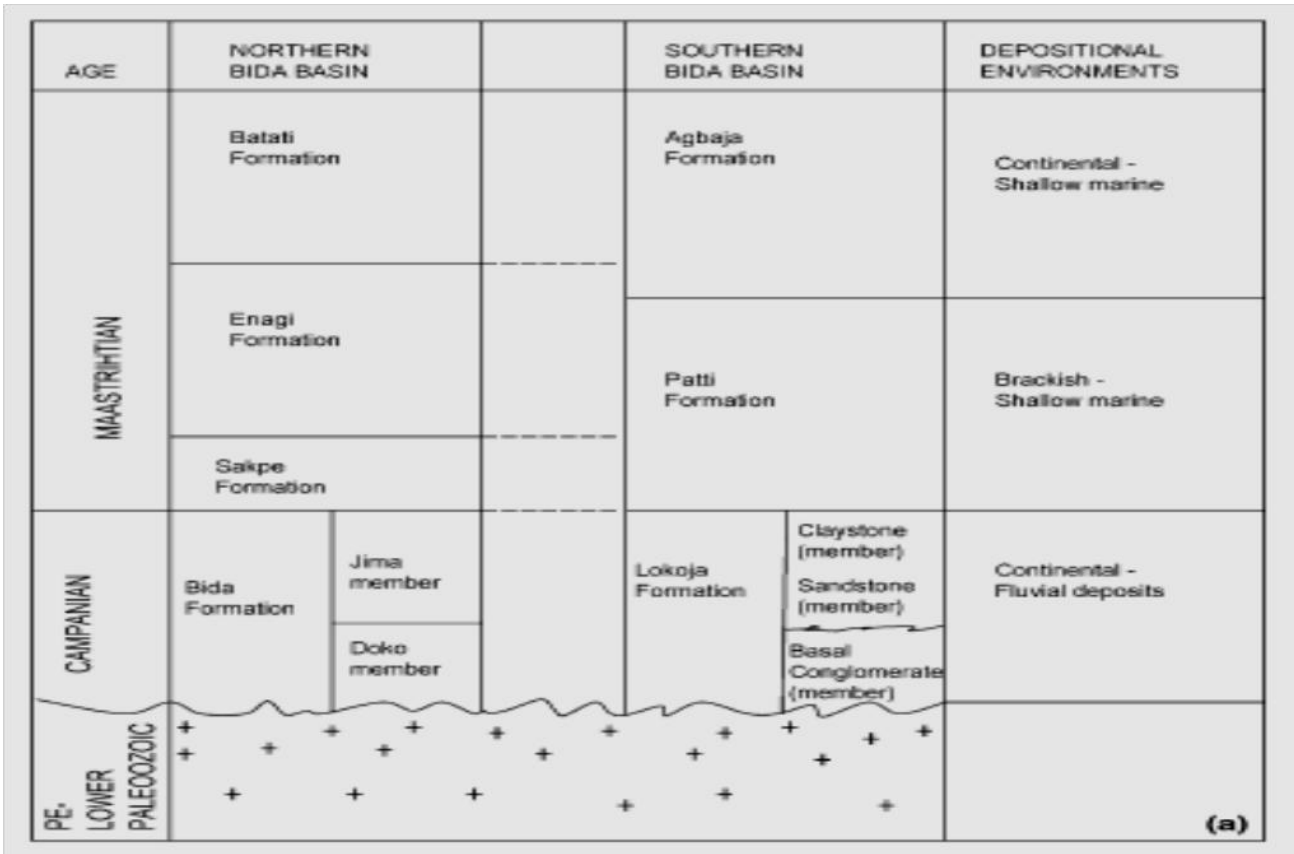


Figure 2: Generalised stratigraphic sub-divisions in the Northern and Southern Bida Basin (from Akande et al, 2005)

Braide (1992) considered the whole stratigraphic succession of northern part of Bida basin as product of continuous sedimentation from alluvial fans at the base through braided and meandering river deposits to lacustrine environment in a continental setting. He argued that the sedimentation was controlled by wrench-fault tectonics. Though the study was based solely on analysis of surface lithostratigraphic sections, he attempted sub-dividing the entire basin into three segments without clearly delineating the bounding faults. Okosun et al. (2009) informed by the map of Bida basin by Adeleye (1974), lumped the Bida Formation and Enagi Siltstones as one unit with interpretations similar to that of Braide (1992).

It has also been observed that more recent researchers based on the understanding that Enagi Siltstone and Patti Formation are lateral equivalents refer to Enagi Siltstone as “Enagi Formation” without property documenting evidences why Enagi Siltstone of Adeleye and Dessauvagies (1972) should now be called “Enagi Formation”.

These observations have led to confusion in nomenclature and use of stratigraphic names based on assumptions. The fact that no regional work covering the entire basin (north and south) has been undertaken recently has compounded issues concerning the understanding of the sedimentology and stratigraphy of the basin.

In order to address some of the issues raised above, the present work was undertaken to document the architecture and stratigraphy of Enagi Siltstone sediments as well as those units thought to be part of it in the northern part of the basin and compare it with the better studied southern part of the basin for better understanding of the regional context of the basin. The objectives are to:

- Identify lithofacies as well as their bounding surfaces based on detailed outcrop studies
- Document results of sieve and thin section analysis of the sediments
- Organise the lithofacies and their bounding surfaces into architectural elements based on Mial (1985; 1996)
- Organise the units into large scale outcrop facies associations (OFA)
- Compare the studied interval with the laterally equivalent units in the southern part of the basin
- Produce a modified stratigraphic column for the sediments
- Provide hypostratotypes for the Enagi Formation

Architectural studies of ancient sedimentary deposits provide three-dimensional information about sedimentary packages (Mial 1985; 1996). Interpretations of depositional environment are therefore better constrained using this method than traditional vertical lithological analysis (Mial, 1996). Due to unavailability of sub-surface data (deep wells and seismic), a good understanding of the architecture and stratigraphy of the various sedimentary units of the basin is key to mapping of possible petroleum system(s) as well as exploration for solid minerals and water resources in the basin.

2. Methodology

This study was based mainly on field and laboratory analysis. The units thought to belong to Enagi Siltstones were examined in the field using detailed outcrop analysis covering parts of the northern portion of Bida basin where exposures are fair to good. The field outcrop study was at regional scale; as a result, it was divided into three routes for convenience. The first traverse included mapping of exposed parts of Enagi Formation in areas around Batati, Enagi and Mokwa (Fig. 3; L5, L6 and L7) respectively, where at least five graphic logs covering the lower, middle and upper parts of the formation were constructed. The second traverse concerned the mapping of areas around Kandi, Doko, Patti-Shaba Kolo and Doko-Jima Junction and (Fig 3; L1, L2, L3 and L4) localities in the southern part of the study area. Four graphic logs summarising the observed features of Enagi Formation in these areas have been produced. The uppermost part of the formation was assessed in Patti-Shaba Kolo and Kandi localities while the lowermost boundary was inferred in Doko locality. Fieldwork for the third traverse covering the northern part of the study area was also carried out in areas around Zungeru, Kawo, Manigi 1 and Manigi 2 (Fig. 3. L11, L8, L9 and L10).

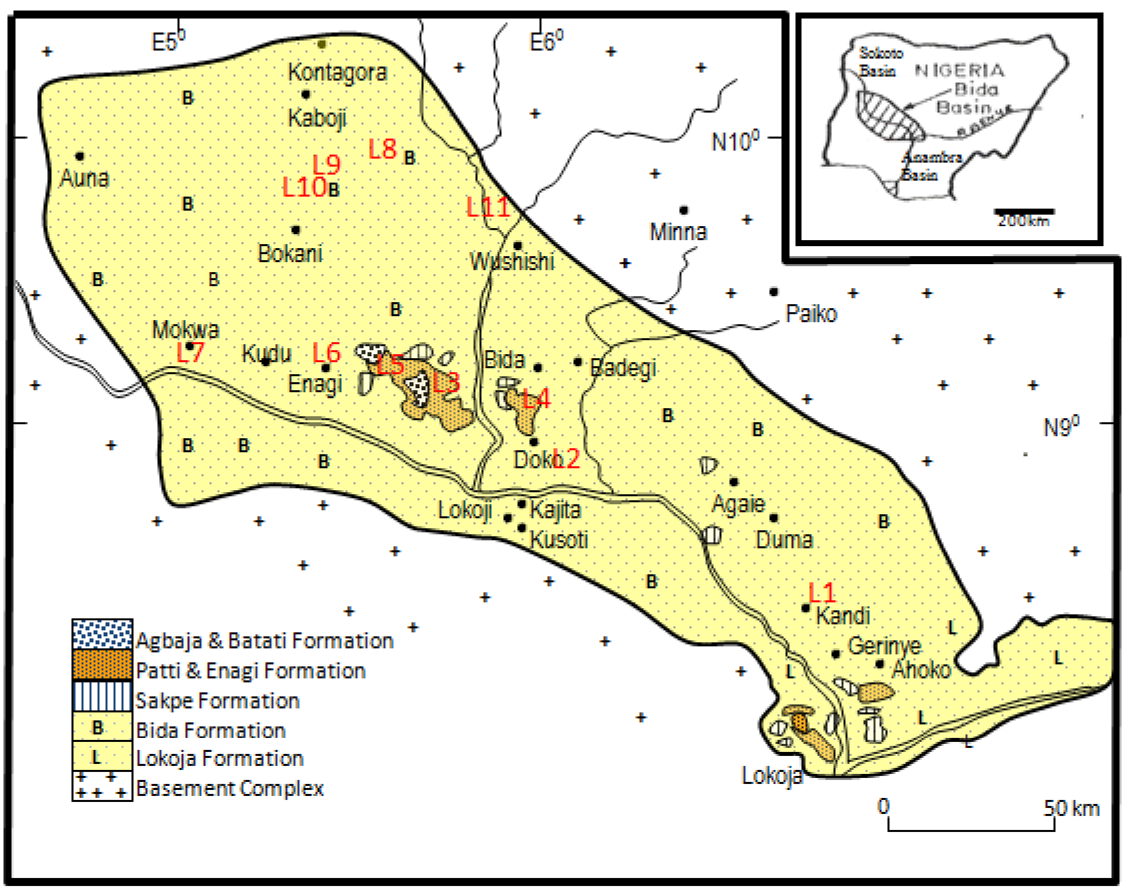


Figure 3: Simplified Geological Map of Bida Basin (Modified from Adeleye, 1976) Showing Locations of Studied Outcrops. Note: 1=Kandi 2=Doko 3=Patti Shaba Kolo 4=Doko-Jima Junction 5=Batati 6=Enagi 7=Rabba 8=Kawo 9=Manigi1 10=Manigi2 11=Zungeru.

A three level examination procedure was followed during the fieldwork as follows:

1. Identification of lithofacies based on examination of bedding, grain size, texture and sedimentary structures and trace fossil content.

2. Recognition of architectural elements based on identification of distinct assemblages of lithofacies, internal geometry and external form (Mial, 1985, 1996).

3. Grouping of the studied interval into large scale units "outcrop facies associations (OFA)" based on the dominant facies as well as architectural elements and stratigraphic level.

The laboratory analyses involved sieve and thin section analyses. Standard procedures were followed in obtaining grain size distribution of selected representative samples (56 in number). The grain size data were plotted bivariate diagrams in order to further discriminate the various identified lithofacies and to serve as aid to depositional environment interpretation. Seventy seven (77) representative rock samples were selected and impregnated with araldite to make them workable for thin section making due to their friable nature. Petrographic analysis was carried out with the aid of a research petrographic microscope using transmitted light and having a digital camera attached to it. Due to the weathered nature of the outcrop samples, binding cements and other diagenetic aspects were not studied but the grain size; grain shape and level of compaction in the sediments were accessed.

3. Results and interpretations

3.1 Facies and facies distribution

Eight lithofacies have been identified in the field as follows: conglomerate facies (F1); trough cross bedded sandstone facies (F2); planar cross bedded sandstone facies (F3); epsilon cross bedded sandstone facies (F4); tabular bedded sandstone facies (F5); heterolithic mudstones-siltstone-sandstone facies (F6); erosive based siltstone facies (F7); and mudstone facies (F8) lithofacies. Presented below are summaries of the main features and distribution of the lithofacies. Appendix I present graphic logs showing the distribution of the lithofacies in some of the studied localities.

3.1.1 Conglomerate Facies (F1)

This facies consists of poorly sorted, clast-supported pebbly, coarse to very coarse grained conglomeratic sandstones. They are a few centimetres to 0.5 m thick and occur above sharp, sometimes undulating surfaces. The pebbly types are confined to the lower and middle part of the studied interval. Sub-rounded to well rounded small to medium pebble sized clasts are abundant in the lower part of the formation (Fig. 4A - B) and they are set in matrix of coarse to very coarse grained sandstones. The sub-rounded to well rounded pebbles are absent towards the middle part of the formation, here only the gravel and very coarse particle sizes are present (Fig. 4C-F). In some units, this facies is composed of matrix supported rip-up clast conglomerates. The sediments are usually conformably overlain by the sediments of F2, F3 or F4 as in Figures 5, 6 and7. These sediments overlie 3rd, 4th and 5th order surfaces throughout the studied interval.

Figure 4: Pictures of conglomerate lithofacies (F1) showing: [A] high spericity, subrounded pebble clasts within F1, Rabba [B] pebble clast conglomerates of F1 with mud rip-up clasts, Enagi; [C & D] mud rip up clast rich conglomerates, with matrix of medium to very coarse sand, Enagi; [E] gravelly conglomerate unit with matrix of medium to cosra sand in the middle part, Kawo; [F] mud rip up clast rich unit with matrix of fine sand in the upper part.

3.1.2 Trough cross bedded sandstone facies (F2)

It consists of medium to very coarse grained trough cross bedded sandstones. This facies is the most abundant facies in the lower parts of the interval. They also occur in association with F3 and F4 in the sandy parts of the middle and upper parts of the formation. It makes up the bulk of the sediments exposed in Rabba and Enagi sections and the lower part of Kutigi and Doko sections. They are often sparsely bioturbated, but some units show moderate to intense bioturbation as indicated by the mottled character (Fig 5C, D, G). Colour mottles include brown, reddish-brown, orange, purple, and light grey. Well preserved ?*Palaeophycus* ichnofossils (Fig. 5C) were observed in Rabba section and *?Ophiomorpha* (Fig. 5D) *as well as ?Thalassinoides* (Fig. 5G) were identified in the lower part of the studied interval (e.g. Enagi section). The sediments transitionally overlie F1 sediments and are usually overlain by the sediments of F3, F4, F5 or F6.

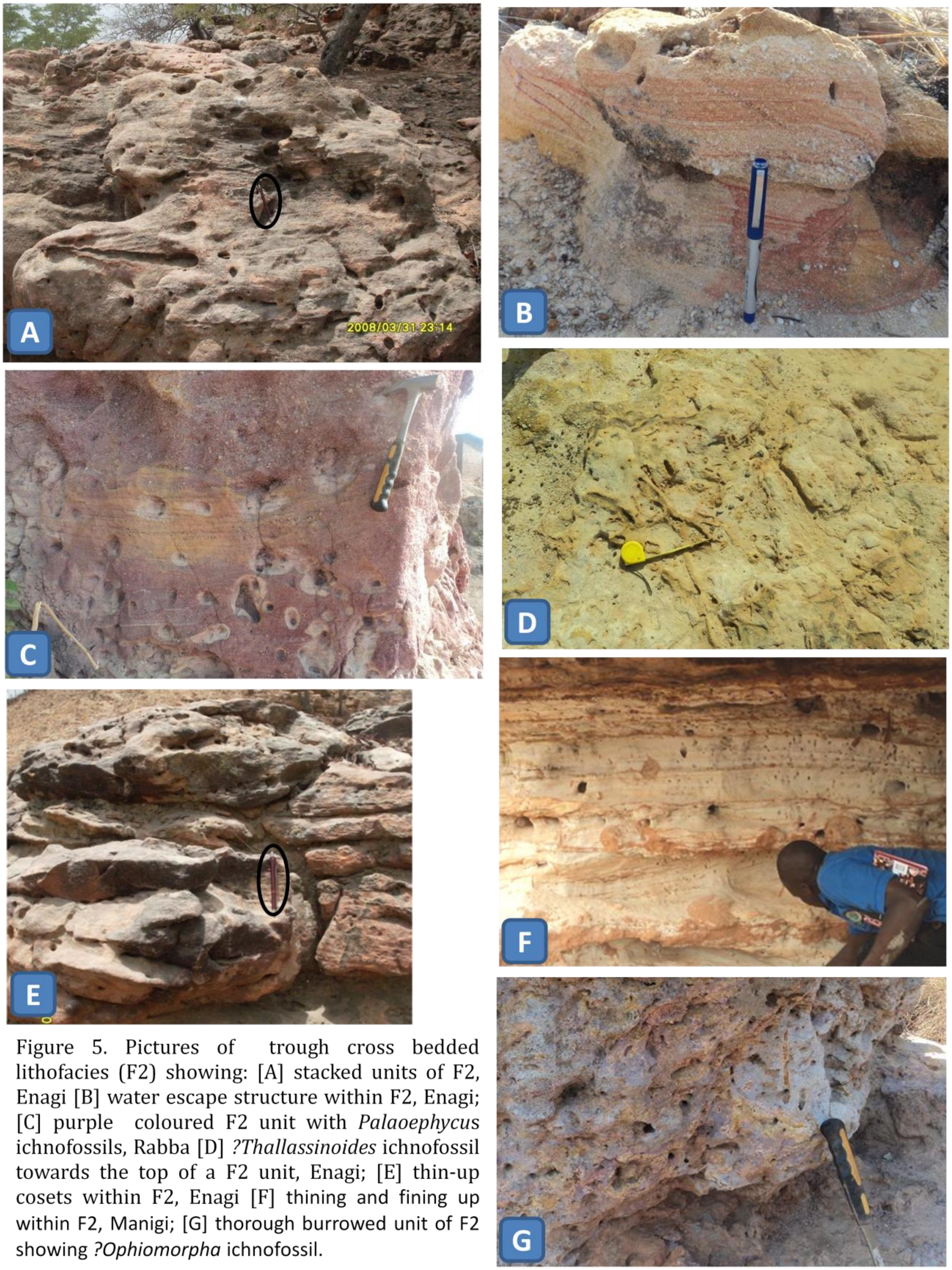


Figure 5. Pictures of trough cross bedded lithofacies (F2) showing: [A] stacked units of F2, Enagi [B] water escape structure within F2, Enagi; [C] purple coloured F2 unit with *Palaoephycus* ichnofossils, Rabba [D] *?Thallassinoides* ichnofossil towards the top of a F2 unit, Enagi; [E] thin-up cosets within F2, Enagi [F] thining and fining up within F2, Manigi; [G] thorough burrowed unit of F2 showing *?Ophiomorpha* ichnofossil.

3.1.3 Planar cross bedded sandstone facies (F3)

This facies consists of medium to thick beds of tabular cross bedded fine to medium grained sandstones (Fig. 6A). Coarse grained types are locally present especially at the lower part of the formation. This facies are more abundant at the middle part of the formation where they occur as large scale planar cross bedded units (up to 2 m) (e.g. Doko, Jima and Kutigi areas). They overlie the F1 sediments and are overlain by the F5, F6 or F8. Abundant mud streaks may be found along foreset laminae of some units especially towards the upper of the formation. Locally abundant, sporadically distributed *?Ophiomorpha* ichnogenera are observed in some units.

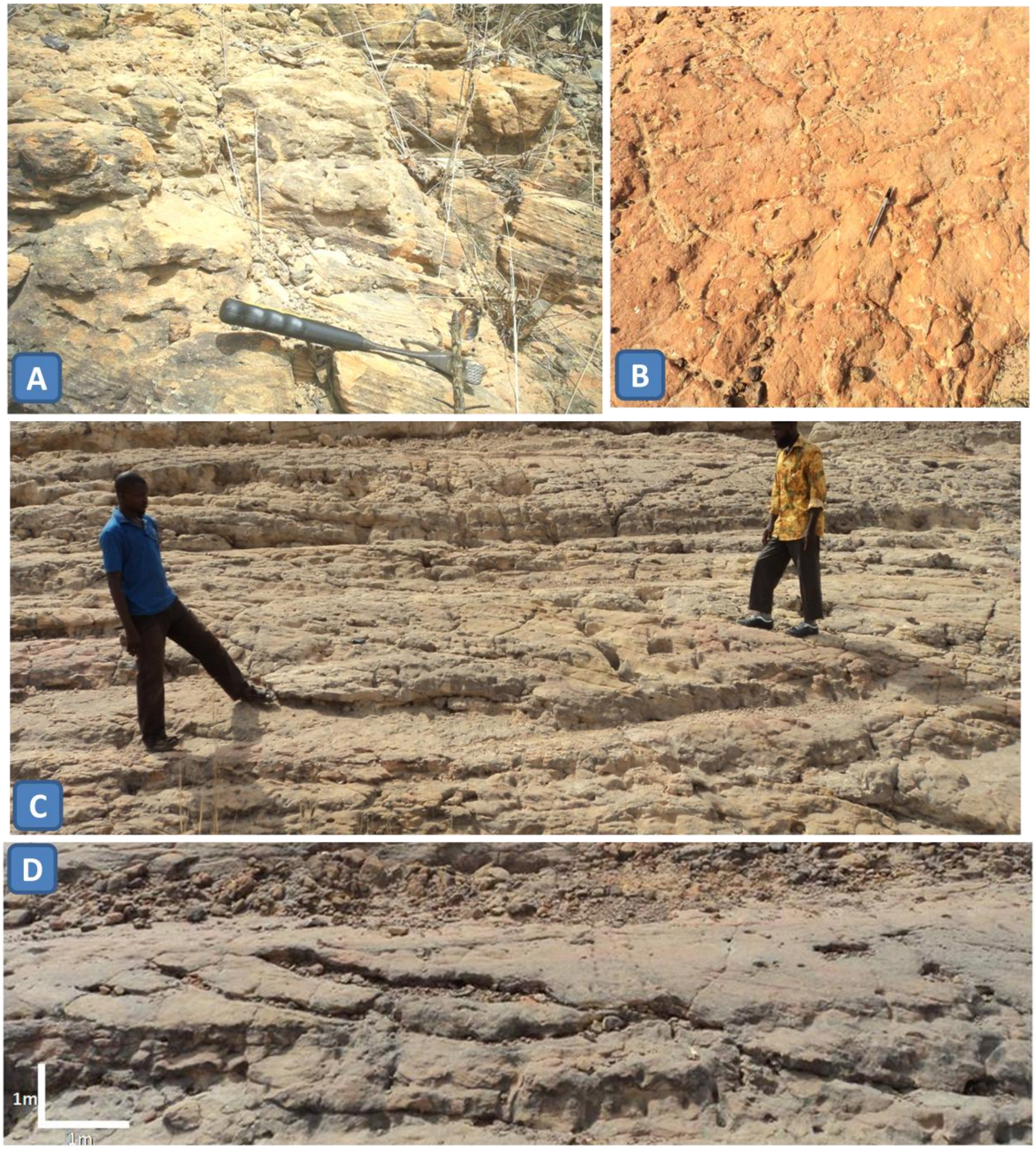


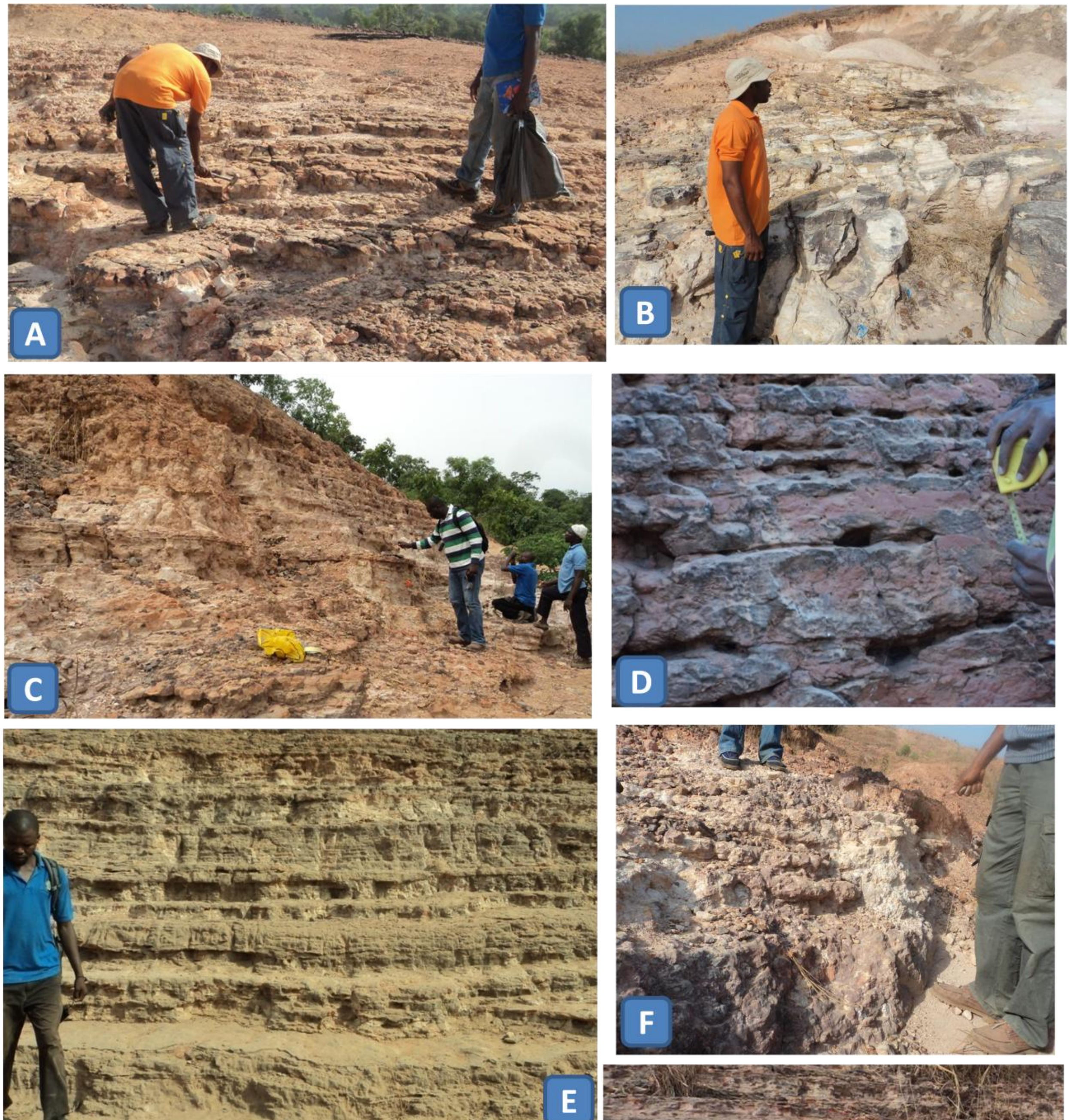
Figure 6. Pictures of Tabular cross bedded sandstone facies (F3) and Epsilon cross bedded sandstone facies (F4) showing: [A] thining up sets of tabular cross bedded sandstones, Doko [B] locally bioturbated unit corresponding to upper finer parts of F3 unit, Doko [C] epsilon cross bedded sandstone unit, the two geologists are standing on two large scale lateral accretion surfaces (LA), Kawo; [D] mud drapes on lateral accretion surfaces, Kawo;[E] localised bioturbated unit within F4.

3.1.4 Epsilon cross-bedded sandstone facies (F4)

This facies consists of epsilon cross bedded fine to coarse grained (Fig. 6C) sandstones. They are associated with trough cross beds (F2). Sedimentary structures include fining up grain size profile, alternation of very fine to fine sands and silt to clay lamina, ripple lamination towards their upper parts as well as lateral accretion surfaces (Fig. 6C, D). The epsilon cross bedding may be up to 3 m thick and the LAs sometimes run from the top to the base of the sandstone unit. Small scale fining-up of grain size was also observed within sediments that occur between the LA surfaces. Some of the LA surfaces are mud draped (Fig. 6C). Sporadic moderate to intensely bioturbated units are present (e.g. Fig. 6E)

3.1.5 Tabular bedded fine grained sandstone facies (F5)

It consists of thin, tabular beds of very fine to fine and sometimes medium grained micaceous sandstones (Fig. 7A-B). Sedimentary structures include: ripple lamination, horizontal lamination, mud streaks on foreset laminae, tabular bedding and large elliptical nodules (up to 1 m in diameter). They have sharp or gradational bases and the upper boundary may be sharp or gradational depending on the succeeding lithofacies. They are rare in the lower part of the formation but abundant in the middle and upper portion of the formation. They are well exposed in Doko, Jima, Kutigi and Kawo areas. This facies overlie the F2, F3 or F4 facies. They are usually overlain by mudstones/siltstones of F8 facies and sometimes F6 or F7. They often display colour mottling as well as fining and thinning up profile (e.g Kutigi, Manigi; Fig. 7A-C).



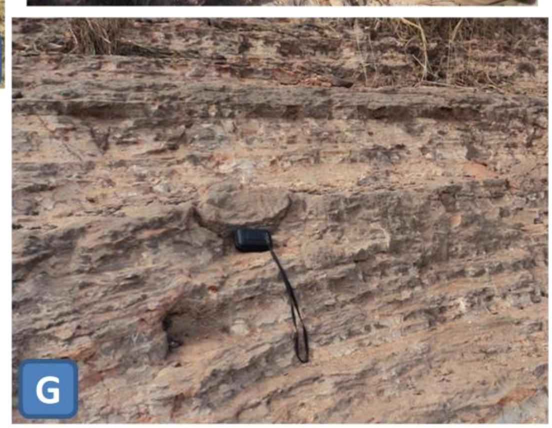


Figure 7. Pictures of tabular bedded siltstone lithofacies (F5), Heterolithic mudstone and siltstone lithofacies (F6) showing: [A] F5 unit, Kutigi [B] F5 unit transiting upward to F8 unit, Kutigi ; [C] F5 unit, Manigi [D] close-up view showing wavy ripples within F6 unit, Patti Shaba-Kolo [E] laterally extensive F6 unit, Manigi; [F] F6 unit, Doko; [G] elliptical concretion within F6

3.1.6 Heterolithic mudstone - siltstone - sandstone facies (F6)

The sedimentary units belonging to this facies are mainly mudstones and siltstones with subordinate very fine to fine grained sandstone beds (Fig. 7). They occur as thin laterally extensive interbedded tabular beds (7-25 cm or 40 - >100cm) of mudstones, siltstones, very fine grained sandstones and sometimes fine grained sandstones (Fig 7). Internally, the beds are either parallel laminated (Fig. 7C) or massive and mottled (Fig 7D). Wave ripples are seen at the top of some siltstone beds (Fig. 7E). On outcrops, the sandstone units and to some extent, siltstones beds form ridges while the mudstone beds are seen as recess formers due to their vulnerability to erosion. This facies is also characterised by concretions that occur at certain intervals and can be traced for several hundred meters laterally (Fig. 7F). The concretions are mostly siltstones that are ferruginized and assume mainly circular to elliptical shapes, although some are irregular in shape. They are differentiated from F5 mainly by laterally extensive sheet-like nature. They are more abundant in the upper part of the studied interval

3.1.7 Erosive-based mudstone - siltstone facies (F7)

This facies consists mainly of siltstones/mudstones. They predominate at the upper part of the formation. These sediments are usually interbedded with the mudstones of lithofacies F8 (Fig. 8A, F). They have sharp, planar or concave-up lower boundaries upon which flat mud pebble lags that are grain diameter thick may be present. Internally they may display fining upwards grain size trend or may be homogeneous. The lower boundary pinches out within a few meters laterally (e.g. Patti-Shaba Kolo). Internally the sediments appear massive.

3.1.8 Mudstone facies (F8)

This facies is mainly mudstones and displays light grey to white colours. They are abundant in the middle and upper part of the formation but rare at the lower part. In the lower part, they occur as laterally discontinuous thin to medium beds within stacked Lithofacies F2 units (Fig. 8E)). In the middle part, they are thicker and more laterally extensive. Up to 6 m has been mapped (Fig. 8B) and are found in association with all other facies. These sediments are interbedded with the siltstones and very fine grained sandstones of F7, F6, and F5 (e.g. fig. 8D, F) in the upper portions of the formation. They may be massive (Fig. 7D - G) or organised in to very thin to thin tabular beds (Fig. 8C, D).

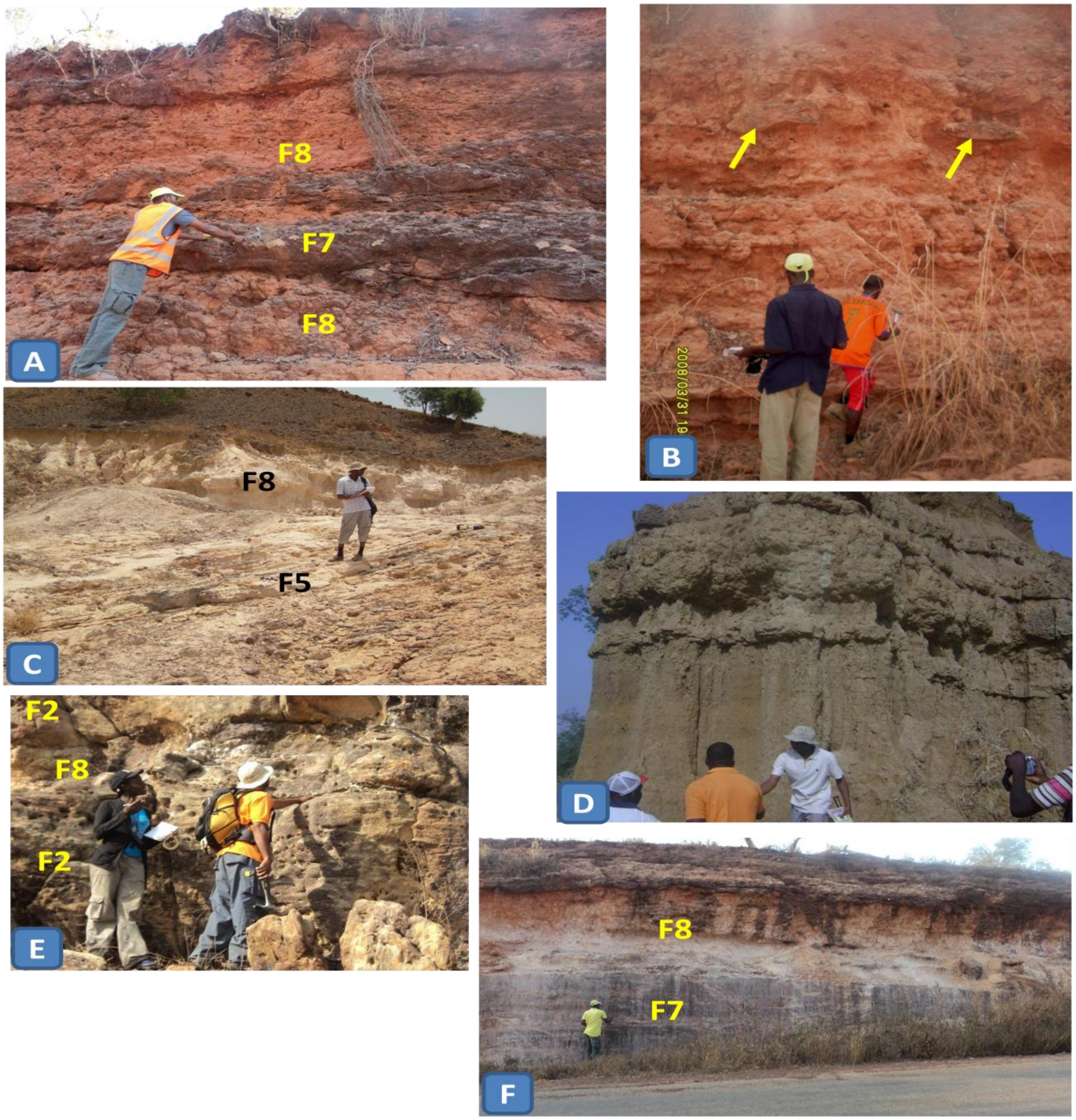


Figure 8: Pictures of erosional based siltstone lithofacies (F7) and mudstone lithofacies (F8) showing: [A] erosionally based siltstone (F7) unit with coarse lag encased within mudstones of F8, Patti Shaba-Kolo; [B] thick unit of F8 with elliptical concretions (arrows), Patti Shaba Kolo; [C] F5 directly overlain by mudstones (F8), Kutigi; [D] laterally extensive mudstone with thin units of silstone and sandstones, Zungeru; [E] F2 inter-beded with F8 (indicated by double headed arrow), Enagi; [F] F7 overlain by F8, Kandi.

3.2 Thin section petrography

As the samples are from outcrops, weathering effects are well pronounced thereby affecting the amount of information that could be generated from them. Most of the grains appear stressed because they are presently undergoing gradual disintegration (which would lead to release of their constituent minerals or grains). Apart from the ferruginised sandstones that show iron rich cements, the cementing materials have not been accessed too. Diagenetic studies were not conducted based on thin section analysis as a result of these difficulties. Nonetheless, grain size and sorting, grains shapes, grain contacts as well as some cement (iron oxide) were observed from representative samples. The grain size observations were found to be in agreement with field and sieve analyses results. Thin section photomicrographs illustrating some of the key features of the identified lithofacies are displayed in figures 9, 10 and 11. The sandstones are mostly grains supported and show floating and point contacts indicative of lack of intense compaction.

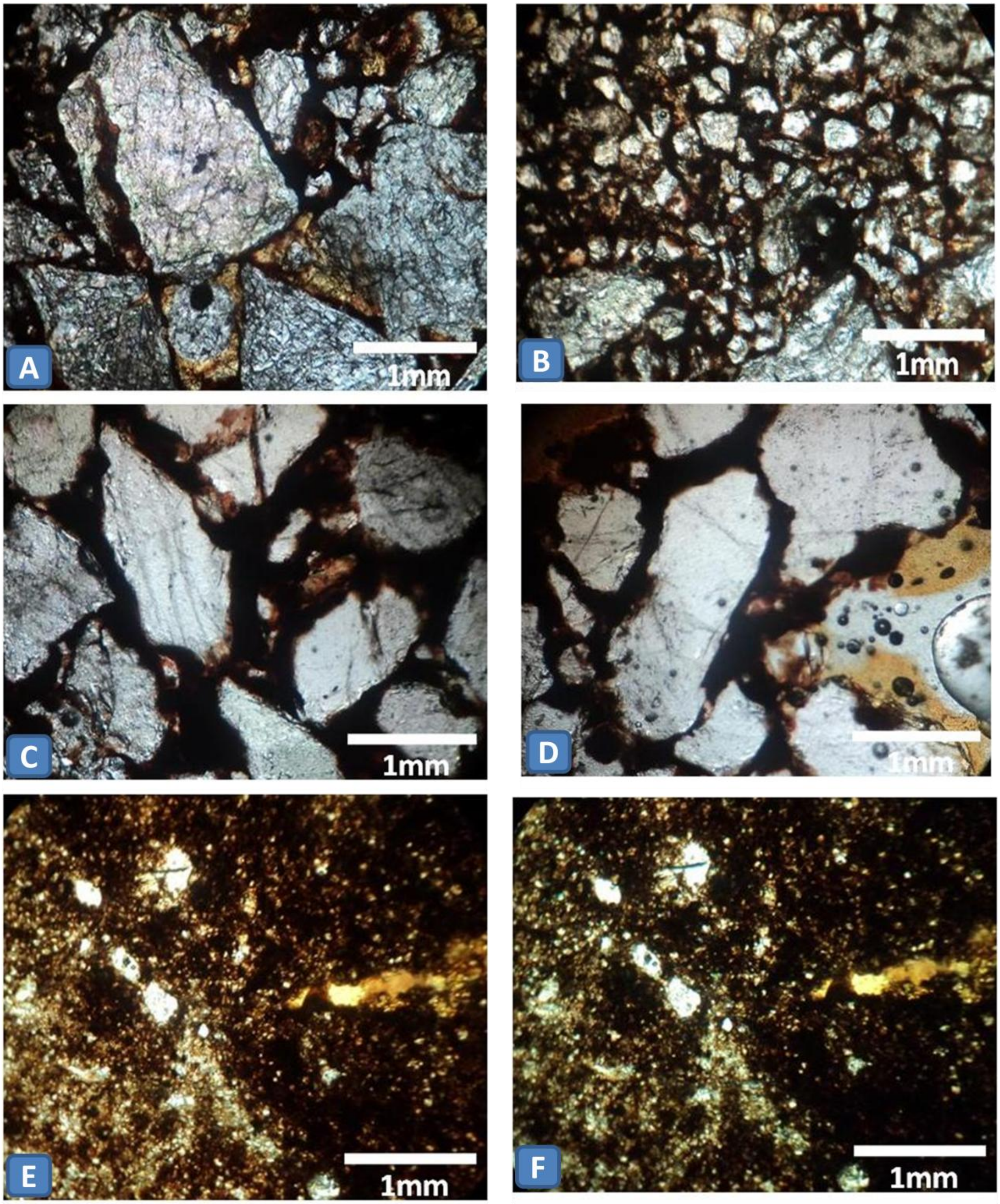


Figure 9: Photomicrographs from lower part of study interval showing: [A] conglomerate lithofacies (F1); [B] sandstone matrix within F1; [C & D] ferruginized examples of trough cross bedded sandstone lithofacies (F2), note: iron cement pre-dates compaction, Kutigi; [E &F] typical mudstone lithofacies (F8) viewed under Ppl and Xpl respectively; from Enagi.

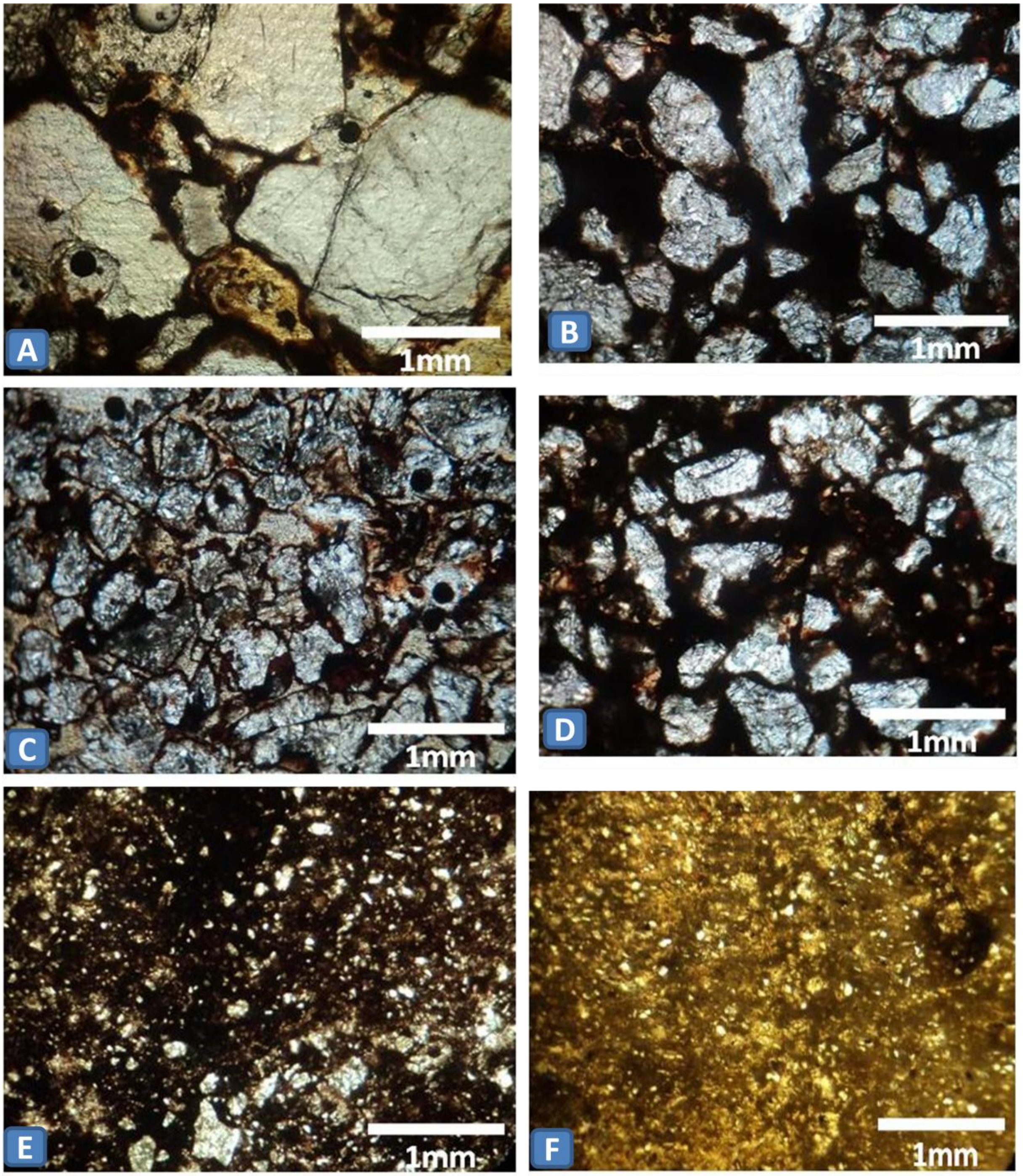


Figure 10: Photomicrographs from middle part of study interval showing: [A] conglomerate lithofacies (F1) kawo; [B] medium to coarse grained sandstone (F4), Kawo; [C] tabular cross bedded sandstone (F3), Doko; [D] fine to medium grained sandstone (F4), Kawo; [E] siltstone (F5), Doko; [F] mudstone lithofacies (F8), Kawo. Note that F3 appera to be relatively more compacted than F4.

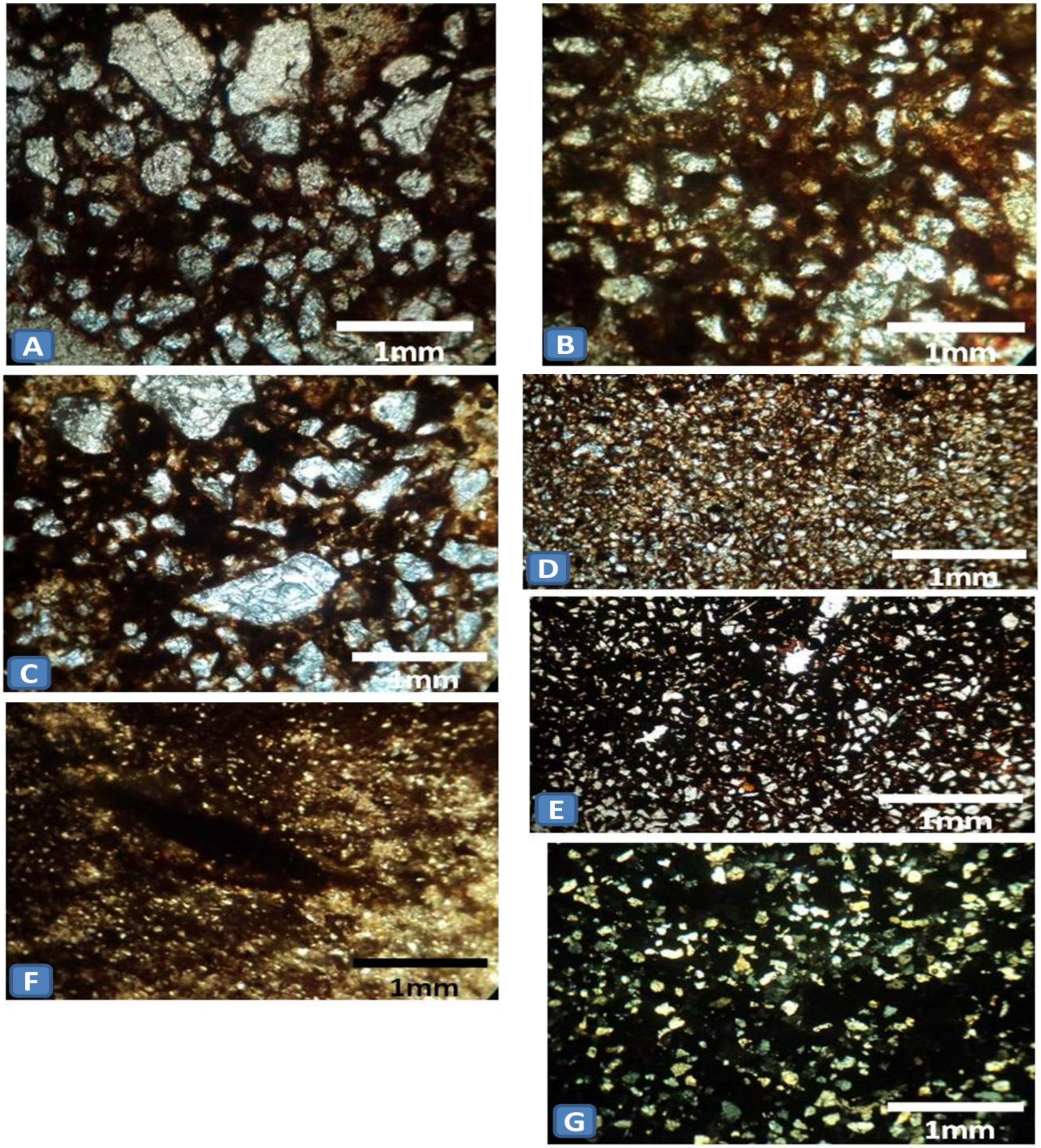


Figure 11: Photomicrographs from upper part of study interval showing: [A] fine to medium grained sandstones (F2), Manigi; [B] fine grained sandstone F3, Manigi; [C, fine grained sandstone (F2) Manigi; [D] siltstone (F8), Batati; [E] sandy silstone (F8) Kandi; [F] bioturbated silty mudstone (F7), kandi;[G], sandy siltstone (F5), Manigi. Note: sediments relatively uncompacted.

3.3 Architectural element analysis

Five architectural elements have been identified including: downstream accretion macroforms (DA element); sandy bed forms (SB element); lateral accretion deposits (LA element); channels (CH element) and overbank fines (OF element).

3.3.1 DA element

This element is identified by the possession of flat 4th order surface at the base, with abundant internal surfaces (3rd order) some of which are overlain by lag deposits. Paleocurrent direction based on trough cross bedding was observed to be generally unidirectional and mostly dip in the same direction as the bounding surfaces. The upper boundary is usually flat or convex-up. The element is dominated by stacked trough and sometimes planar cross bedded medium to very coarse sandstones (F2 and F3). Fining up and reduction in size of cross beds is seen in some units. They have wide spread occurrence in the lower part of the studied interval where they are seen either as 50 cm to 2 m thick individual elements overlain by thin OF element or as vertically stacked (4 - 8 m) thick units overlain by OF element (Fig. 12).

3.3.2 SB element

This element appear as tabular sheets consisting of large scale tabular cross bedded sandstones (F3) and trough cross bedded sandstones (F2) overlain by tabular bedded fine grained sandstones (F5). They internally show upwards decrease in the thickness and size of sedimentary structures as well as fining up grain size profile. They sharply overlie gravel to very coarse grained sediments of conglomerate lithofacies (F1) or directly overlie a basal erosional surface where the F1 lithofacies are not present. They outcrop mostly to the south of the middle part of the studied intervals around Doko, Kutigi, and Jima areas (Fig. 13B). Thicknesses of SB elements range between 45 cm and 4.5 m. The conglomerate lithofacies that commonly underlie them are 10 – 20 cm thick.

3.3.3 LA element

This element is composed of abundant fine to coarse grained, epsilon, planar and trough cross beds of F5, F3, and F2 lithofacies separated laterally by large scale lateral accretion surfaces, with minor amount of gravel (F1) at their bases (Figure 13A). Some units show ripple cross lamination towards their tops. These elements were mapped more or less at the middle part of the formation around the northern tip of the basin. they form the bulk of the sedimentary units at Kawo area.

3.3.4 CH element

The recognition of sloping channel margins was impossible in the lower to middle part of the study interval due to the scale of exposures visited. However, it is possible to map out channel margins and even complete channels near the upper part of the study interval around Kasanga and Kawo areas. The outcrops are located along Kaduna-Tegina-Makera road. These macroforms and are given by F1, F2, F3, and F4 facies organised into SB or LA elements with rare DA elements, and underlain by 5th order (Mial, 1996) flat or convex-up erosional surface. From base to top, the element contains thin conglomerate facies (F1) overlain by LA, SB or DA element with or with our ripples in their upper part. . Locally, sparse moderately bioturbated units are found within the element. The channel elements are either stacked or interbedded with thick OF elements (Fig. 13 C & D). Field relation show that they are stratigraphically either above or at the same level with the SB element dominated outcrops mapped around Doko area.

3.3.5 OF element

This element comprises F5, F6, F7 and F8 facies (Figs. 12, 13 & 14). This element is sparsely distributed in the lower part of the formation. It is found inter-bedded with SB, LA and DA elements in the middle part and dominate the upper part of the studied interval. Where stacked unit of OF occur, they are punctuated by laterally extensive units of concretions or ferruginized thin silty beds. Slump structures were also observed (e.g Batati section).

3.4 Outcrop facies associations

Three types of outcrop facies associations (OFA) have been recognized based on nature of associated elements, stratigraphic position of the elements, and proportion of DA, SB and CH elements to overbank element. They are summarised below

3.4.1 Outcrop facies association (OFA1)

This OFA consists predominantly of conglomerate facies (F1), DA and OF elements. It is however DA element dominated. The average grain size of this OFA1 is coarse to very coarse which exceeds those of OFA2 (medium to coarse) and OFA3 (fine to medium). They form the bulk of the outcrops around Enagi, Rabba and Kutigi areas. When viewed from far, their light grey to whitish colour may be confused with the whitish colour of the siltstones of Enagi Siltstone unit.

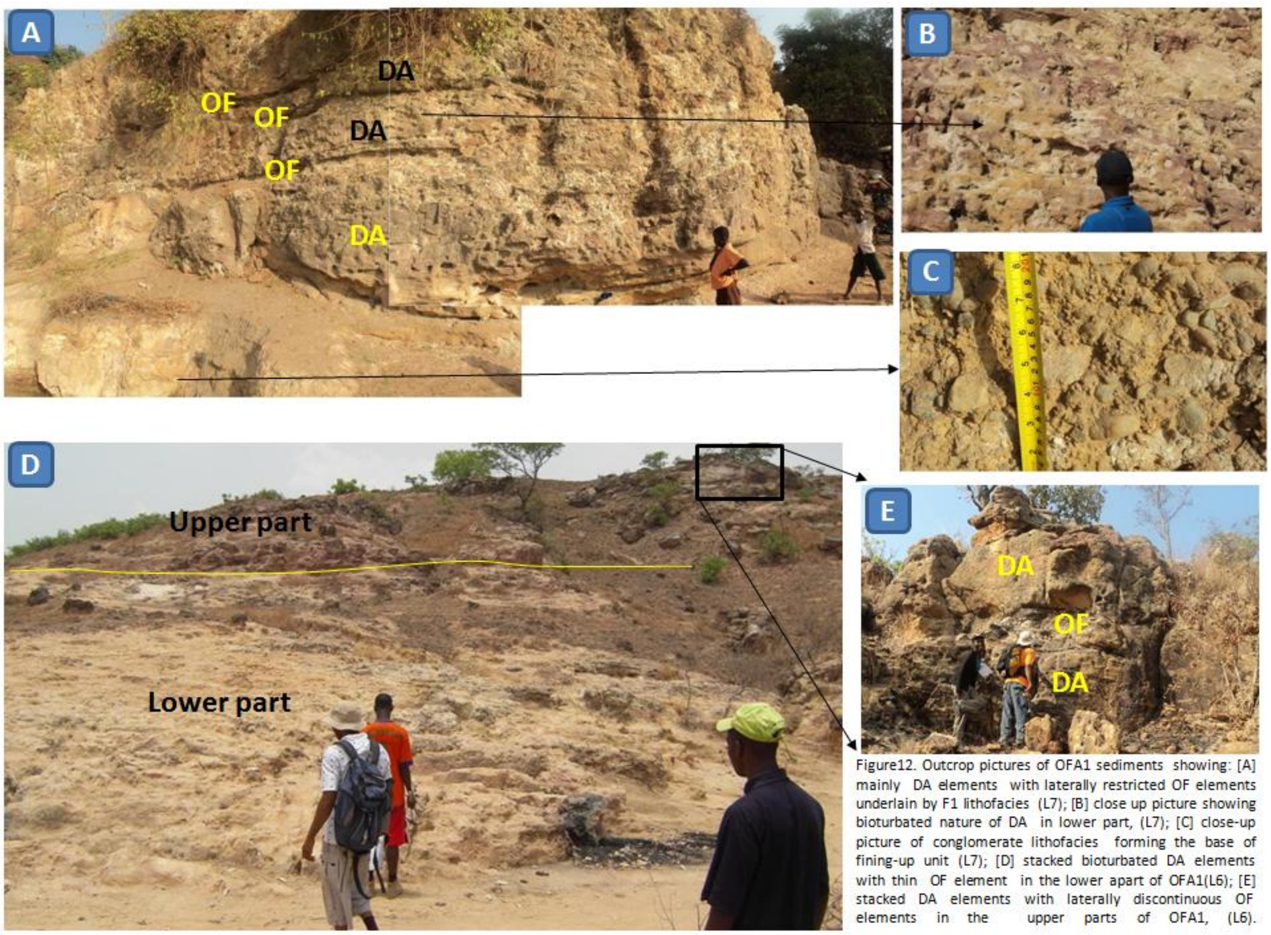


Figure12. Outcrop pictures of OFA1 sediments showing: [A] mainly DA elements with laterally restricted OF elements underlain by F1 lithofacies (L7); [B] close up picture showing bioturbated nature of DA in lower part, (L7); [C] close-up picture of conglomerate lithofacies forming the base of fining-up unit (L7); [D] stacked bioturbated DA elements with thin OF element in the lower apart of OFA1(L6); [E] stacked DA elements with laterally discontinuous OF elements in the upper parts of OFA1, (L6).

They are characterised by abundant downstream accretion elements (DA). The DAs appear as 0.5 m to 2 m individual units or may be stacked to form 4 m to 8 m thick units. The DA elements are also laterally persistent. They are however punctuated by thin laterally restricted 0.3 – 1.2 meters thick OF elements. This association occupy the lower part of the studied interval. The lower boundary has not been accessed in the field but the upper boundary is picked at the point where more than 2 m thick OF as well as SB elements begin.

3.4.2 Outcrop facies association (OFA2)

This facies association consists of interbedded SB/LA and OF elements. It is the dominant OFA in the middle portion of the studied interval. About 80 m has been estimated around Doko-Jima area. The lower boundary appears transitional with the OFA1 association; it is picked at the first appearance of large-scale tabular cross bedded channel sandstones (SB) above which is thick unbioturbated fine grained (OF) mudstones around Doko area. The SB elements associated with this interval are thought to be laterally correlatable to CH and LA elements mapped around the northern tip of the basin based on their stratigraphic position and the nature of the inter-bedded overbank element. The upper boundary has not been assessed in the field.

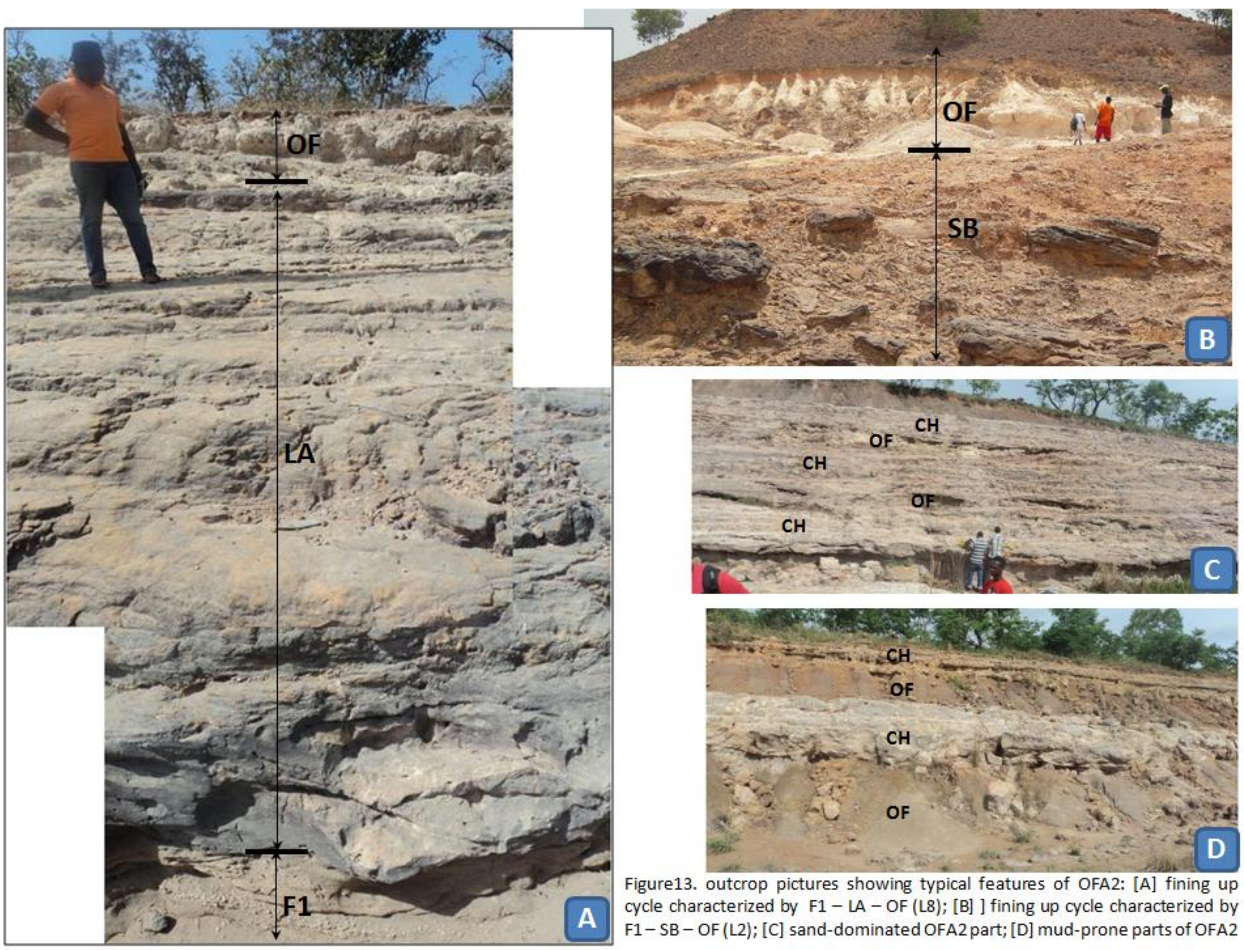


Figure13. outcrop pictures showing typical features of OFA2: [A] fining up cycle characterized by F1 – LA – OF (L8); [B]] fining up cycle characterized by F1 – SB – OF (L2); [C] sand-dominated OFA2 part; [D] mud-prone parts of OFA2

This association is characterised by fining upwards units characterized by CH → OF, F1 → LA → OF in the north or F1 → SB → OF in the southern part of study area. The ratio of sand (CH, LA, and SB) to mudstone (OF) deposits is approximately 60:40 %. In some areas the sand prone elements tend to predominate while in some areas the overbank elements are more significant. The channel elements show both vertical and lateral amalgamation/stacking.

3.4.3 Outcrop facies association (OFA3)

This OFA comprises predominantly OF element with subordinate SB, CH, DA elements and minor amount of conglomerate facies (F1). It is estimated to be more than 100 m thick around Patti Shaba- Kolo. The lower boundary has not been accessed in the field but may be marked by turn around interval where OF element comprises more than 50 % of the sedimentary unit. The upper boundary appears transitional; it is marked by the appearance of prominent ironstone intervals (marks the beginning of Batati Formation). The sandy macroforms are restricted to the

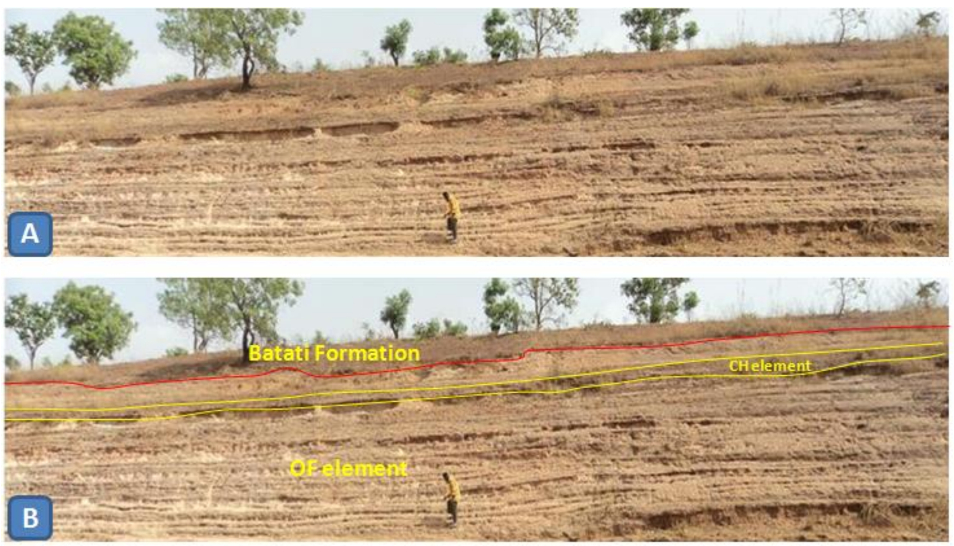


Figure 14. Panoramic views of of OFA3 sediments in the northern and southern parts of the study area showing: [A] Uninterpreted photo illustrating laterally extensive nature, vertically isolated CH within OF elements, upper boundary with the overlying Batati Formation (L10); [B] interpreted picture of [A]; [C] upper boundary Enagi Formation marked by the beginning of ironstone bed at the upper part of OFA3 (L1); [D] close-up view shoing the top of Enagi Formation marked by the first ironstone bed (L1).

lower to intermediate part of this succession while the upper parts are devoid of them; here the only sediments with convex-up lower boundaries are represented by the erosional based siltstone-mudstone (F7) facies. The OF element are laterally extensive with more than 500 m wide units mapped. The CH elements occur as vertically isolated units within the OF. However lateral connection of the element is observed in some places with mud rip up clast interval serving as amalgamation surface.

3.5 Granulometric Analysis

The results of granulometric analyses of fifty (57) representative sandstone samples are summarized in Table 1 below. The mean grain size ranges from fine to very coarse with average grain size of falling within the coarse sand. The sediments are generally poorly sorted with a few displaying moderate sorting. Generally the sediments display positive skew (fine skew) to nearly symmetrical skewness with a few samples showing negative skew (coarse tail).

Table 1. Granulometric analysis results of representative sandstone samples of Enagi Formation sediments, Northern Bida basin, Nigeria.

Sample No	Mean	Sorting	Skewness	Kurtosis
S1	0.39, Coarse sand	0.96, Moderately sorted	0.06, Nearly symmetrical	1.89, Very Leptokurtic
S2	0.50, Coarse sand	1.69, Poorly sorted	-0.03, Nearly symmetrical	1.05, Mesokurtic
S3	0.23, Coarse sand	1.86, Poorly sorted	0.36, Very Positively Skewed	0.78, Platykurtic
S4	0.30, Coarse Sand	1.21, Poorly sorted	-0.09, Nearly Symmetrical	1.93, Very Leptokurtic
S5	0.24, Coarse sand	1.40, Poorly sorted	-0.07, Nearly symmetrical	1.81, Very Leptokurtic
S6	1.77, Medium Sand	1.82, Poorly sorted	0.65, Nearly symmetrical	1.01, Mesokurtic
S7	0.20, Coarse sand	2.03, Very Poorly sorted	0.11, Positively skewed	1.18, Leptokurtic
S8	1.77, Coarse sand	1.21, Poorly sorted	0.10, Positively skewed	1.17, Leptokurtic
S9	0.17, Coarse sand	2.02, Very Poorly sorted	0.30, Positively skewed	0.90, Platykurtic
S10	0.52, Coarse sand	1.81, Poorly sorted	0.04, Nearly symmetrical	1.17, Leptokurtic
S11	0.50, Coarse Sand	1.02, Poorly sorted	1.02, Very Positive Skewed	1.16, Leptokurtic
S12	1.00, Coarse sand	0.90, Moderately sorted	0.90, Positive skewed	1.02, Mesokurtic
S13	0.43, Coarse sand	1.96, Poorly sorted	1.96, Very Positive skewed	1.34, leptokurtic
S14	0.83, Coarse sand	1.58, Poorly sorted	1.58, Very positive skewed	0.99, Mesokurtic
S15	0.83, Coarse sand	1.89, Poorly sorted	1.89, Very Positive skewed	0.98, Mesokurtic
S16	1.05, Medium sand	0.49, Well sorted	-0.25, Negatively skewed	0.78, Platykurtic
S17	0.80, Coarse sand	1.40, Poorly sorted	1.40, Very positively skewed	0.85, Platykurtic
S18	0.38, Coarse sand	1.12, Poorly sorted	3.20, Very Positively skewed	0.58, Very platykurtic
S19	0.70, Coarse sand	1.71, Poorly sorted	-0.01, Very coarsely skewed	0.78, Platykurtic
S20	0.35, Coarse sand	1.38, Poorly sorted	0.11, Positively skewed	0.78, Platykurtic
S21	1.05, Medium sand	1.14, Poorly sorted	0.01, Nearly Symmetrical	0.85, Platykurtic
S22	0.03, Coarse sand	1.00, Poorly sorted	0.13, Positively skewed	0.58, Very Platykurtic
S23	-0.64, Very Coarse sand	1.78, Poorly sorted	-0.16, Nearly Symmetrical	0.51, Very platykurtic
S24	1.06, Medium Sand	0.81, Moderately sorted	-0.01, Nearly Symmetrical	0.84, Platykurtic
S25	-0.03, Very Coarse sand	2.19, Extremely poorly sorted	0.47, Very positively skewed	0.81, Platykurtic
S26	-0.10, Very coarse sand	1.60, Poorly sorted	0.04, Strongly fine skewed	1.02, Mesokurtic
S27	1.16, Medium sand	0.70, Moderately sorted	1.66, Strongly fine skewed	1.12, Leptokurtic
S28	0.90, Coarse sand	1.50, Poorly sorted	0.53, Strongly fine skewed	0.85, Platykurtic
S29	2.32, Fine sand	0.51, Well sorted	0.10, Near symmetrical	0.97, Mesokurtic
S30	1.90, Medium sand	1.28, Poorly sorted	-0.20, Coarse skewed	0.72, Platykurtic
S31	2.03, Fine grained	1.20, Poorly sorted	-0.54, Strongly negative skewed	1.75, Very leptokurtic
S32	1.05, Medium grained	1.12, Poorly sorted	0.26, Positively skewed	2.90, Very leptokurtic
S33	0.20, Coarse grained	1.93, Poorly sorted	0.09, Nearly symmetrical	1.01, Messokurtic
S34	1.00, Coarse grained	1.51, Poorly sorted	0.09, Nearly symmetrical	0.77, Platykurtic
S35	1.73, Medium grained	1.38, Poorly sorted	-0.34, Strongly negative skewed	1.20, Leptokurtic
S36	0.46, Coarse sand	0.70, Moderately well sorted	0.09, Near symmetrical	4.37, Etremely leptokurtic
S37	2.00, Fine sand	1.27, Poorly sorted	-0.23, Negative skewed	0.74, Platykurtic
S38	1.13, Medium sand	1.20, Moderately sorted	0.23, Positive skewed	3.52, Extremely leptokurtic
S39	0.50, Coarse sand	2.26, Very poorly sorted	0.01, Nearly symmetrical	0.81, Platykurtic
S40	0.61, Coarse sand	0.24, Very well sorted	-0.16, Negative skewed	0.99, Mesokurtic
S41	1.85, Medium sand	0.84, Moderately sorted	-0.50, Strongly negative skewed	0.92, Mesokurtic
S42	-0.27, Very coarse sand	0.98, Moderately sorted	-0.20, Positive skewed	2.11, Very leptokurtic
S43	-0.33, Very coarse sand	1.08, Poorly sorted	-0.29, Negative skewed	4.75, Extremely leptokurtic
S44	-0.88, Very coarse sand	0.73, Moderately well sorted	1.65, Strongly positive skewed	0.47, Very platykurtic
S45	1.51, Medium sand	1.09, Poorly sorted	-0.53, Strongly negative skewed	0.95, Mesokurtic
S46	0.63, Coarse sand	1.36, Poorly sorted	0.30, Positive skewed	1.93, Very leptokurtic
S47	2.96, Fine sand	1.15, Poorly sorted	0.43, Very positive skewed	2.05, Very leptokurtic
S48	-0.49, Very coarse sand	2.40, Very poorly sorted	-0.30, Positively skewed	0.58, Very platykurtic
S49	1.22, Medium sand	1.10, Poorly sorted	-0.31, Positively skewed	1.64, Very leptokurtic
S50	0.87, Coarse sand	1.03, Poorly sorted	0.22, Positive skewed	1.38, Leptokurtic
S51	2.85, Fine sand	1.06, Poorly sorted	0.40, Very positive skewed	1.50, Very leptokurtic
S52	1.70, Medium sand	0.90, Moderately sorted	0.33, Strongly positive skewed	1.61, Very leptokurtic
S53	1.68, Medium sand	1.09, Poorly sorted	0.10, Positively skewed	1.02, Mesokurtic
S54	0.70, Coarse sand	2.34, Very poorly sorted	0.19, Positively skewed	1.13, Leptokurtic
S55	1.20, Medium sand	2.45, Very poorly sorted	0.15, Positively skewed	0.81, Platykurtic
S56	0.90, Coarse sand	1.38, Poorly sorted	0.21, Positively skewed	1.06, Mesokurtic
S57	1.57, Medium sand	2.19, Very poorly sorted	-0.08, Nearly symmetrical	0.65, Very platykurtic

3.6 Interpretation

Lines of evidence underpinning the interpretation of the CH sediments as channelized deposits are the presence of sedimentary structures such as erosional base mantled with mud rip-up clasts conglomerates (F1), fining upward of grain size, progressive upwards decrease in size of cross bed sets and unidirectional paleoflow trend within the DA, SB and LA elements. Cross bedding record migration of subaqueous 2D and 3D dunes.

The dominance of DA elements within the OFA1 suggests the presence of complex bar deposits; which when considered together with dipping of bounding surfaces along paleocurrent direction records downstream accretion within channels (Mial, 1996). This scenario is typical of multiple-channel rivers even though may be found in a variety of fluvial styles (Mial, 1996).

The basal concave-up 5th order surfaces (Mial, 1996) that characterise the LA element dominated (CH3) part of OFA2 records channel basal scour surface. The F1 give evidence for deposition of coarse material at channel floor while the lateral accretion surfaces record successive increments in the lateral growth of the channel and the trough cross beds represent migration of subaqueous dunes and the planar cross beds record migration of 2D dunes (e.g. Mial, 1985; Collinson, 1996; Tucker, 2003; Boggs, 2005). The identification of LA elements suggests deposition by high sinuosity channels (Mial, 1996; Collinson, 1996). The SB dominated part of OFA2 on the other hand indicates that the channels in this part were created by gradual increments of the SB element which are products of normal regime bedflow sedimentation.

Within the OFA3 association, the presence of reactivation surfaces and mud drapes on foresets of cross beds may indicate tidal effects on the channels (e.g. Reineck and Singh, 1982). Changes in river stages and fluctuating energies are responsible for the formation of these structures (Tucker, 2003). Formation of sand balls are related to sediment gravity loading of more competent intervals in the midst of less competent ones at upper reaches of channels units where energies are lesser allowing heteroliths to develop. The amalgamation surface that merges the SB units together laterally may represent a large reactivation surface or marks the outline of another channel.

The sediments of OF (F5, F6, and F7) show the usual characteristics of overbank architectural element (Mial, 1985; 1988, 2006). The interbedded thin tabular siltstones and mudstones occurring close to the top of the sandy macroforms may be interpreted as levee deposits while the laterally extensive interbedded mudstones and siltstones with wave ripples can be interpreted as lacustrine deposits (e.g. Nadon, 1994). The mottled, massive mudstone intervals are assumed to be marsh deposits (e.g. Smith, 1983). The erosive based mudstone-siltstone units are interpreted as abandoned channel deposits based on the geometry of the units (Makaske, 2001).

Granulometric analysis results based on 56 samples also shows that the sediments of the study interval were likely deposited in rivers rather than inland sands dunes. These are illustrated in bivariate plots of mean versus standard deviation of (Moiola and Weiser, 1968) and Friedman (1971) as illustrated in Figures 15 and 16 below.

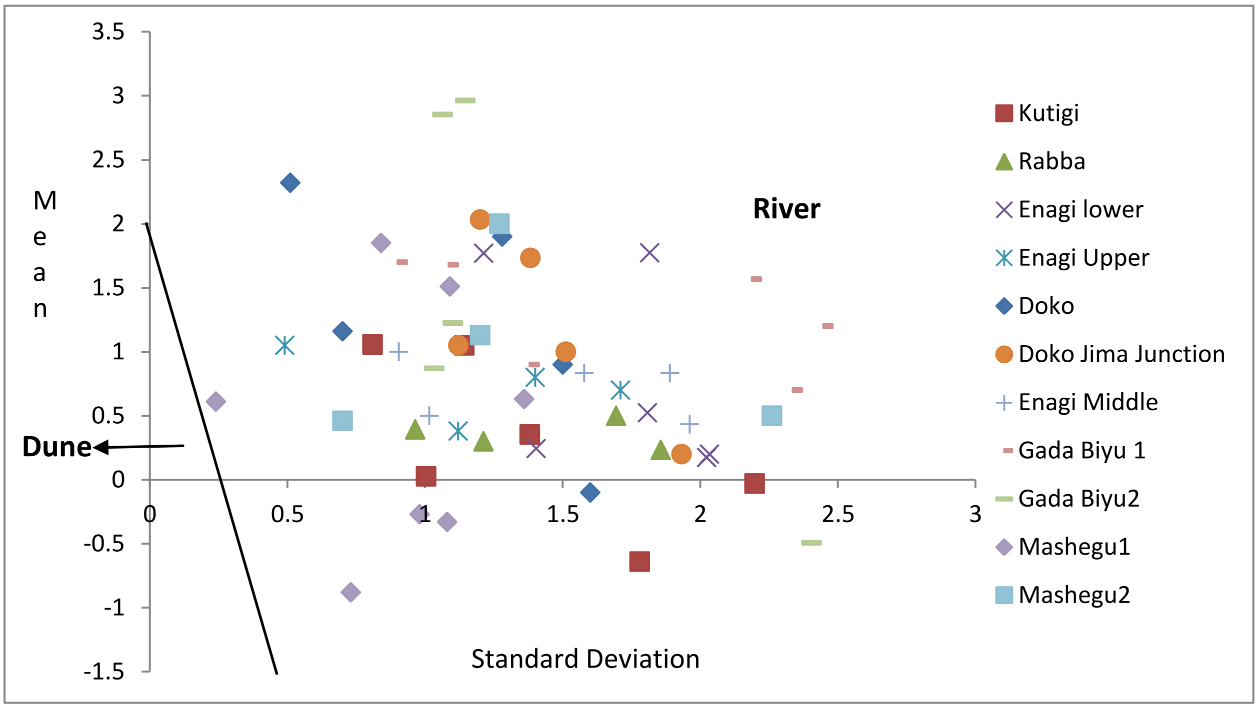


Figure 15: Bivariate plot of mean against standard deviation for whole samples (after Moiola and Weiser, 1968).

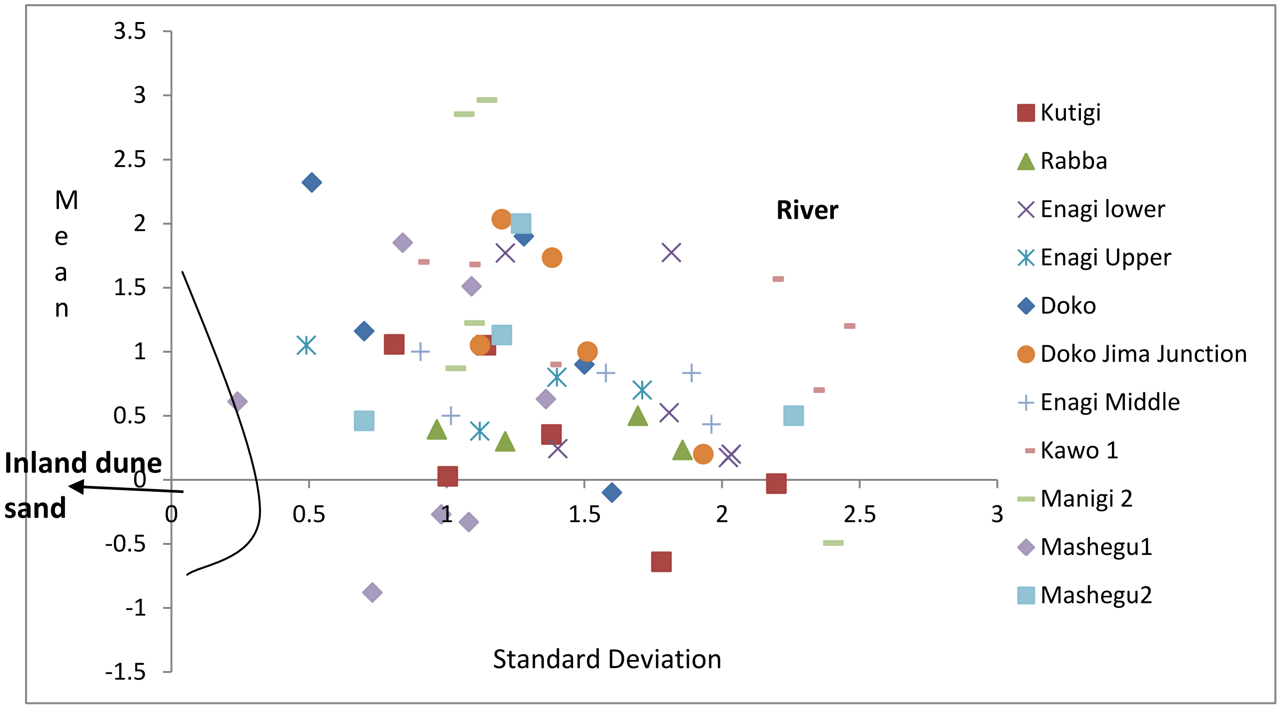


Figure 16: Bivariate plot of mean against standard deviation for whole sample (after Friedman 1979)

4. Discussion

4.1 Stratigraphic placement of Enagi Siltstone

Notable published regional works on the sediments of the northern part of Bida basin includes Adeleye and Dessauvagie (1972), Adeleye (1974), Braide (1992) and Okosun et al (2009). The pioneering work of Adeleye and Dessauvagie (1972) which recognised the stratigraphic successions commonly used to explain the stratigraphy of the northern part of the basin described the Enagi Siltstone as consisting of mainly siltstones with minor amount of sandstones and mudstones. They also attempted correlating the units with the southern part (Fig. 2) where the Enagi Siltstone (sensu Adeleye and Dessauvagie, 1972; Adeleye, 1974) has been regarded as the lateral equivalent of Patti Formation in the southern part of the basin. However, analysis of more recent literature on the southern part (e.g Ojo and Akande, 2009) shows that Enagi Siltstone described by Adeleye and Dessauvagie (1972) may be regarded as just a part of Patti Formation – more precisely the Shale-Clay Member of the Patti Formation – if the descriptions of Adeleye and Dessauvagie (1972) have to be followed strictly. This upper unit of Patti Formation (i.e. the

Enagi Siltstone of Adeleye and Dessauvagie, 1972), the variegated siltstone facies of Braide (1992) and the OFA3 of the present study have similar sedimentological features and stratigraphic position and are therefore considered correlatable units (Fig. 17).

Furthermore, the identification of OFA3 towards the northern tip of the basin dismisses the notion that the shale-clay member of the Patti Formation does not have regional coverage. This idea was probably informed by the geological map of Bida basin produced by Adeleye (1974) which shows that the bulk of the sediments in the northern part belong to Bida Formation. The work of Okosun et al. (2009) was also guided by this map and led to the lumping of Bida Formation and Enagi Siltstone sediments as one unit.

<table>
<tr><th colspan="3">ADELEYE 1973</th><th>OKOSUN ET AL., 2008</th><th colspan="3">OJO AND AKANDE 2009</th><th>Ojo, 2012</th><th colspan="2">PRESENT WORK</th></tr>
<tr><th colspan="2">Northern Bida Basin</th><th>Southern Bida Basin</th><th>Northern Bida Basin</th><th colspan="3">Southern Bida Basin</th><th>Northern Bida Basin</th><th colspan="2">Northern Bida Basin</th></tr>
<tr><td colspan="2">Batati Ironstone</td><td>Agbaja Ironstone</td><td></td><td colspan="3">Agbaja Ironstone</td><td></td><td colspan="2">Batati Ironstone</td></tr>
<tr><td colspan="2" rowspan="2">Enagi Siltstone</td><td rowspan="6">Patti Formation</td><td rowspan="10">Bida Formation</td><td rowspan="6">Patti Formation</td><td>Non marine swamp/overbank</td><td rowspan="4">Shale – Clay Member</td><td rowspan="5"></td><td rowspan="5">Enagi Formation</td><td rowspan="2">OFA3</td></tr>
<tr><td>Fluvial channel</td></tr>
<tr><td colspan="2">Sakpe Ironstone</td><td rowspan="2">Tidal marsh to swamp</td><td rowspan="3">OFA2</td></tr>
<tr><td rowspan="7">Bida Formation</td><td rowspan="4"></td></tr>
<tr><td>Tidal channels and flood plain</td><td rowspan="2">Sandstone Member</td></tr>
<tr><td>Shoreface and tidal channels</td><td>Shoreface and tidal channels</td><td rowspan="5">Bida Formation</td><td rowspan="3">OFA1
Jima Member</td></tr>
<tr><td rowspan="4">Lokoja Formation</td><td colspan="3" rowspan="4">Lokoja Formation</td><td rowspan="4">Bida Formation</td></tr>
<tr><td rowspan="2">Jima Member</td></tr>
<tr><td rowspan="2">Doko Member</td></tr>
<tr><td>Doko Member</td></tr>
</table>

Figure 17. Lithostratigraphic successions of the Bida basin, North western Nigeria based on different sources.

The successful interpretation of Bida Formation and Enagi Siltstone as one unit without identifying any major surface separating them by Okosun et al. (2009) also brings to mind the observations of Braide (1992) who noted that the lithostragraphic subdivisions of Adeleye and Dessauvagie (1972) cannot be followed strictly in the field. The regional extent of the shale – clay member equivalent in the northern part is further strengthened by the identification of coal horizons (mire facies of Okosun et al,. 2009 in shallow boreholes around Kudu and Bokani in Nigeria state). These units were also captured by the geological map of the area by Obaje et al. (2012) even though details were not provided due to preliminary nature of the work.

The Bida Sandstone of Adeleye and Dessauvagie (1972) and the Lokoja Sandstone in the southern part have also been regarded as lateral equivalents but the sub-division of the Bida Sandstone into Doko Member at the base and Jima Member at the top is not recorded in the southern part. The description of Jima Member (Adeleye, 1974) is quite similar to the lower part of Patti Formation described by Ojo and Akande (2009) as well as the OFA1 and OFA2 of this work. Additionally, the cross stratified sandstone facies, epsilon cross stratified sandstone facies together with the siltstone facies of Braide (1992) are captured within the OFA2 facies association. It has also been noted by the authors that the descriptions of Jima Member (Adeleye, 1974) encapsulates the OFA1/OFA2 interval. More recently, Ojo (2012) described units with similar attributes to the OFA1 of this work around Shonga area in Kwara state. These units cannot be considered Enagi Siltstone if the descriptions of Adeleye and Dessauvagie (1972 sensus) is considered. The area covered by their study cannot be representative of northern Bida basin considering that it is less than 10 % of the northern part of Bida basin. The units can best be regarded as Jima Member of Bida Formation in this part of the basin which may be the lateral equivalence of sandstone member of Patti Formation. Their interpretation may have been informed by the assumption that Patti Formation is holistically equivalent to Enagi Siltstone of Adeleye and Dessauvagie (1972).

4.2 Proposed revision

It is clear from the above that the Stratigraphy of the Enagi Siltstone requires redefinition (especially its lower boundary) and elevation of its name to Enagi Formation rather than "Enagi Siltstone". We therefore propose the following revisions based on lithostratigraphic principles.

1. The elevation of the name Enagi Siltstone to Enagi Formation – this revision is necessary due to the heterogeneous nature of the sediments essentially owing to the presence of significant amount of sandstones and mudstones in the interval. The proposed Enagi Formation includes the OFA2 and OFA3 outcrop facies associations of this work.

2. A lower boundary represented by the gradational boundary between OFA1 and OFA2. This boundary is marked by the appearance of thick, light grey to white mudstone intervals between thick sandstone units (OFA2). This boundary marks a basin wide change in sedimentation pattern.

3. The Enagi Formation can therefore be described in terms of a lower sandstone dominated interval (i.e. OFA2; Sandstone Member) and an upper mudstone/siltstone dominated interval (i.e. OFA2; Siltstone-Mudstone Member) similar to the sub-divisions of the Patti Formation in the southern part.

4. The OFA1 of the present work is considered part of the underlying Bida Formation due to high proportion of sandstone to mudstone/siltstone ratio (>70:30 %). Its vertical position and widespread cross bedded nature make it more suitable as part of the Jima Member. a composite log that summarises the field observations as well as the proposals made herein is shown in Figure 14 below.

5. Three reference sections (Hypostratotypes) are proposed to illustrate heterogeneities within the Enagi Formation. Reference Sections (a) and (b) below are lateral equivalents because they occupy the same stratigraphic position but different geographic locations. Their difference lies in the nature of their architectural elements.

    a. The lower portion (sandstone member) as well as the transitional lower boundary of the formation can be studied at Doko locality with a proposed reference section represented by a mesa located less than 500 m south of Doko town. This section characterizes the nature of the sandstone member in the central to southern part of the northern Bida basin.

b. Another reference section is proposed to illustrate the nature of the lower sandstone member in the northernmost part of the basin. It is represented by a road-cut along Kaduna-Tegina-Makera highway about 2 km south of Kawo village.

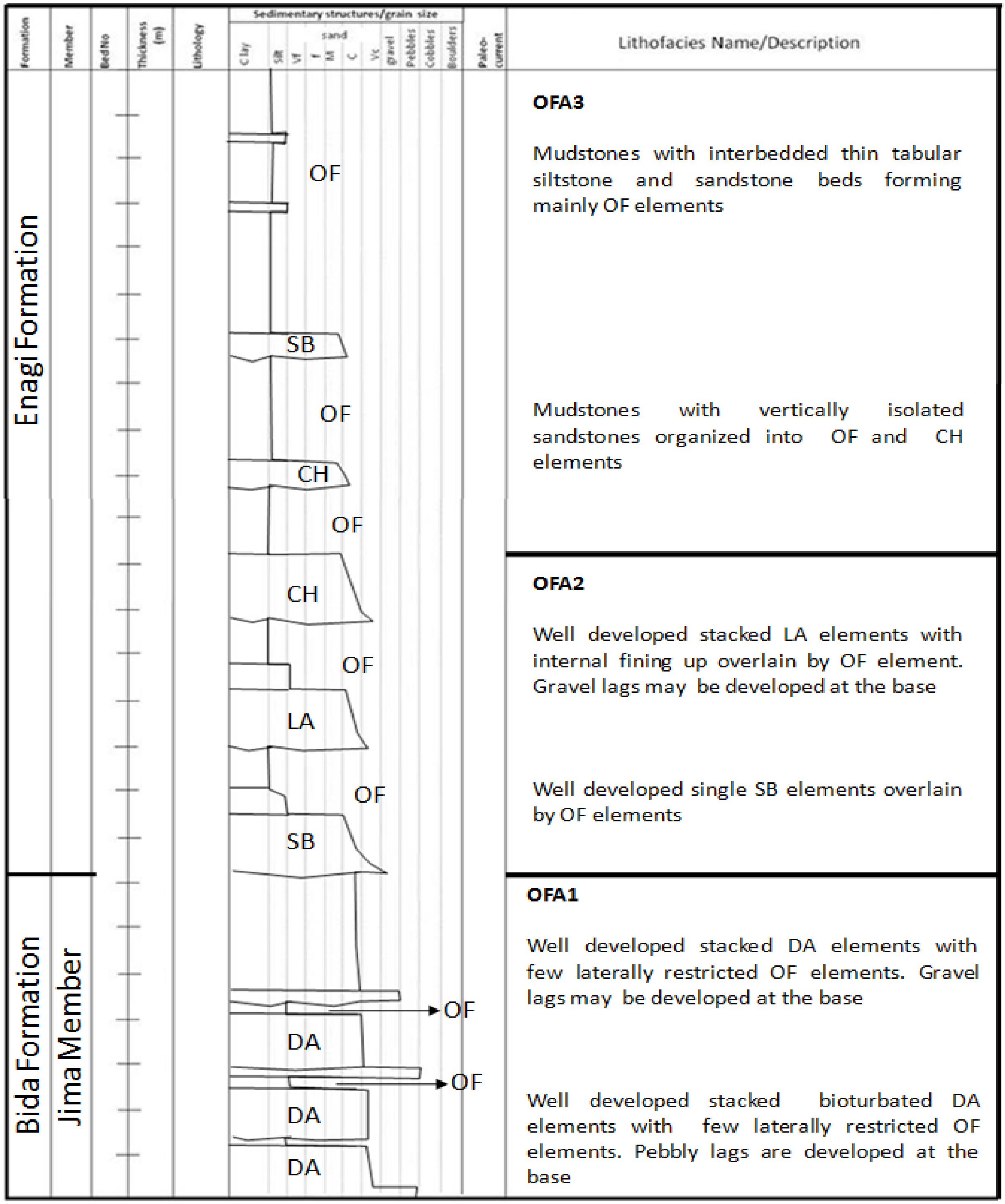


Figure 18: A composite graphic log depicting the typical features of the outcrop facies associations and their stratigraphic positions as well as the proposed revision.

c. Typical features of the Mudstone-Siltstone Member are observed in a road-cut, here proposed as reference section located 3 km east of Manigi village along Kaduna-Tegina-Makera highway.

4.2.1 Reference section (Hypostratotype) I

Status: Sandstone Member of Enagi Formation typical of the central to southern part of the Northern Bida basin

Location: N8^o 56’46.5” E5^o 57’31.9”. A mesa about 500 m south-east of Doko town, Niger state, Nigeria (L2, Appendix I).

Description: at least 60 % of the member consists of sandstone. The remaining 40 % are mainly siltstones and mudstones. Lithofacies present include: conglomerate facies (F1); planar cross bedded sandstone facies (F3); tabular bedded sandstone facies (F5); and mudstone facies (F8). Architectural elements consist of SB, and OF elements. The sediments are organised into fining up units with F1 at the base overlain by F3 and F5 and capped by F8 facies. F5 is absent in some units while some do not show both F5 and F8.

Sedimentary structures include: large scale planar cross bedding; horizontal lamination; ripple lamination; large elliptical to spherical concretions with concentric layers; sporadically distributed, locally abundant unidentified trace fossils.

Facies and architectural element analyses suggest that the rocks were deposited in fluvial channel system with channels filled by normal regime flow sedimentation.

4.2.2 Reference section (Hypostratotype) II

Status: Sandstone Member of Enagi Formation typical of the northern part of the Northern Bida basin. It is the lateral equivalent of the Reference Section I (Doko)

Location: N9^o 54’45.7” E5^o 42’59.6”. Road-cut 2 km south of Kawo village, Niger state, along Kaduna-Tegina-Makera highway, Nigeria (L8, Appendix I).

Description: at least 60 % of the member consists of sandstone. The remaining 40 % are mainly siltstones and mudstones. Lithofacies present include: conglomerate facies (F1); epsilon cross bedded sandstone facies (F3); trough cross bedded sandstone facies; tabular bedded sandstone facies (F5); and mudstone facies (F8). Architectural elements include CH, LA, and OF elements. The sediments are organised into fining up units with F1 at the base through F4 and F5 then capped by F8 facies. Stacked CH elements are significant locally.

Sedimentary structures include: epsilon cross bedding; lateral accretion surfaces; horizontal lamination; ripple lamination; large ferruginised, elliptical to spherical concretions with concentric layers; sporadically distributed, locally abundant unidentified trace fossils.

Facies and architectural element analyses suggest deposition in high sinuosity fluvial channels.

4.2.3 Reference section (Hypostratotype) III

Status: Mudstone- Siltstone Member of Enagi Formation. This reference section characterizes the lower part of this member.

Location: N 09^{O}46’33.7” E 005^{O}32’16.7” Manigi1 and Manigi 2 (L9 and L10 in Appendix I)

Description: more than 50 % of the member consists of mudstones and siltstones. The remaining part consists of fine to coarse sandstones embedded within the mudstones. Lithofacies present include: mainly mudstone facies (F8); heterolithic mudstone and siltstone facies (F6); and subordinate planar and trough cross bedded sandstone facies (F2, F3); and conglomerate facies (F1). Architectural elements consist of SB, DA and OF elements. The OF elements are laterally extensive while the SB and DA elements are embedded within them.

Sedimentary structures include: small scale planar and trough cross bedding; mud drapes on foreset of cross beds; horizontal lamination; ripple lamination; small concretions with or without concentric layers; sands balls, reactivation surfaces.

Facies and architectural element analyses suggest deposition in suspended load fluvial system influenced by tidal action.

4.2.4 Reference section (Hypostratotype) IV

Status: Mudstone- Siltstone Member of Enagi Formation. This reference section characterizes the lower part of this member.

Location: N 09^{O}02'06.6" E 005^{O}56'53.6". a road-cut near Patti-Shaba Kolo, about 5 km south of Bida city, Niger state.

Description: predominantly mudstones and siltstones. Lithofacies present include: mudstone facies (F8); heterolithic mudstone and siltstone facies (F6); and erosive based siltstone facies (F7). Architectural elements consist mainly of OF element.

Sedimentary structures include: horizontal lamination; ripple lamination; ripple bedding; elliptical to spherical concretions with or without concentric layers; bioturbate structure in form of mottles; and massive bedding.

Facies and architectural element analyses suggest deposition in levee, lacustrine and other overbank areas outside the confines of channels.

5.0 Conclusions

This study analysed the sedimentology and stratigraphy of Enagi Siltstone in the northern part of Bida basin, northern western Nigeria. Detailed facies analyses lead to the identification of eight lithofacies within the studied interval. Consideration of the geometry and bounding surfaces of the lithofacies allowed the definition of five architectural elements including downstream accretion, sandy bedforms, and lateral accretion macroforms, channel and overbank elements. The combination the eight lithofacies and the five architectural elements also allowed the grouping of the sediments into three large scale outcrop facies associations.

The OFA1 occupy the lowest stratigraphic level and is characterized by predominance of DA elements with subordinate OF elements inferred to be the product of deposition in multiple channel river system. The OFA2 is composed of mainly SB, LA, and CH elements associated with thick OF element. The OFA2 is distinguished from the OFA1 by its possession of thicker OFA elements and its higher stratigraphic position. It is inferred to record deposition in high sinuosity river system. The OFA3 is characterised by an intercalated gradational upper contact and a possible gradational lower contact. It is dominated by the mudstones and siltstones of OF elements with the other elements (CH, LA, DA or SB) occurring within them.

This work suggests the elevation of Enagi Siltstone of Adeleye (1972) and Adeleye and Dissauvagie (1974) to Enagi Formation status. This is necessary in order to account for the heterogeneities within the interval as illustrated in this study. The proposed lower boundary of this formation is the base of the OFA2 facies association and the upper boundary is the top of the OFA3 facies association. The OFA1 of this work is considered to be part of Bida Formation. It is also noted that the OFA3 of this work is the lateral equivalent of the Shale – Clay Member of the Patti Formation and its presence in the south and central parts as well as the northern tip of the basin establishes its regional coverage contrary to earlier assumptions of its absence in the northern part of the basin.

With the recent economic and academic interests in the inland basins of Nigeria (especially the Bida basin), a proper understanding of the lithostratigraphical successions in the basin is a basic requirement for resolving issues concerning exploration for hydrocarbon, solid minerals and water recourses in the basin. The utilization of detailed field outcrop analysis of the sediments of Enagi Formation as demonstrated in this contribution is crucial in understanding better the stratigraphy of Bida basin. This is fundamental for better delineation of a possible petroleum system in the basin.

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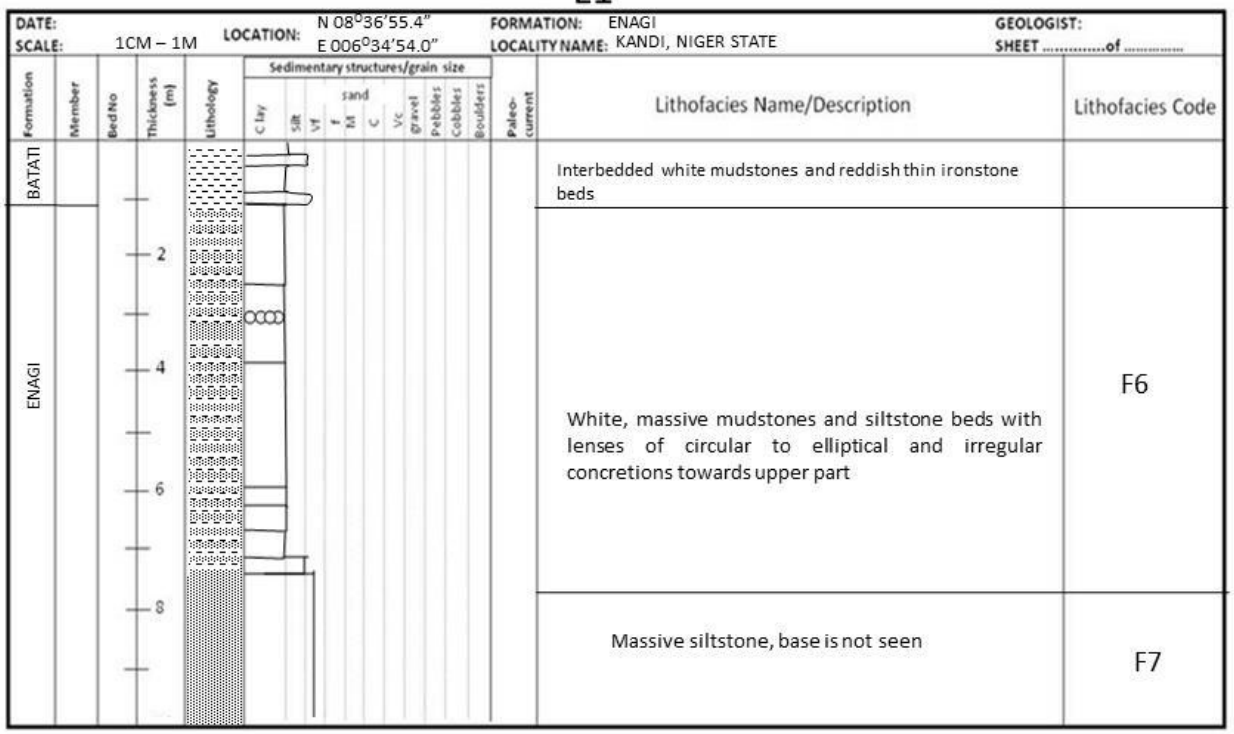
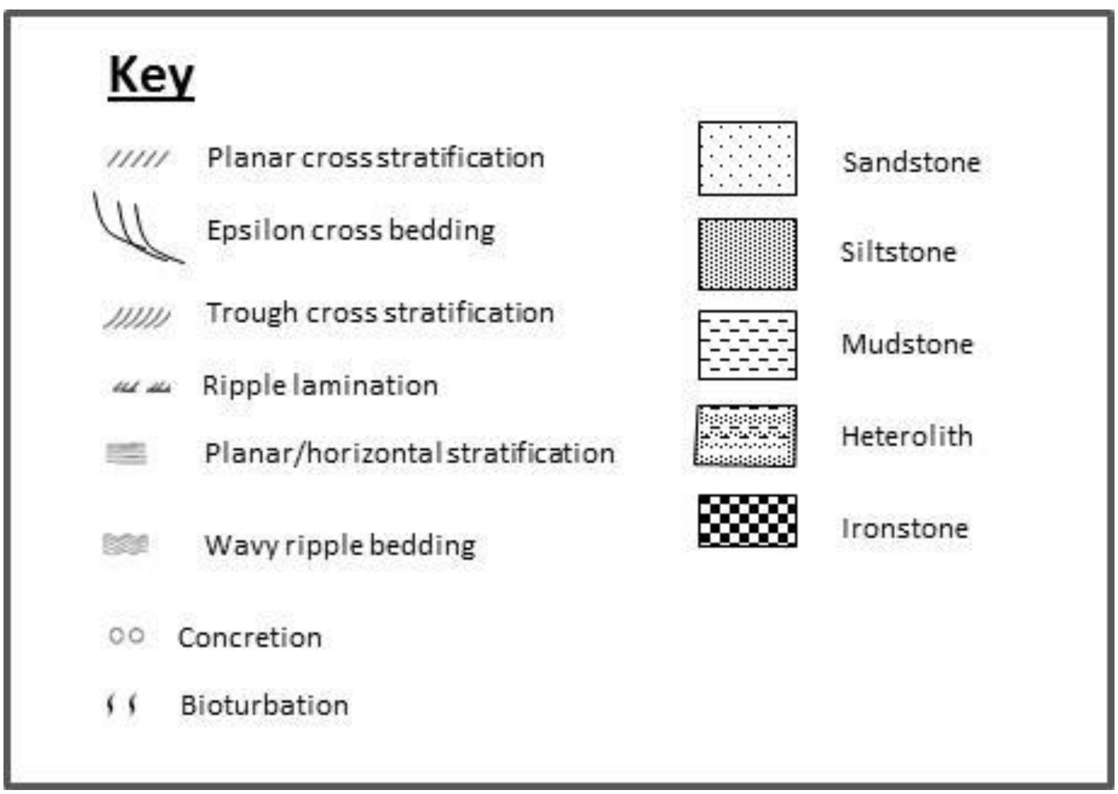
Appendix I

Graphic logs summarising the main features of the studied localities. Approximate positions of the localities (i.e. L1 – L11) are shown in Figure 3.

L1

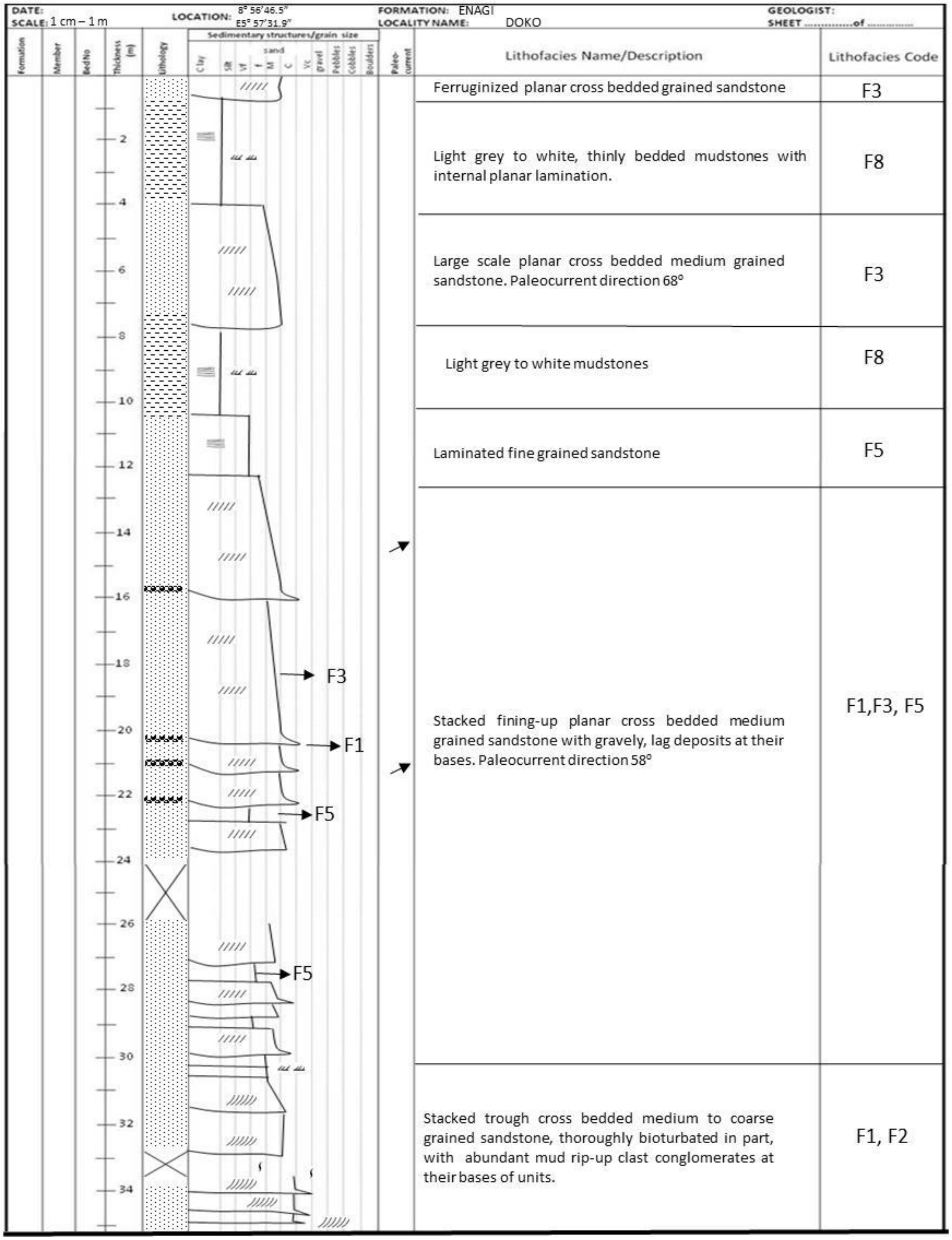


DATE:
SCALE: 1CM – 1M
LOCATION: N 08°36'55.4" E 006°34'54.0"
FORMATION: ENAGI
LOCALITY NAME: KANDI, NIGER STATE
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
C lay
Silt
vf
f
M
C
Vc
sand
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
BATATI
ENAGI
2
4
6
8
Interbedded white mudstones and reddish thin ironstone beds
White, massive mudstones and siltstone beds with lenses of circular to elliptical and irregular concretions towards upper part
F6
Massive siltstone, base is not seen
F7

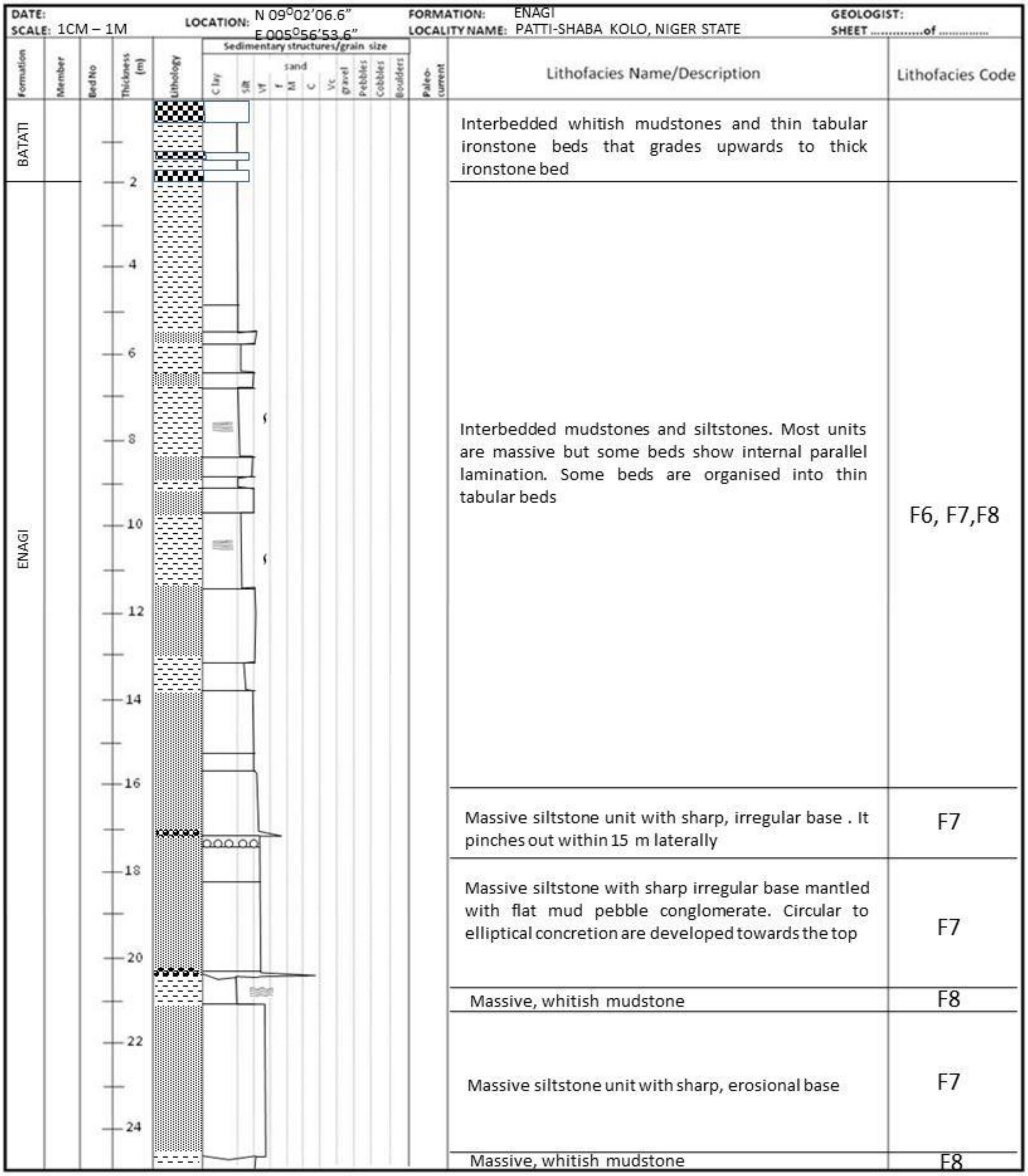


Key
Planar cross stratification
Epsilon cross bedding
Trough cross stratification
Ripple lamination
Planar/horizontal stratification
Wavy ripple bedding
Concretion
Bioturbation
Sandstone
Siltstone
Mudstone
Heterolith
Ironstone

L2


DATE:
SCALE: 1 cm – 1 m
LOCATION: 8° 56'46.5" E5° 57'31.9"
FORMATION: ENAGI
LOCALITY NAME: DOKO
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
Clay
Silt
sand
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
Ferruginized planar cross bedded grained sandstone
F3
Light grey to white, thinly bedded mudstones with internal planar lamination.
F8
Large scale planar cross bedded medium grained sandstone. Paleocurrent direction 68°
F3
Light grey to white mudstones
F8
Laminated fine grained sandstone
F5
Stacked fining-up planar cross bedded medium grained sandstone with gravely, lag deposits at their bases. Paleocurrent direction 58°
F1,F3, F5
Stacked trough cross bedded medium to coarse grained sandstone, thoroughly bioturbated in part, with abundant mud rip-up clast conglomerates at their bases of units.
F1, F2
F3
F1
F5
F5
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

L3


DATE:
SCALE: 1CM – 1M
LOCATION: N 09°02'06.6" E 005°56'53.6"
FORMATION: ENAGI
LOCALITY NAME: PATTI-SHABA KOLO, NIGER STATE
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
C lay
Silt
sand
Vf
F
M
C
Vc
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
BATATI
ENAGI
2
4
6
8
10
12
14
16
18
20
22
24
Interbedded whitish mudstones and thin tabular ironstone beds that grades upwards to thick ironstone bed
Interbedded mudstones and siltstones. Most units are massive but some beds show internal parallel lamination. Some beds are organised into thin tabular beds
F6, F7,F8
Massive siltstone unit with sharp, irregular base . It pinches out within 15 m laterally
F7
Massive siltstone with sharp irregular base mantled with flat mud pebble conglomerate. Circular to elliptical concretion are developed towards the top
F7
Massive, whitish mudstone
F8
Massive siltstone unit with sharp, erosional base
F7
Massive, whitish mudstone
F8

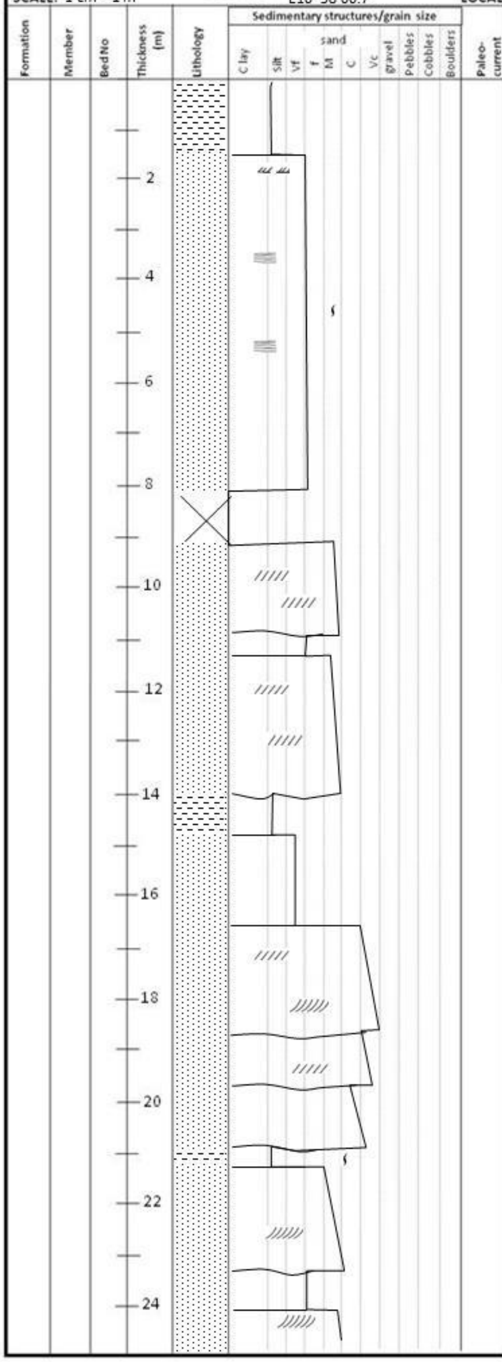
L4

DATE:
SCALE: 1 cm – 1 m

LOCATION: N9° 58'42.4" E10° 58'00.7"

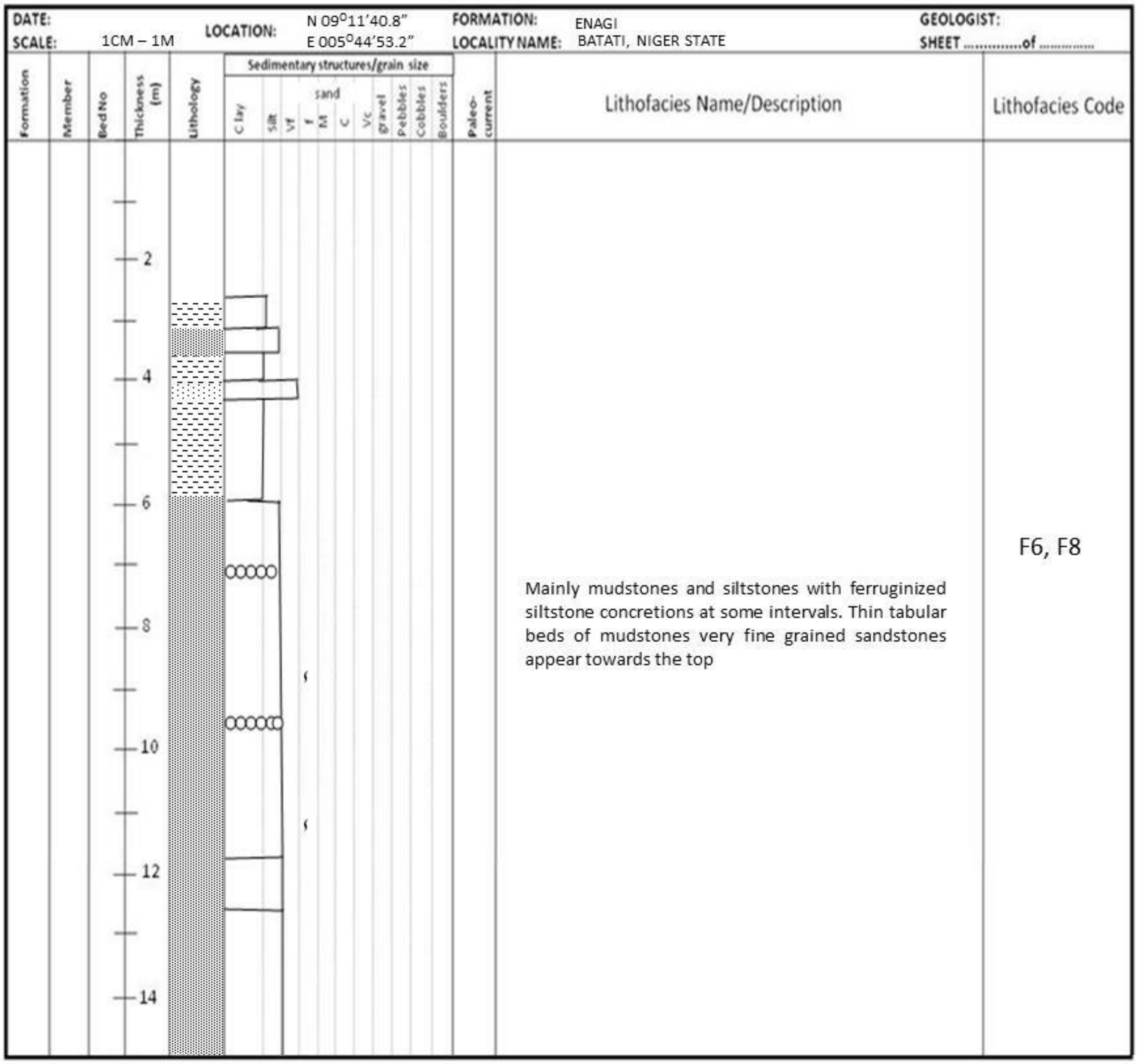
FORMATION: ENAGI
LOCALITY NAME: JIMA-DOKO JUNCTION

GEOLOGIST:
SHEET ....of ....



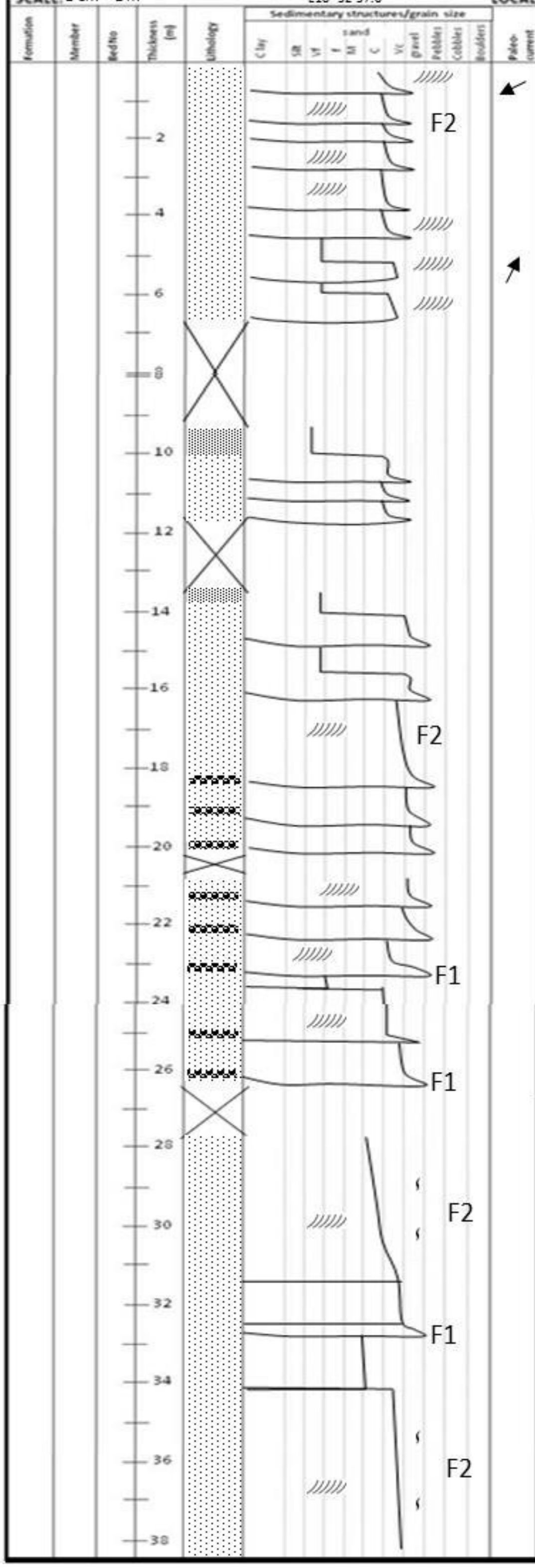
Lithofacies Name/Description	Lithofacies Code
Laterally restricted grey mottled mudstone	F8
Thin tabular beds of ripple or parallel laminated very fine to fine grained sandstones interbedded with siltstones. Show colour mottling	F5
Medium grained planar cross bedded sandstone	F2
Mottled micaceous fine grained sandstone	F5
Micaceous medium grained planar cross bedded sandstone with unidentified trace fossils	F3
Grey mottled mudstone	F8
Mottled fine grained sandstones with clay streaks	F5
Stacked units of scour based cross bedded medium to coarse grained sandstone	F3
Mottled micaceous fine grained sandstone	F2
Trough cross bedded medium grained sandstone	F2
Mottled fine grained sandstone	F5
Trough cross bedded medium grained sandstone	F2

L5


DATE:
SCALE: 1CM – 1M
LOCATION: N 09°11'40.8" E 005°44'53.2"
FORMATION: ENAGI
LOCALITY NAME: BATATI, NIGER STATE
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
C lay
Silt
Vf
f
M
C
Vc
sand
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
2
4
6
8
10
12
14
Mainly mudstones and siltstones with ferruginized siltstone concretions at some intervals. Thin tabular beds of mudstones very fine grained sandstones appear towards the top
F6, F8

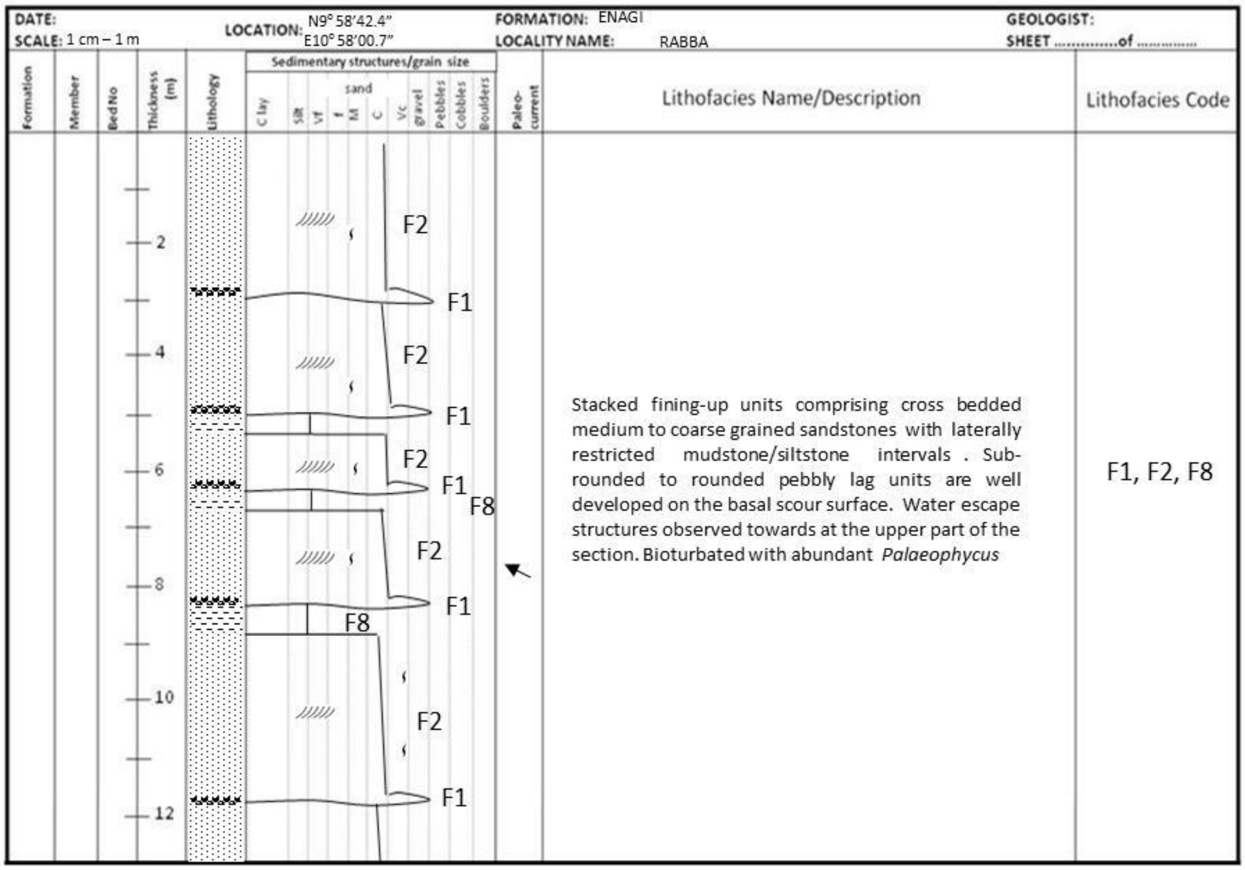
L6

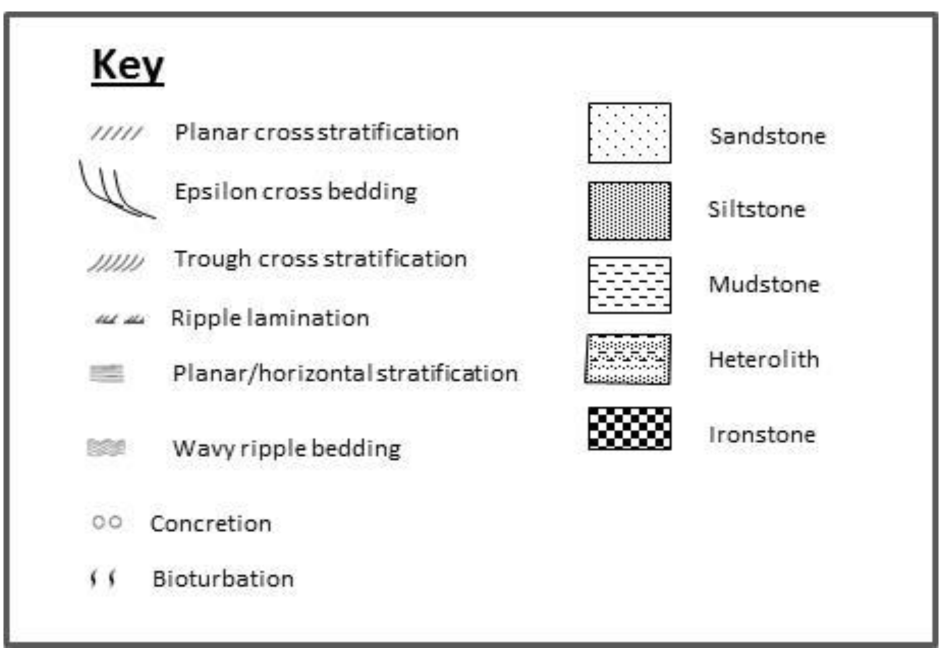
DATE:
SCALE: 1 cm – 1 m
LOCATION: N9° 07'56.6" E10° 32'37.0"
FORMATION: ENAGI
LOCALITY NAME: ENAGI
GEOLOGIST:
SHEET ....of ....



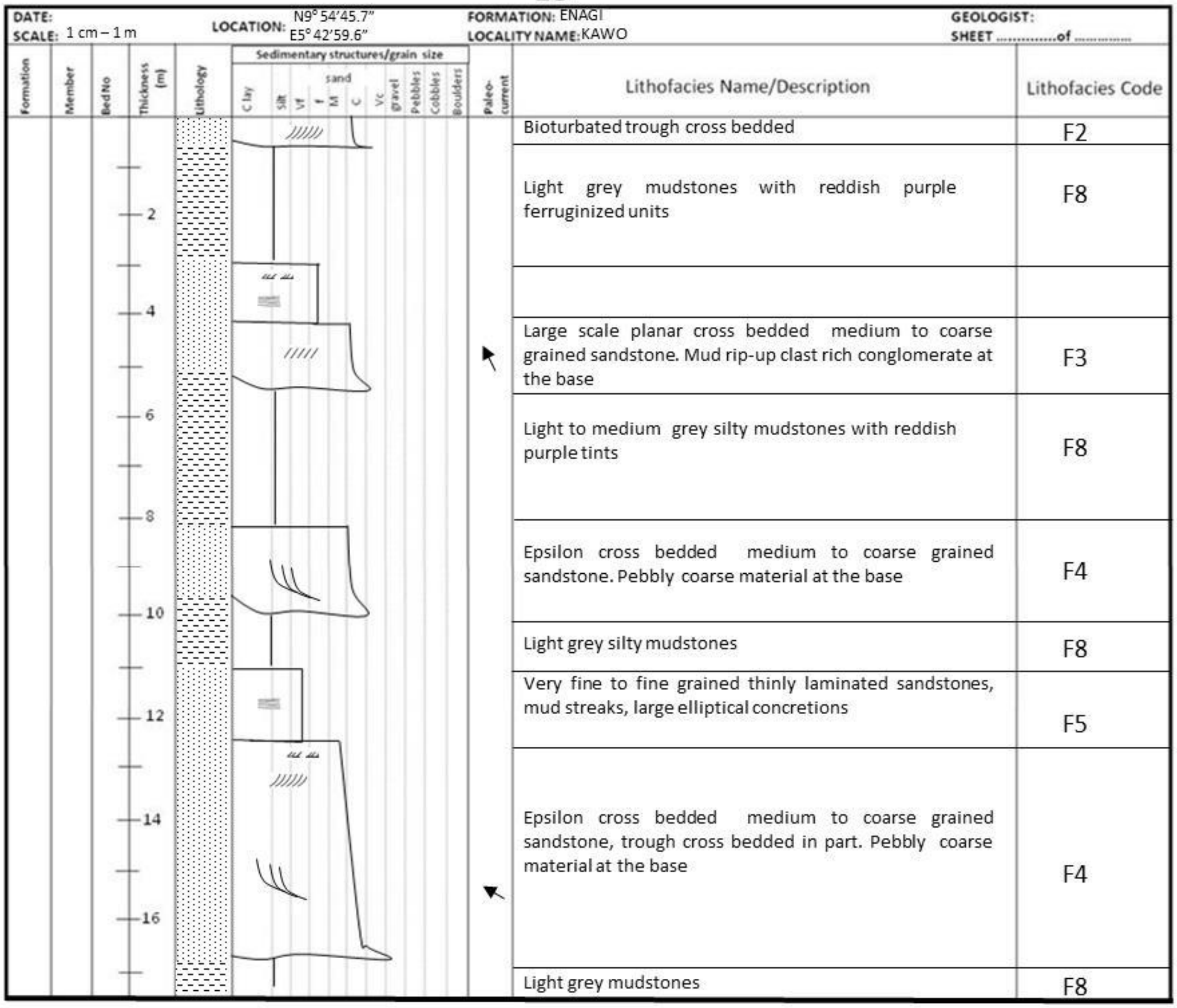
Lithofacies Name/Description	Lithofacies Code
Stacked fining-up units comprising cross bedded medium to coarse grained sandstones with laterally restricted mudstone/siltstone intervals. Most units have well developed coarse basal parts consisting of abundant mud rip-up clasts. Water escape structures present in some beds towards the upper part of the section	F1, F2, F8
Stacked massive to cross bedded medium to very coarse grained moderate to highly bioturbated sandstones. Trace fossils include ?*Thallassinoides* and ?*Ophiomorpha*.	F1, F2, F8

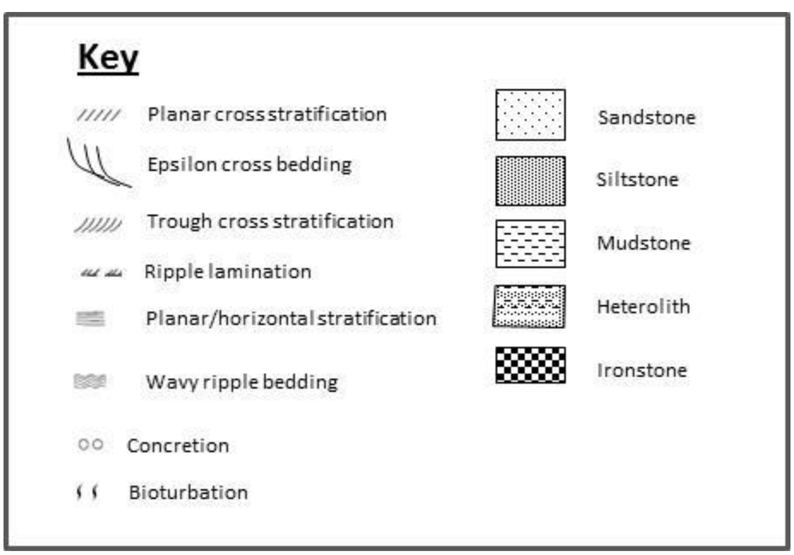
L7


DATE:
SCALE: 1 cm – 1 m
LOCATION: N9° 58'42.4" E10° 58'00.7"
FORMATION: ENAGI
LOCALITY NAME: RABBA
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
Clay
Silt
Vf
f
M
C
Vc
gravel
Pebbles
Cobbles
Boulders
sand
Paleo-current
Lithofacies Name/Description
Lithofacies Code
2
4
6
8
10
12
F2
F1
F2
F1
F2
F1
F8
F2
F1
F8
F2
F1
Stacked fining-up units comprising cross bedded medium to coarse grained sandstones with laterally restricted mudstone/siltstone intervals . Sub-rounded to rounded pebbly lag units are well developed on the basal scour surface. Water escape structures observed towards at the upper part of the section. Bioturbated with abundant *Palaeophycus*
F1, F2, F8

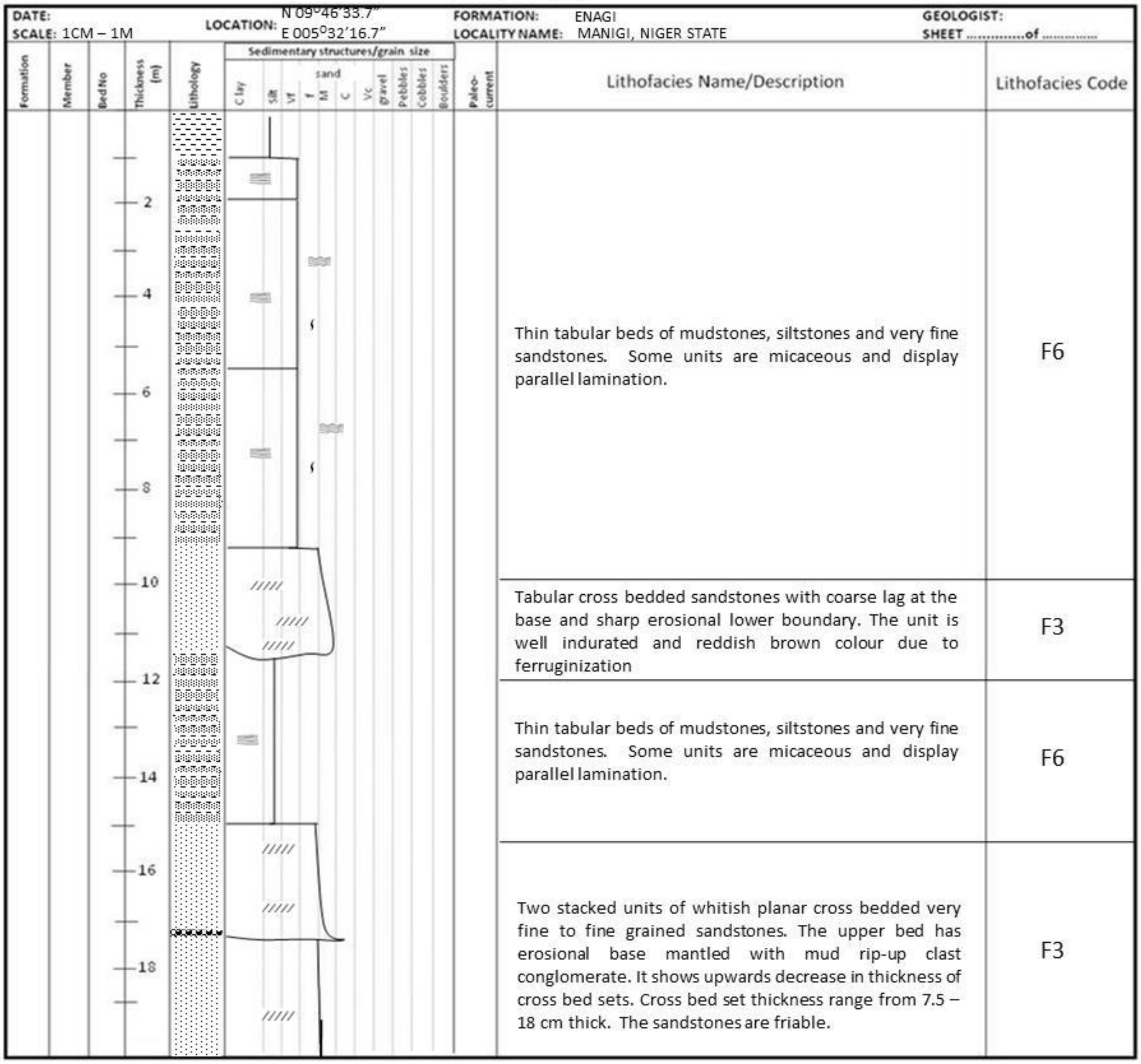

Key
Planar cross stratification
Epsilon cross bedding
Trough cross stratification
Ripple lamination
Planar/horizontal stratification
Wavy ripple bedding
Concretion
Bioturbation
Sandstone
Siltstone
Mudstone
Heterolith
Ironstone

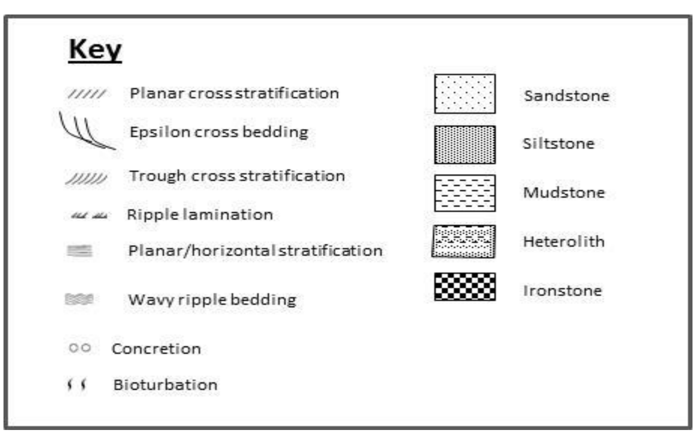
L8


DATE:
SCALE: 1 cm – 1 m
LOCATION: N9° 54'45.7" E5° 42'59.6"
FORMATION: ENAGI
LOCALITY NAME: KAWO
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
Clay
Silt
sand
Vf
f
M
c
Vc
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
2
4
6
8
10
12
14
16
Bioturbated trough cross bedded
F2
Light grey mudstones with reddish purple ferruginized units
F8
Large scale planar cross bedded medium to coarse grained sandstone. Mud rip-up clast rich conglomerate at the base
F3
Light to medium grey silty mudstones with reddish purple tints
F8
Epsilon cross bedded medium to coarse grained sandstone. Pebbly coarse material at the base
F4
Light grey silty mudstones
F8
Very fine to fine grained thinly laminated sandstones, mud streaks, large elliptical concretions
F5
Epsilon cross bedded medium to coarse grained sandstone, trough cross bedded in part. Pebbly coarse material at the base
F4
Light grey mudstones
F8

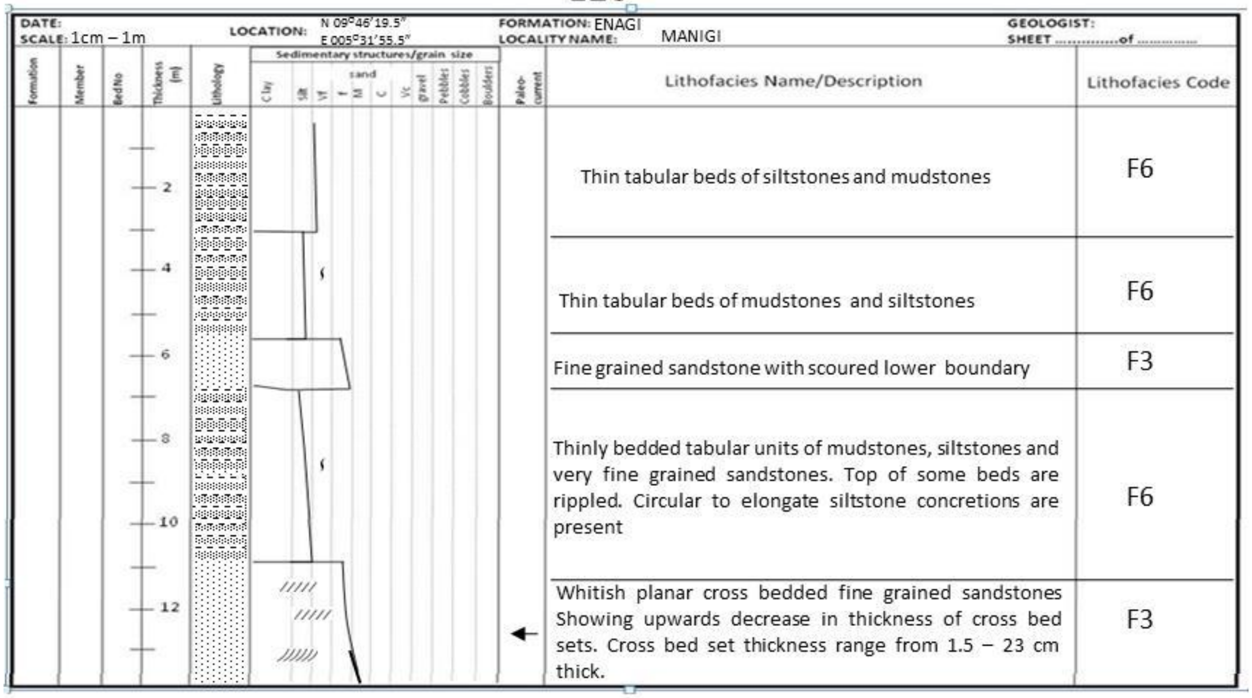

Key
Planar cross stratification
Epsilon cross bedding
Trough cross stratification
Ripple lamination
Planar/horizontal stratification
Wavy ripple bedding
Concretion
Bioturbation
Sandstone
Siltstone
Mudstone
Heterolith
Ironstone

L9

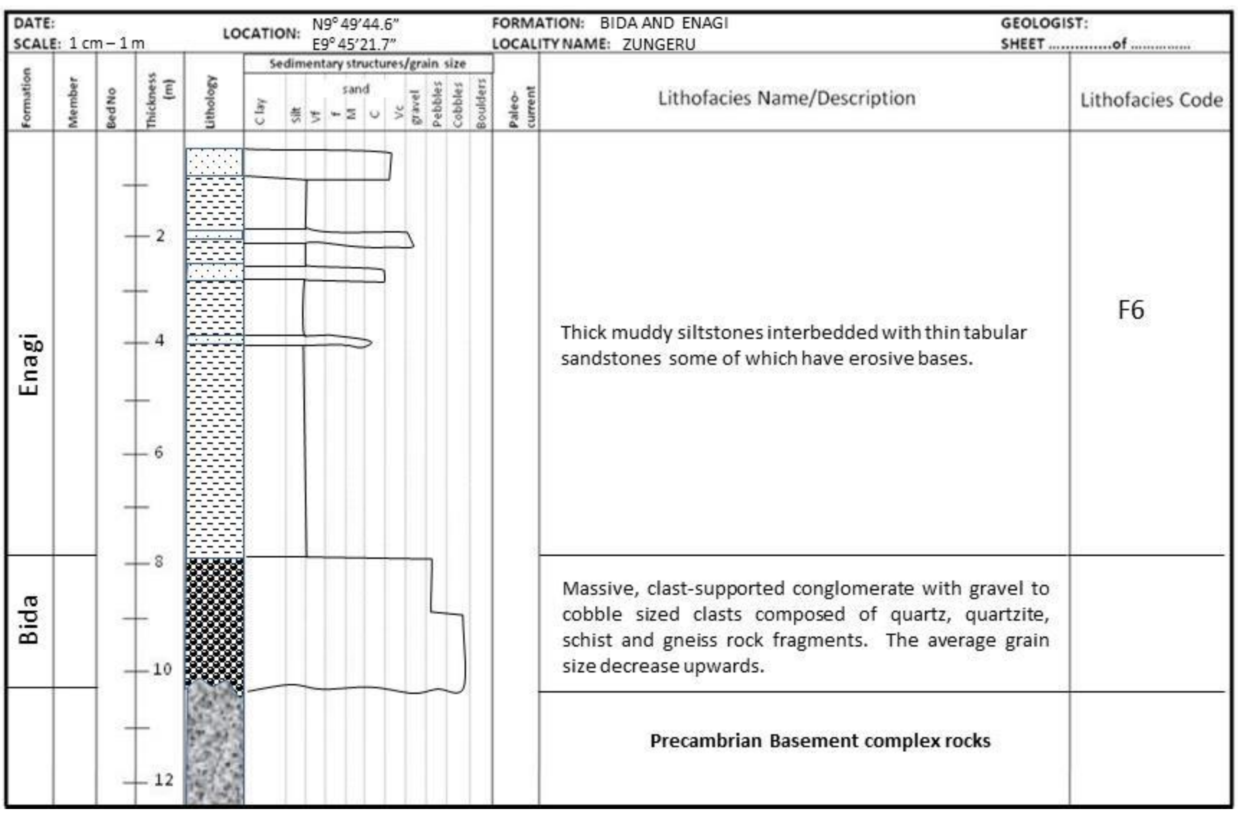

DATE:
SCALE: 1CM – 1M
LOCATION: N 09°46'33.7" E 005°32'16.7"
FORMATION: ENAGI
LOCALITY NAME: MANIGI, NIGER STATE
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
Clay
Silt
Vf
f
M
C
Vc
gravel
Pebbles
Cobbles
Boulders
sand
Paleo-current
Lithofacies Name/Description
Lithofacies Code
2
4
6
8
10
12
14
16
18
Thin tabular beds of mudstones, siltstones and very fine sandstones. Some units are micaceous and display parallel lamination.
F6
Tabular cross bedded sandstones with coarse lag at the base and sharp erosional lower boundary. The unit is well indurated and reddish brown colour due to ferruginization
F3
Thin tabular beds of mudstones, siltstones and very fine sandstones. Some units are micaceous and display parallel lamination.
F6
Two stacked units of whitish planar cross bedded very fine to fine grained sandstones. The upper bed has erosional base mantled with mud rip-up clast conglomerate. It shows upwards decrease in thickness of cross bed sets. Cross bed set thickness range from 7.5 – 18 cm thick. The sandstones are friable.
F3


Key
Planar cross stratification
Epsilon cross bedding
Trough cross stratification
Ripple lamination
Planar/horizontal stratification
Wavy ripple bedding
Concretion
Bioturbation
Sandstone
Siltstone
Mudstone
Heterolith
Ironstone

L10


DATE:
SCALE: 1cm – 1m
LOCATION: N 09°46'19.5" E 005°31'55.5"
FORMATION: ENAGI
LOCALITY NAME: MANIGI
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
Clay
Silt
sand
Vf
f
M
C
Vc
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
2
4
6
8
10
12
Thin tabular beds of siltstones and mudstones
F6
Thin tabular beds of mudstones and siltstones
F6
Fine grained sandstone with scoured lower boundary
F3
Thinly bedded tabular units of mudstones, siltstones and very fine grained sandstones. Top of some beds are rippled. Circular to elongate siltstone concretions are present
F6
Whitish planar cross bedded fine grained sandstones Showing upwards decrease in thickness of cross bed sets. Cross bed set thickness range from 1.5 – 23 cm thick.
F3

L11


DATE:
SCALE: 1 cm – 1 m
LOCATION: N9° 49'44.6" E9° 45'21.7"
FORMATION: BIDA AND ENAGI
LOCALITY NAME: ZUNGERU
GEOLOGIST:
SHEET ....of ....
Formation
Member
Bed No
Thickness (m)
Lithology
Sedimentary structures/grain size
Clay
Silt
sand
Vf
f
M
C
Vc
gravel
Pebbles
Cobbles
Boulders
Paleo-current
Lithofacies Name/Description
Lithofacies Code
Enagi
Bida
2
4
6
8
10
12
Thick muddy siltstones interbedded with thin tabular sandstones some of which have erosive bases.
F6
Massive, clast-supported conglomerate with gravel to cobble sized clasts composed of quartz, quartzite, schist and gneiss rock fragments. The average grain size decrease upwards.
Precambrian Basement complex rocks