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Caractéristiques sédimentologiques et ichnologiques de la séquence silicoclastique du Dur At Talah. Importance dans l'interprétation des séries tidales et fluviatiles (Eocène supérieur, le bassin de Syrte, Libye)

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Abstract

Dur At Talah sedimentary sequence, located at the southern side of the Sirt Basin in central Libya, is composed of 150 m thick of mainly siliciclastic rocks. The importance of this sequence is linked to the importance of the Sirt Basin as one of large hydrocarbon reservoirs in Libya. The sequence is also an excellent site for vertebrate fossils of Late Eocene, the age of the sequence.

Previous studies, though very limited compared to the importance of this area, are focused on its paleontological content. Sedimentology received only scant attention before this project. This thesis is an outcrop based study in which the focus is given to the sedimentary and biogenic (trace fossils) structures, aiming at defining and interpreting depositional facies which building up the sequence. The study is mainly based on field data which are analyzed on the light of related published literature and on the comparison with modern sedimentary environments.

Results of facies analysis have led to splitting the entire sequence into three genetically related intervals. The oldest, we called the New Idam Unit (around 80m), is composed of very fine sandstones to mudstones. New Idam Unit is unconformably overlain by the Sarir Unit (around 50m), composed of medium grained cross bedded sandstones (the lower 25-30 m) changes up to very coarse and microconglomeratic sandstone (the upper 20-30 m). Thus, the Sarir Unit is split into the lower Sarir Subunit and upper Sarir subunit.

The New Idam Unit presents both classical and unusual sedimentary and biogenic indicators that attribute this unit to estuarine depositional environment. It starts with outer estuarine (the lower 35 m) and ends up with inner estuarine (the upper 45 m). Maximum flooding surface is located in between. Above this surface the fluvial indicators increase and tidal indicators decrease, thus providing clue for basinward (North) migration of the shoreline.

The lower Sarir subunit which was previously interpreted as fluvial deposits, preserves multi-scale sedimentary structures that undoubtedly belong to tidal processes. This is especially evidenced at the lower part of the lower Sarir Subunit (LLS). Fluvial indications over dominates the tidal ones in the upper part of the lower Sarir (ULS). Due to this configuration the whole lower Sarir subunit is interpreted as shallow marine, deltaic, depositional system, occurred during sea level ¨normal¨ regression. This time, maximum flooding surface is located between the LLS and ULS.

The lower Sarir subunit is terminated by subaerial unconformity, with evidences of subaerial exposure preserved at the top of the ULS. These are intruded by the upper Sarir subunit which presents clear evidences of strictly fluvial environment of deposition.

The deposits of the upper Sarir subunit record the low stand system tract part of the Dur At Talah sequence. In addition to the outlined results, the sequential pattern of the depositional events is suggested for the entire sequence of Dur At Talah. This study provides a valuable information regarding the depositional and sequential aspects of the Sirt Basin during the late Eocene, it also provide an unique case study for the better understanding of the shallow marine tidal deposits.

Key words: Dur At Talah, Late Eocene, Tidal indicators, Sirt Basin, sedimentary structures, trace fossils, burrows of crayfish, bioturbation

Résumé

La séquence sédimentaire du Dur At-Talah, située dans la partie sud du bassin de Syrte au centre de la Libye, est composée de 150 m d'épaisseur de roches principalement siliciclastiques (grès, siltites et argiles). L'importance de cette séquence est liée en partie à l'importance du bassin de Sirt qui est un des plus grands réservoirs d'hydrocarbures de Libye. La séquence est également un des plus important site de fossiles de vertébrés de l'Eocène supérieur, l'âge de la séquence.
Les études antérieures, bien que très limitées par rapport à l'importance de cette zone, se sont concentrées principalement sur le contenu paléontologique de la séquence. L'étude sédimentologique n'avait été jusqu'à ce jour que très peu abordée. Cette thèse est un travail basé sur l'examen des affleurements et où l'accent est mis sur les structures sédimentaires et biogéniques (traces fossiles), visant à définir et à interpréter les faciès sédimentaires qui ont construit la séquence du Dur At Talah.
L' étude de la séquence a conduit à diviser la totalité de l'affleurement en trois intervalles génétiquement liés. Le plus ancien que nous avons appelé la « New Idam Unit » (environ 80 m d'épaisseur), est composé de grès très fins, de siltites et d'argiles. Cette unité (New Idam Unit) est recouverte en discordance par la « Sarir Unit » (environ 50 m d'épaisseur), composée de grès fins à moyens à faisceaux de litages entrecroisées dans sa partie inférieure (environ 25-30 m d'épaisseur) et de grès grossiers à microconglomératiques dans sa partie supérieure (environ 20-30 m d'épaisseur). La « Sarir Unit » est ainsi divisée en « Sarir inférieur » et « Sarir supérieur ».
La « New Idam Unit » présente des dépôts qui sont attribués à un milieu main estuarien. La série débute par des dépôts d'environ 35 m d'épaisseur typiques d'un estuaire externe. Les 45 mètres qui lui font suite passent progressivement à des dépôts tidaux caractéristiques d'un estuaire interne. La Surface d'inondation maximale se situe entre les deux intervalles. Au-dessus de cette surface les indicateurs fluviaux augmentent et les indicateurs de marées diminuent progressivement, offrant ainsi un indice pour la migration de la rive de rivage vers le bassin (vers le Nord).
La sous-unité du Sarir inférieur qui avait été interprétée avant ce travail comme dépôts fluviatiles, préserve pourtant des structures sédimentaires multi-échelles qui sont le résultat incontestable de processus de marée. Ceci est particulièrement évident dans la partie inférieure de l'unité « Sarir inférieur » (la Lower Lower Sarir Unit ; LLS). Dans la partie supérieure de l'unité Sarir inférieur (Upper Lower Sarir; ULS), les indicateurs de dynamique fluviale dominent largement sur ceux de la marée. Le Sarir inférieur est donc interprété comme un système deltaique mis en place lors d'une régression normale. Cette fois-ci, la surface maximale d'inondation se situe entre le LLS et ULS.
Le « Upper Lower Sarir » (ULS) se terminée par une discordance subaérienne, avec de nombreuses traces d'émersion conservées au sommet de l'ULS. Celles-ci sont recoupées par le « Upper Sarir » qui montre des marqueurs fiables d'environnement de dépôt strictement fluvials.
Les dépôts du « Upper Sarir » enregistre la séquence de bas niveau marin. Cette étude fournit des informations précieuses concernant le dépôt des séquences dans le bassin de Syrte au cours de la fin de l'Éocène. Elle fournit également une étude originale sur la dynamique tidale dans des milieux marins margino-littoraux.

Mots clés: Dur à Talah, Eocène supérieur, indicateurs de marée, bassin de Syrte, structures sédimentaires, traces fossiles, terriers d'écrevisses, bioturbations

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Introduction to the thesis

This thesis presents an outcrop-based sedimentological study of a 150 m thick siliciclastic rooks dominated escarpment, located in southern fringes of Sirt basin, Libya. The thesis includes five chapters.

Chapter one

Location and general preview about Dur At Talah escarpment

This chapter introduces the study area, its location, geomorphology, age, and present outlines of the previous works accomplished in the study area. The aim of this study is to present the sedimentology of the Dur At Talah escarpment, using outcrop data gathered during two seasons of field work.

Chapter two

Combination of sedimentary and biogenic structures provides recognition of emersion surfaces and leads to distinguishing outer and inner estuarine environments

Chapter two describes in detail the sedimentary facies involved in the fine grained sandstones and mudstones of the New Idam Unit (the lower 80-100m of the sequence), based on sedimentary structures, fossils and trace fossils. This Unit was previously interpreted as pure tidal deposits. The work in this chapter allows identification of several emersion features among other environmental indicators. Accordingly, many newly recognized subenvironments have been detected. This leads to better understanding and thus refining the depositional environment of the New Idam Unit. Instead of tide-dominated sequence, it is now proved that this unit succession is commences with tide dominated outer estuarine (coastal) environment and ends up with inner estuarine mixed tidal-fluvial environment. Recognition of wind accumulated sand at the lower part and fresh water trace fossils at the upper part is among the most significant outcomes of this chapter.

Chapter three

The sedimentary geology of the Sarir unit, the constituting facies and their interpretation, recording a jump from shallow marine to fluvial system

Chapter three is devoted to study the coarse sandstones of the Sarir Unit (50m thick) which is superposing the New Idam Unit. It focuses on the description and interpretation of the sedimentary facies composing the Sarir Unit. 14 facies have been described from the base to top of the unit. Based on the shared common features these facies are assembled into three facies groups. Characteristic sedimentary aspects of each group allowed identification of three environmental setting. Tide-dominated environment at the base, mixed tidal-fluvial at the middle, and exclusively fluvial environment at the top. This chapter paid supplementary attention to the contact between this unit and the underlaying New Idam Unit, and proves that this contact is recording an erosional transgressive surface. Within the Sarir unit itself, this chapter provides evidences of transitional relationship between the tide dominated and the mixed tidal fluvial environment, and unconformity between the mixed environment and the fluvial environment.

Chapter four

Sedimentary structures association and their implications in recognizing ancient tidal bed forms (dunes and megaripples). Example from Lower Sarir Unit, Dur At Talah outcrop, Late Eocene, Sirt Basin, Libya.

Chapter four concentrates on the cross-bedded sandstones of the Lower part of the Sarir Unit which was previously attributed to fluvial environment. This chapter is dedicated to describe and interpret sedimentary structures and link them to tidal rather than fluvial processes. It exposes an essential sedimentary structure analysis, complementary to the chapter three. Undoubtedly-tidal sedimentary structures are presented as an association of multi-scale exclusively tide-generated structures. These impart crucial significance in the recognition and distinguishing of the tidal dunes. This chapter comes up with subtidal and intertidal bathymetry as a dominating depositional setting for the sandstones of this interval, and display evidences of semidiurnal regime acted during their deposition.

Chapter five

Sequential analysis of Dur At Talah sequence

Chapter five put emphasize on the main outcomes presented in the chapters (1-4) of the thesis. It compiles the main results from the facies interpretation of the strata building up the entire Dur At Talah sequence. This chapter also presents the relationships between these different stratigraphic units based on the elaborated geological models constructed for each unit of the sequence. Accordingly, sequential interpretation linked to sea level fluctuation has been suggested.

Appendixes

1- Abouessa et al. (2012)

This appendix encloses the results of a published article (Abouessa et al., 2012), Journal of African Earth Sciences, entitled: New insight into the sedimentology and stratigraphy of the Dur At Talah tidal-fluvial transition sequence (Eocene–Oligocene, Sirt Basin, Libya). This chapter is started with the general geographical and geological information about the study and the escarpment. The article is based mainly on the general and initial informations collected from the first field trip to the area. The article provides a comprehensive understanding of the Geology of the Dur At Talah escarpment. It considers the few previous published studies and essentially comes up with new results about stratigraphy, sedimentary structures, bioturbations and depositional environments.
The chapter subdivides the Dur At Talah succession into two new rock units. The lower unit (80-100 m), named the New Idam Unit, composed of bioturbated fine sandstones and mudstones. Tide dominated estuarine environment is assigned for this Unit. The Upper unit (50m) called the Sarir Unit, composed of coarser cross-bedded sandstones which is splitted, according to the sedimentological variations, into lower (Lower Sarir subunit, dominantly medium grained) and upper (upper Sarir subunit, dominantly coarse grained) parts. Transitional tidal fluvial setting is assigned for the lower part and fluvial for the upper part.

2- Abstracts (oral presentations)
- The 5th Technology of Oil and Gas Forum (Tripoli, 12-14/10/2010)

Abouessa A., Duringer Ph., Pelletier J., Schuster M., Salem M.J., Hlal O. Tidal influenced Eocene deposits of Dur at Talah (Libya) compared with present-day tidal sediments of the bay of Mont Saint Michel (France). (oral)

- The 13ème Congrès Français de Sédimentologie (ASF), Dijon (14-16/11/2011)

Abouessa A., Pelletier J., Duringer Ph., Schuster M., Rubino J.-L. 2011. Characteristic sedimentary structures of a fluvial-tidal transitional zone (Dur at Talah sequence, upper Eocene, Libya). Livre des résumés 68, 1-2. (oral)

- 30th meeting of the International Association of Sedimentologists (IAS), Manchester (2-5/09/2013) .

Abouessa, A., Duringer, P., Schuster, M., Pelletier, J., 2013. Identification and implication of emersion phases in a tidal-fluvial depositional system: lessons from the sedimentary facies and bioturbations of the Dur at Talah (Eocene, Sirt Basin, Libya). (oral)

CHAPTER 1

1. Location and general preview about Dur At Talah escarpment

1.1. The location and geomorphology of the Dur At Talah escarpment

Dur At Talah escarpment is located in the southern margins of the Sirt basin (Fig. 1) extends in an east-west direction for about 150 Km, starting from the southeastern corner of Al Haruj basaltic massif, and occupies part of the northern limit of Sarir Tibesti. The escarpment can easily be distinguished into three morphological elements (Fig. 1): (i) the low-re-

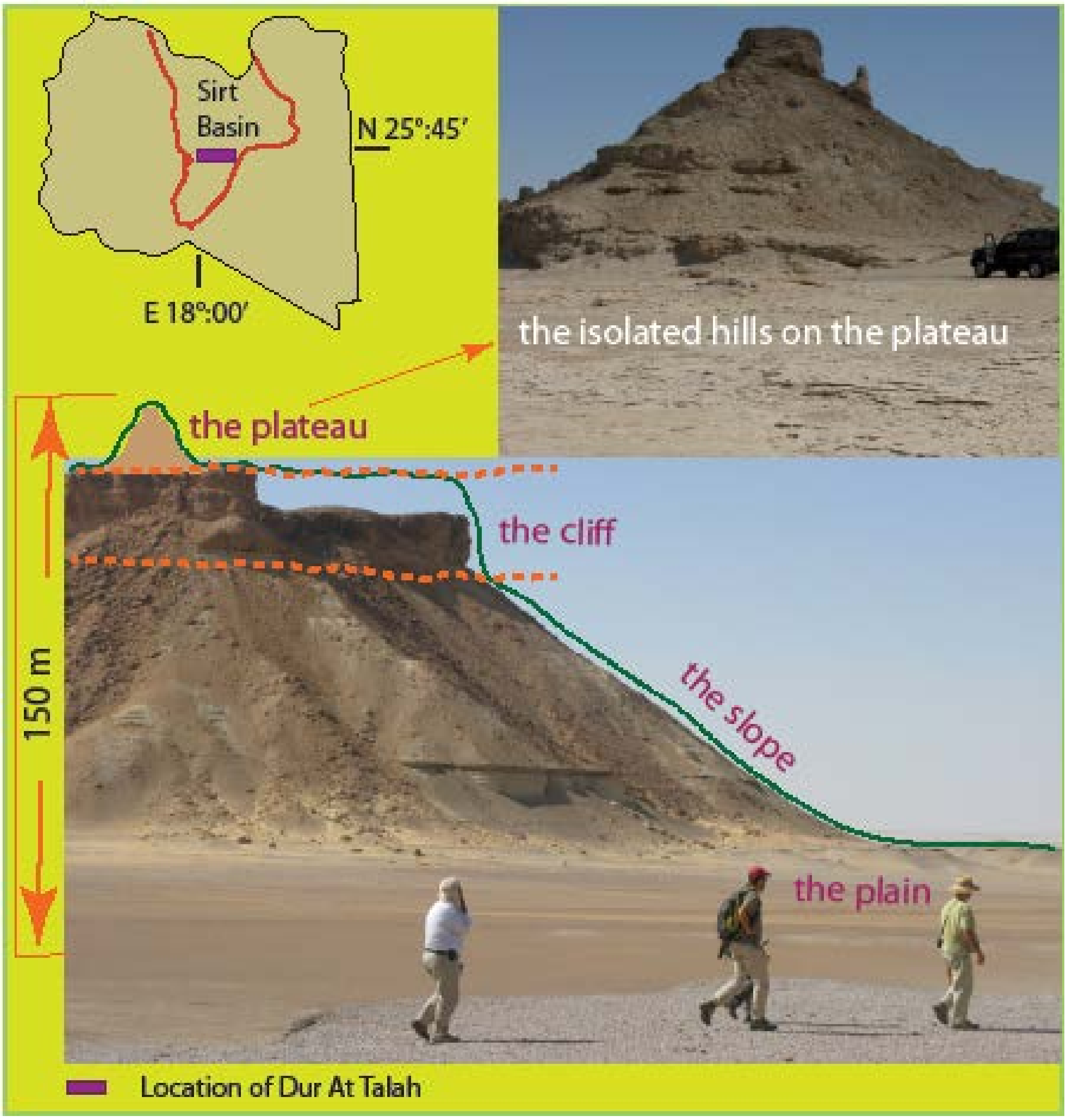


Fig. 1. Location of the Dur At Talah area (the purple rectangle) in the southern part of the Sirt Basin, central Libya. the three morphological elements of the escarpment is given by the large image, the small photo above shows an example of the isolated hills scattered on the plateau capping the escarpment.

lief plain to the south (Sarir Tibesti) covered by Quaternary sediments, (ii) the middle part started with gentle-moderate slope below, jump into a steep cliff above. This part forms the core of the escarpment, located between the plain below, and extends to the capping plateau. The rocks composing the slope are fine sandstones and the clay-mudstones of a rock unit called New Idam Unit (60-100 m). The cliff (20-30 m) constitutes the medium to coarse cross bedded sandstones, and (iii) the plateau, which is attached to, and capping the escarpment. It consists of scarcely scattered hills (around 20 m thick) made of coarse to microconglomeratic sandstones. The rocks make up the cliff and the plateau is called Sarir Unit. Knowing that the Sirt basin is a structural (rift) basin constructed as a series of troughs and platforms (Fig. 2) Dur At Talah escarpment is regarded as the southern part of Abu Tumayam trough. More details about the morphology is given in Appendix (1; Abouessa et al., 2012).

1.2. Sedimentary filling of the Sirt Basin

The basin is composed of series of horsts and grabens (i.e. troughs). In the troughs of the basin, the thickness of sedimentary rocks to the basement exceeds 7000 m. This sedimentary infill ranges in age from Cambro-Ordovician to Quaternary (e.g., Sinha and Mriheel, 1996). The Early Paleozoic history of the basin reflects a relatively undisturbed intracratonic sag basin (Bellini and Massa, 1980) as part of the Gondwana continent. Cambro-Ordovician siliciclastic sedimentary rocks are only locally preserved (El-Hawat et al., 1996). These rocks occur today as erosional remnants occupying some parts of the basin floor. Rocks of Silurian-Devonian age are known only from few localities in the basin. Furthermore, there are no reports as yet of rocks of Carboniferous-Permian age (Sinha and Mriheel, 1996). Devonian to Triassic rocks are evident in some parts of the basin (Tawadros, 2001). The area was probably positive during these periods, attributed to the Hercynian orogeny (Conant and Goudarzi, 1967; Bellini and Massa, 1980). Jurassic to Early Cretaceous sandstones known as “Continental Mesozoic” or “Nubian Sandstones” uncomfortably overlies Early Paleozoic rocks.
Sediments of Late Cretaceous to Late Miocene age include marine carbonates, evaporites and shales, and paralic non-marine sandstones and shales, (e.g., Selley, 1968; Sinha and Mriheel, 1996). The basin witnessed several phases of marine transgressive episodes interrupted by periods of regression (Gumati and Kanes, 1985; Sinha and Mriheel, 1996).
The main source of clastic material supplied to the study area as well as to the Sirt Basin in general, was the higher hinterland to the south, around Tibesti Massif, where the basement as well as Paleozoic and Mesozoic rocks was continuously exposed (e.g. Barr and Weegar, 1972; Benfield and Wright, 1980; Hallett and El Ghoul, 1996; Ahlbrandt, 2002; Vasic and Sherif, 2007). A major marine transgression in Paleogene times extended southward, from the basin centre far into the embayment (Epicontinental Sea; Bradly et al., 1980; Gumati and Kanes, 1985). During the Late Eocene, this transgression had reached the Tibesti area and possibly beyond (e.g., Barr and Weegar, 1972; Benfield and Wright, 1980). This transgression is best recorded by the marine fossil dominated carbonate rocks (Wadi Thamat Formation) exposed beneath the Dur At Talah strata. Post-Eocene sediments in the basin were deposited in the period of overall regression which commenced with the onset of Oligocene (Benfield and Wright, 1980). In North Africa, Upper Eocene-Lower Oligocene sedimentary sequences resembling that of Dur At Talah are reported (Bown, 1982; Abdel-Fattah et al., 2010; Underwood et al., 2011) in the area of the Fayum depression (Egypt). Fossil assemblages of both sequences, Dur At Talah and Fayum, are also comparable (e.g., Savage, 1971; Wight, 1980; Jaeger et al., 2010a).

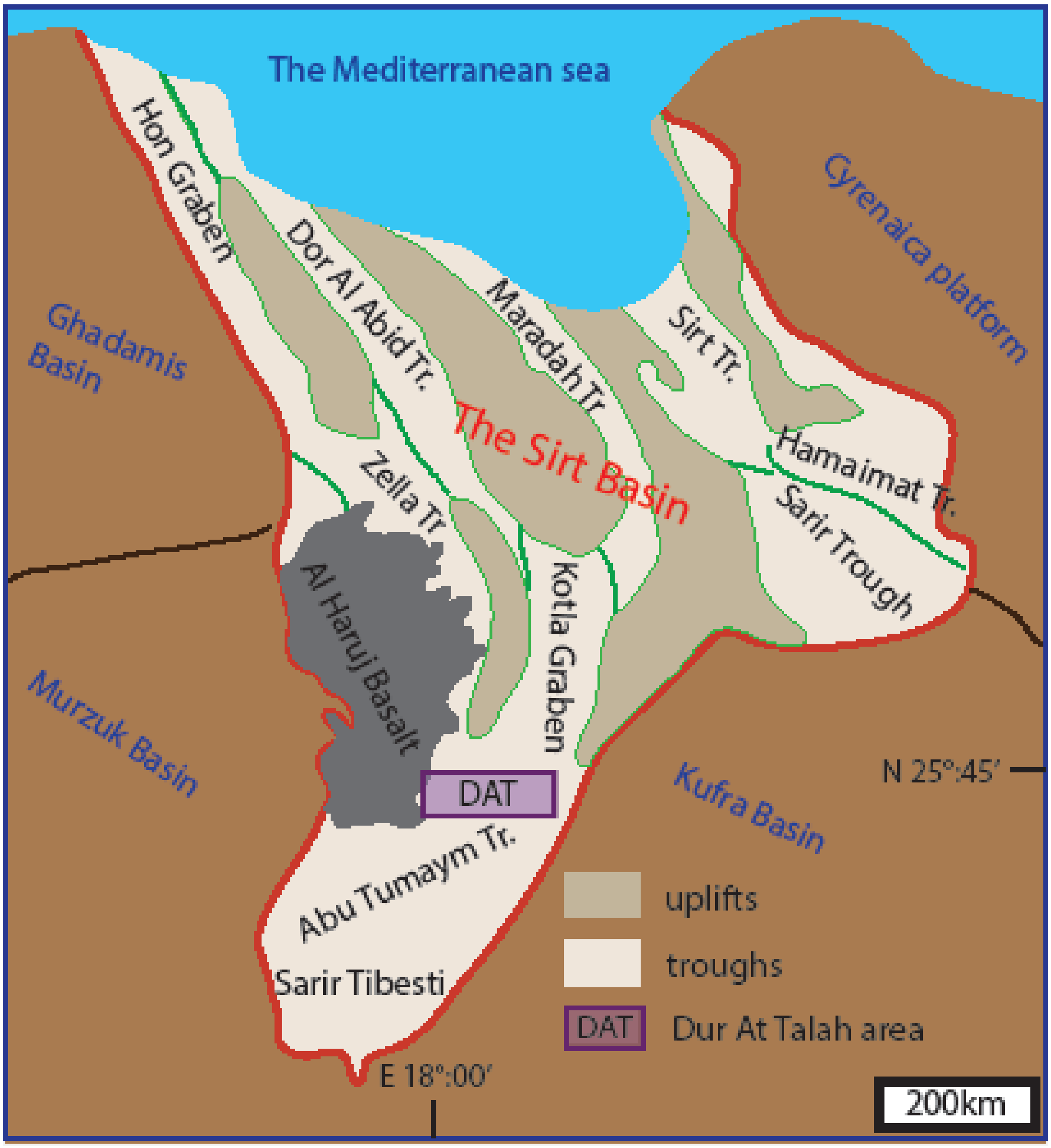


Fig. 2. Shows the location of the Dur At Talah relative to the major structural elements (uplifts and troughs) of the Sirt Basin.

1.3. The previous studies of the Dur At Talah sequence

The name of the Dur At Talah escarpment was first written "Dor al-Talha" in a geological context given by Bellair et al. (1954). It means "the home of the acacia". Bellair and the coauthors were working within a group of French geologists exploring for petroleum resources in the deserts of Libya. Probably for the first time, they reported the occurrence of Tertiary vertebrates at a few locations. The French paleontologist Camille Arambourg provided a preliminary description of this outcrops and the fossil mammals they provide (Arambourg and Magnier, 1961). Most importantly, Arambourg showed that a few archaic proboscideans and hyracoids recovered from Libya were nearly identical to ones from the Fayum (Egypt). Those of the Fayum had been discovered in the early part of the century (Andrews, 1906; Osborn, 1908). Savage and his student Wight A.R.W. spent several weeks in 1968 and 1969 working from a camp set up at the escarpment to characterize its geology and to collect fossil mammals (Savage, 1971; Wight, 1980). The later brought up the first comprehensive biostratigraphic study that gave strong emphasize to the vertebrates and invertebrate fossil importance of the area. Savage and Wight provided many other paleontological similarities between Dur At Talah and Fayum, in terms of invertebrates as well as vertebrate contents of both sites. This aspect has been emphasized by Rasmussen et al. (2008) and more recently by Jaeger et al. (2010a,b). The latter two groups were interested mainly by the paleontological rather than sedimentological researches.

Worth mentioning is that the greatest part of fauna reported by all those specialists was of fresh water and terrestrial habitants including primates, rodents and fish. Marine types are evident at the basal 30 m of the escarpment. Different types of fossil flora (various species of leaves imprints, fossil fruits) have also been reported from different levels of the escarpment (Wight, 1980, Pelletier, 2012). Pelletier provided further sedimentological description and interpretation putting greater emphasize on the lower part of Dur At Talah sequence, the New Idam Unit. Based on those fossil communities and compared to the Fayum fossil assemblage, lush tropical conditions has been proposed to the study area during Eocene (Wight, 1980; Bown et al., 1982; Rasmussen et al, 2008) which is applicable for North Africa in general (Bown et al., 1982; Rasmussen et al, 2008).

Concerning sedimentology and stratigraphy (Fig. 3), Wight (1980) was the first to subdivide the rock succession of the Dur At Talah into three units. The soft deposits (presented by the slop) under the cliff is made by clays and fine sands have been split into “Evaporite Unit” for the basal part and “Idam Unit” for the upper part. According to our observations, the greatest part of the evaporites in this interval is diagenetic rather than depositional. Wight introduced the name “Sarir Unit” to the cross bedded sandstone composing the cliff. It is obvious that Wight does not include the microconglomeratic sandstone that is exposed on the plateau in his study.

Recently, Vasic and Sherif (2007) first introduced the “Dur At Talah Formation”, to include the entire rock succession from the low relief plain to the top of the isolated hills on the plateau. They come up with the first published geological map of this area scale 1:250,000. They split their formation into two members: (i) the Lower Member, form the plain to the top of the cliff and (ii) the Upper Member consists of coarse and microconglomeratic sandstones composing the hills. It is obvious the Vasic and Sherif ignored the regional erosional (transgressive) contact which breaks their lower member. The jump in slope from gentle-moderate below to steep, cliff forming above is clear and is, moreover, marked by remarkable change at least in grain size.

A gradational contact separates the Dur At Talah Formation from the underlying carbonate rocks of the Wadi Thamat Formation. Middle to Late Eocene is assigned for this formation (Vasic and Sherif, 2007). They suggested the Oligocene age for the Dur At Talah deposits based on the stratigraphic position and correlation with similar sediments in the adjacent areas. The latest published article included the entire (150 m) Dur At Talah rock sequence is Abouessa et al., (2012), the Late Eocene is ascribed here. This article depended on the lithological and ichnological (which had been ignored in the previous studies) differences to divide the sequence into two rock units: the lower is The New Idam and the upper is Sarir.

1.4. The age of the Dur At Talah sequence

The results of the Micropaleontological study by Jaeger et al (2010a,b) was reliable as they used fresh (in situ) fossils via excavation into several level in the outcrops. The age assigned

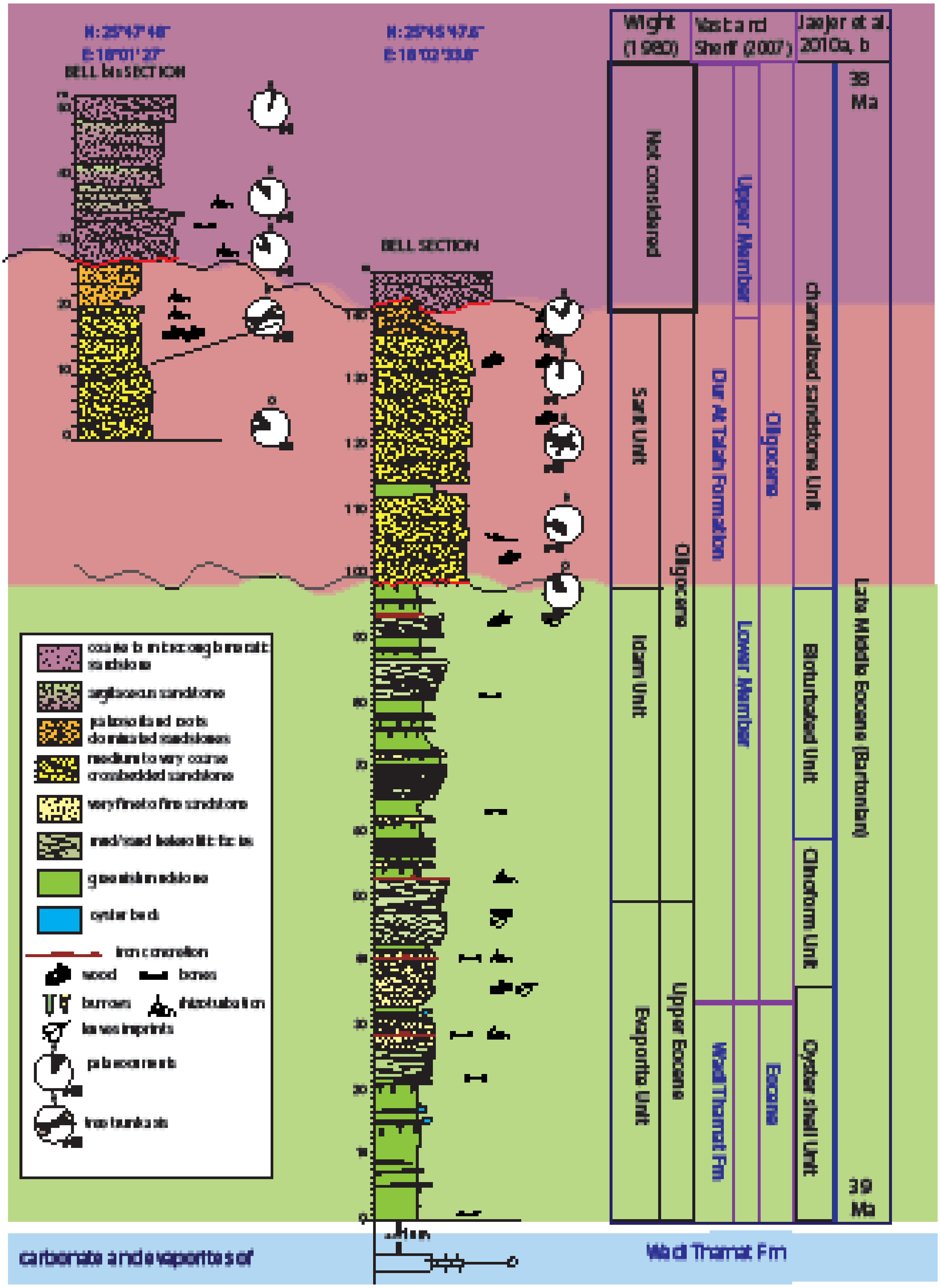


Fig. 3. Sedimentological and stratigraphic log of the studied sequence shows the existing subdivisions. Some geological aspects such as the palaeocurrent directions are included. The sedimentological sequence is taken in two locations (10 km apart) due to the outcrop conditions. The Figure is modified from Abouessa et al. (2012)

is 38-39 Ma (Upper Eocene). But the fossils are collected solely for the lower part of the escarpment, the New Idam Unit. Similarities in paleontological contents between Dur at Talah and Jebel Qatrani Formation (Fayum, Egypt) have already been noticed (e.g. Savage, 1971; Wight, 1980; Rasmussen et al., 2008). Striking similarities also suggested when comparing the sedimentology of Dur at Talah with that reported from the Jebel Qatrani (Bown, 1982; Abdel-Fattah et al., 2010; Underwood et al., 2011). Accordingly Eocene-Oligocene age is proposed by Savage, Wight, and Rasmussen et al. this age supports that assigned by Bellair et al. (1954; uppermost Eocene to the lowermost Oligocene) based on paleontological assemblages. Because of the presence of proboscideans remains (Barytherium and Moeritherium) Arambourg and Magnier (1961) gave the Late Eocene (Priabonian) age for the lower part of the escarpment also compared the Fayum outcrop (Egypt). Vasic and Sherif (2007) acknowledged Lower Oligocene age assigned by Peregi et al. (2003) for equivalent rocks exposed in areas adjacent to the Dur At Talah escarpment. Taking into consideration that all fossils attributing the Dur At Talah sequence to Late Eocene is collected from the Lower part of the sequence and that the upper part is devoid of fossils, then Lower Oligocene cannot be excluded for the upper part of the sequence.

1.5. The methods of the study

This study is mainly outcrop based. Data sets gathered in the course of fieldwork (two field seasons, October- November 2009 and 2010) consists of sedimentological, ichnological, and stratigraphic informations. Through photographing, sketching and detailed logging has been performed. Photo mosaics (and videos) were taken for many exposures that demonstrate large-scale architectural elements. In fact because of the unsecure conditions in Libya during the years 2011/2012 other field trips to the studied area have been prevented. Therefore, the already gathered photos become an essential material for the investigation and analysis.

During the field work, bounding surfaces have been traced to enable accurate distinguishing of the architectural elements, and the continuity of sedimentation units. Obvious surfaces exist between different lithology, different ichnofacies, and different sedimentary structures. Key stratigraphic surfaces separate deposits of different facies association, levels with roots and bioturbations separate depositional zones are traced. For instance, the soil interval above the topmost oyster/mollusk banks in the sequence is detected over wide (around 100 km) lateral extent. Frequently recurring emersion surfaces some of them are very subtle others are obvious has been identified. Sedimentological observations have concentrated on sedimentary structures particularly large and small scale reoccurring patterns, and the associations of multi-scale structures.

Encountered sedimentary structures have been used to define and differentiate different facies. Genetically related facies are grouped into facies associations. All these informations are analyzed and as much as possible studied in the light of the up to date published literature. Facies described in this manuscript are of the rank of facies association. I.e. small scale differences are encountered in the same facies type. For example very fine grained lithology applied for very fine sandstone to siltstone. Very small variations in grain size are sometimes neglected because it does not involve essential change in the facies interpretation. Field trips to modern sedimentary environments have been conducted in order to facilitate recognition of the depositional environments in the light of their encountered sedimentary and biogenic structures. Tidal structures were compared to the modern tidal environments in the Mont Sainte Michel Bay of France. Bioturbations, especially firmground traces were compared to similar ones from the Kampot delta, located in South Cambodia. Those field trips were very useful in better understanding of the modern tidal and fluvial environments, which are analogous to those ancient environments acting in Dur At Talah area during Late Eocene. Great emphasis has been given to analyzing sedimentary and biogenic structures to come up with well elaborated interpretation for the depositional environments. These lead to outline the depositional models and figure out their sequential pattern. Satellite image (9km2) has been selected from the best exposed area, with the minimum sand cover, has be investigated for surface geological features. Unfortunately, no specific features have been detected. In order to bring complementary information about paleoenvironments and stratigraphy, fourteen samples of clays from the New Idam Unit have been tested for micro/nanofossils (nano-fossils, dinoflagellates, palynomorphs and foraminifera) and for molecular fossils (biomarkers). Contrasting with the richness of the macropaleontological content of the Dur At Talah outcrop, the micropaleontological content is extremely poor, probably due to the weathering as well as diagenetic processes. Details about the micropaleontological analysis provided in appendix (1). Palynomorphs (spores and pollens) and no dinoflagellates have been detected. Additional tools used are the ground penetrating radar (GPR) operated on the fluvial sand bars of Kampot River. This was a useful practice but the results are not enough to be engaged in this study.

CHAPTER 2

The New Idam Unit

The aim of this chapter is to describe and interpret the New Idam Unit depositional environment via emphasizing on the associated trace fossil. A title "Combination of sedimentary and biogenic structures provides recognition of emersion surfaces and leads to distinguish outer and inner estuarine environments in the New Idam Unit" is given to this chapter.

1. Geological preview of the New Idam Unit

The 150 m thick outcrop of Dur At Talah escarpment provides a cross section of the area along 24°:45′ N. Siliciclastic rocks dominate the escarpment. Most of these rocks show features of waterlain sedimentation. Indications of intertidal to supratidal domains are obviously observed in most, except the upper 30 m of these rocks. General geology and stratigraphy are documented in (Wight, 1980; Vasic and Sherif, 2007; Abouessa et al., 2012), and is summarized in Fig. (1). Extensive marine carbonates and evaporites of Middle Eocene age are underlying this siliciclastic rocks.
Obvious variations in the morphology, grain size and sedimentary structure provide criteria to subdivide the rocks of the escarpment into two units (Abouessa et al., 2012). The lower one, forming the gentle to moderate slope, is the New Idam Unit (NIU, 80-100 m) composed of variably intensively bioturbated fine sand to mudstone, and the upper, forming the cliff and the plateau, is the Sarir Unit (av. 50 m), dominated by medium to very coarse cross-bedded sandstone. The latter is divided into two subunits: the lower Sarir composed of medium grained cross-bedded sandstone with evident tidal influence and the upper Sarir composed of very coarse to microconglomeratic sandstones deposited in fluvial environment (Abouessa et al., 2012). The contact between the New Idam Unit and the Sarir Unit is commonly erosional, although it is difficult to be distinguished in some outcrops.

At a broad scale, two predominant kinds of sequences define the New Idam Unit. Both are similar in terms of the dominating lithology (fine sandstone to mudstone, Fig. 1): (i) fining up sand-mud parasequences (around 0.5-4 m thick each), alternating with (ii) thinly laminated sand-mud successions (up to 9 m thick each).

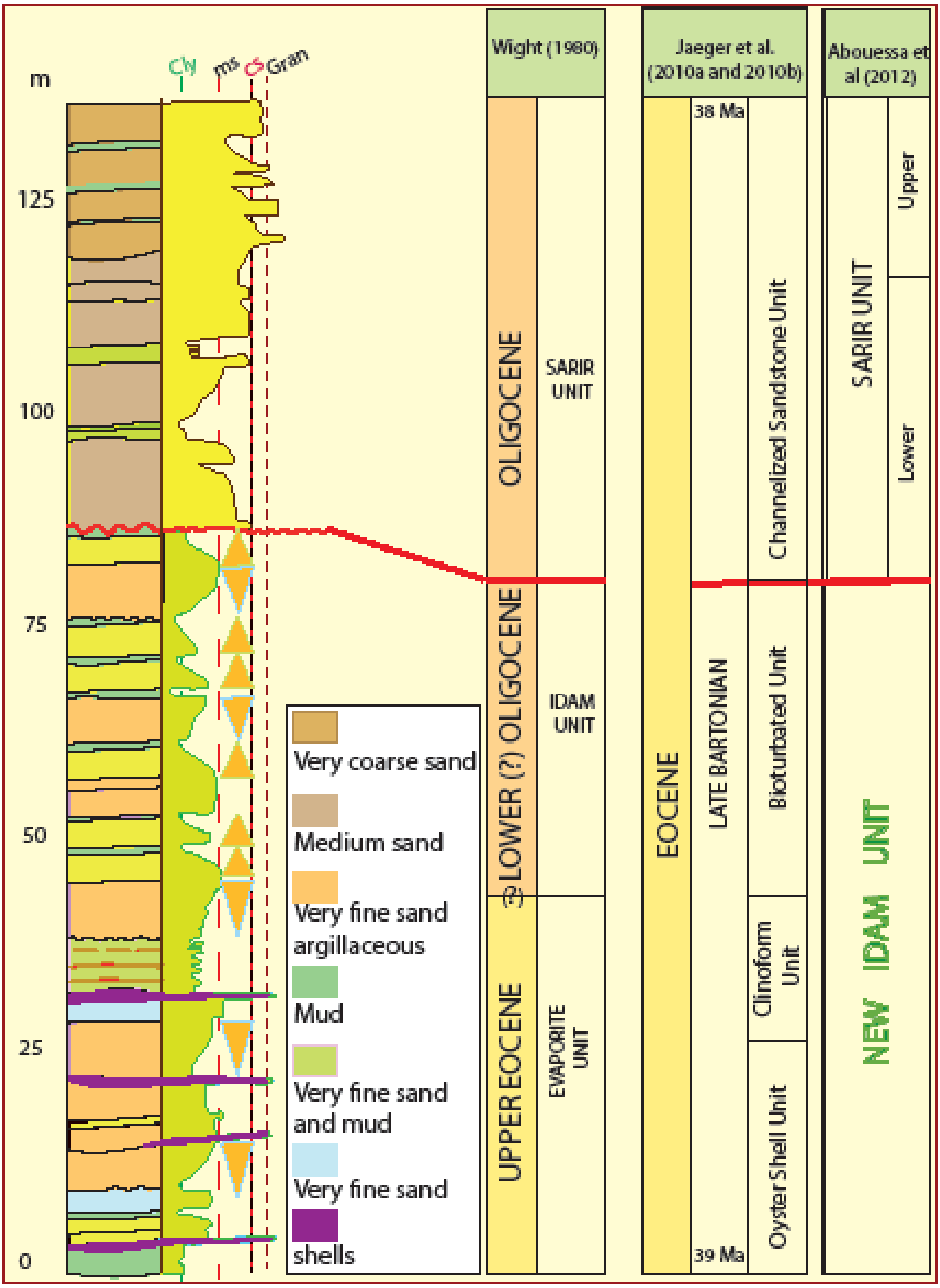


Fig. 1: Generalized synthetic log shows the position of the New Idam Unit (the lower part of the Dur At Talah sequence). Finer grain size is obvious difference between this unit and the overlying (Sarir) Unit. Fining up parasequences are one of the characteristic outcrop features.

These two types of sequences are laterally amalgamated over some hundred metres, vertically interbedded, and are displaying great variations in their content of trace fossils (Fig. 2), fossil and to a less extent the sedimentary structures.

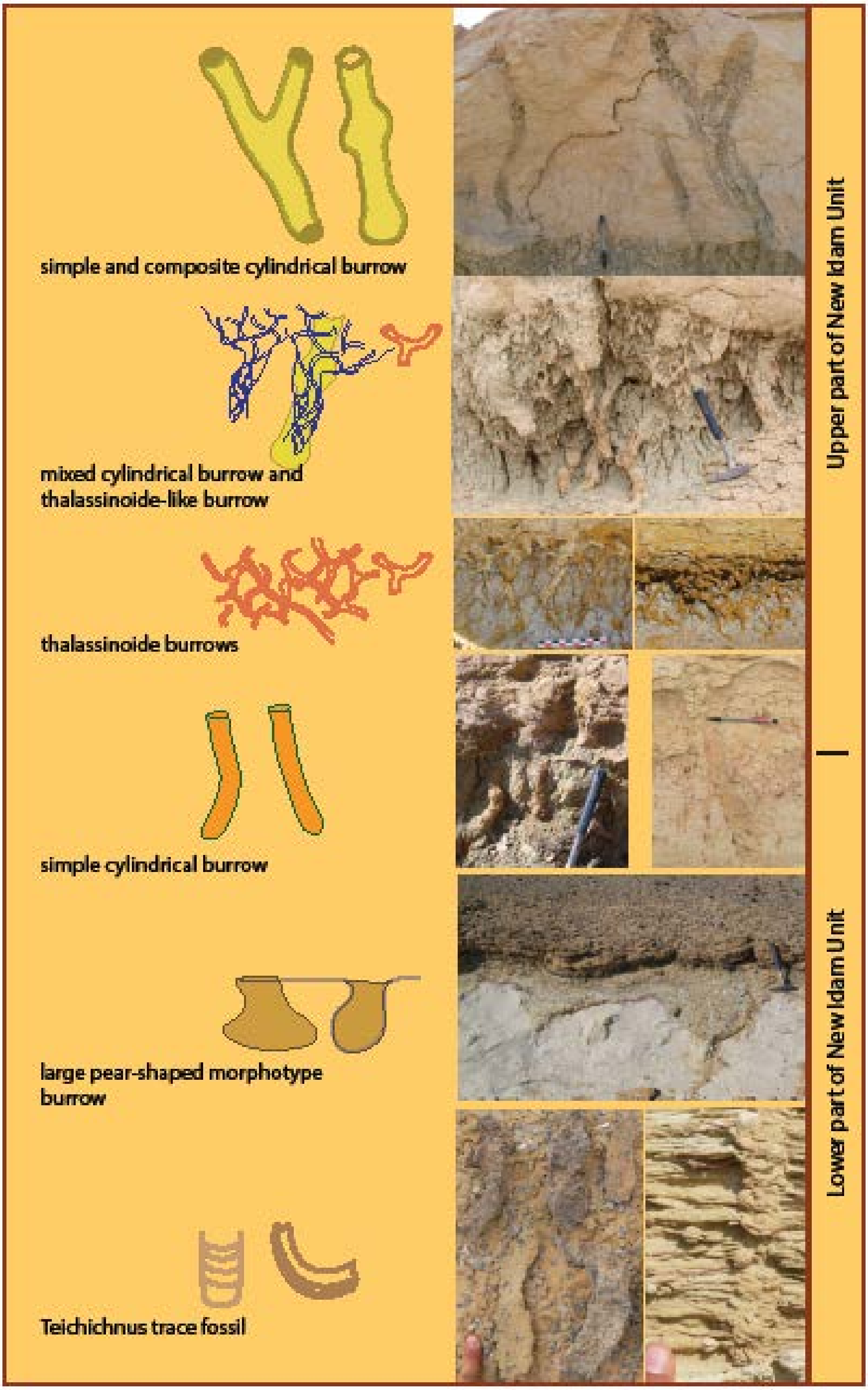


Fig. 2: The figures provide an idea about the significant changes in the types of trace fossils from the base to top of New Idam Unit.

Only at its base (the lower 20-30 m), the New Idam Unit contain several recurring beds (several cm to 1 m in thickness) of marine mollusk shells (Abouessa et al., 2012) interrupting the siliciclastic sequences. Worth mentioning that similar oyster (mollusk) beds are described underneath the studied sequence as a part of the underlaying, limestone dominated Wadi Thamat Formation (Vasic and Sherif, 2012). Differently, vertebrate fossils are observed and reported throughout the entire New Idam Unit. Variety of bones of crocodiles, fishes, proboscideans and many other terrestrial mammals are widely scattered, especially in the fining up parasequences. Details about these vertebrate fossils are reported in Arambourg and Magnier (1961), Wight (1980), Rasmussen et al. (2008), Jaeger et al. (2010a,b), Abouessa et al. (2012), Grohé et al. (2012). Among other fossils, turtles, amphibians, freshwater fishes, rodents and primates are reported by most of the authors. Exceptionally, the terrestrial aquatic fossils are common in the upper part of New Idam Unit (Wight, 1980; Jaeger et al., 2010a,b). On the other hand (Wight, 1980) reported marine species notably whales, turtles, and sirenians in the lower part of the unit.

Considering stratal organization, the thinly laminated sand- mud sequences (tidalite facies in Abouessa et al., 2012) are apparently similar from the base to top of the unit. But certainly this is not the case; they are subtly different in terms of internal sedimentary structures, fossil (fauna and flora) and trace fossil content. Furthermore, there are subtle differences in the degree of color mottling in many intervals. Above all, the thinly laminated sand- mud sequences are morphologically presented as channels of variable dimensions, meanwhile, the fining up parasequences are more or less flat bedded. Upon this similarity and variations, deciphering depositional environments becomes crucial.

Taking into consideration the encountered differences within the New Idam Unit, the unit is split into two parts. The lower part is (30-45 m; Fig. 3) and upper part (40-55 m; Fig. 4). Excluding the mollusk banks in the lower part, lithology is roughly similar in the two parts. Due to the differences in stratal organization, fossils and trace fossils content, the similar lithology presents different sedimentary facies. The description and interpretation of these sedimentary facies enabled better understanding of the New Idam Unit succession. And it led to ascribe the lower part to outer estuarine and the upper to inner estuarine environments.

2. Facies composing the lower part of new Idam Unit

The lower part of New Idam Unit is occupied by four, commonly, recurring association of facies (FA1-4; Fig. 3):

FA1) Interlaminated sand/mud facies.
FA2) Oyster bank/mudstone facies.
FA3) Well sorted sandstone facies.
FA4) Paleosoil facies.

Notably, the paleosoil facies occupies the top of the lower part of the New Idam Unit, with no sharp contact with the upper part. Other pedogenically altered horizons are frequent throughout the entire Unit, but are not as well developed as in this facies.

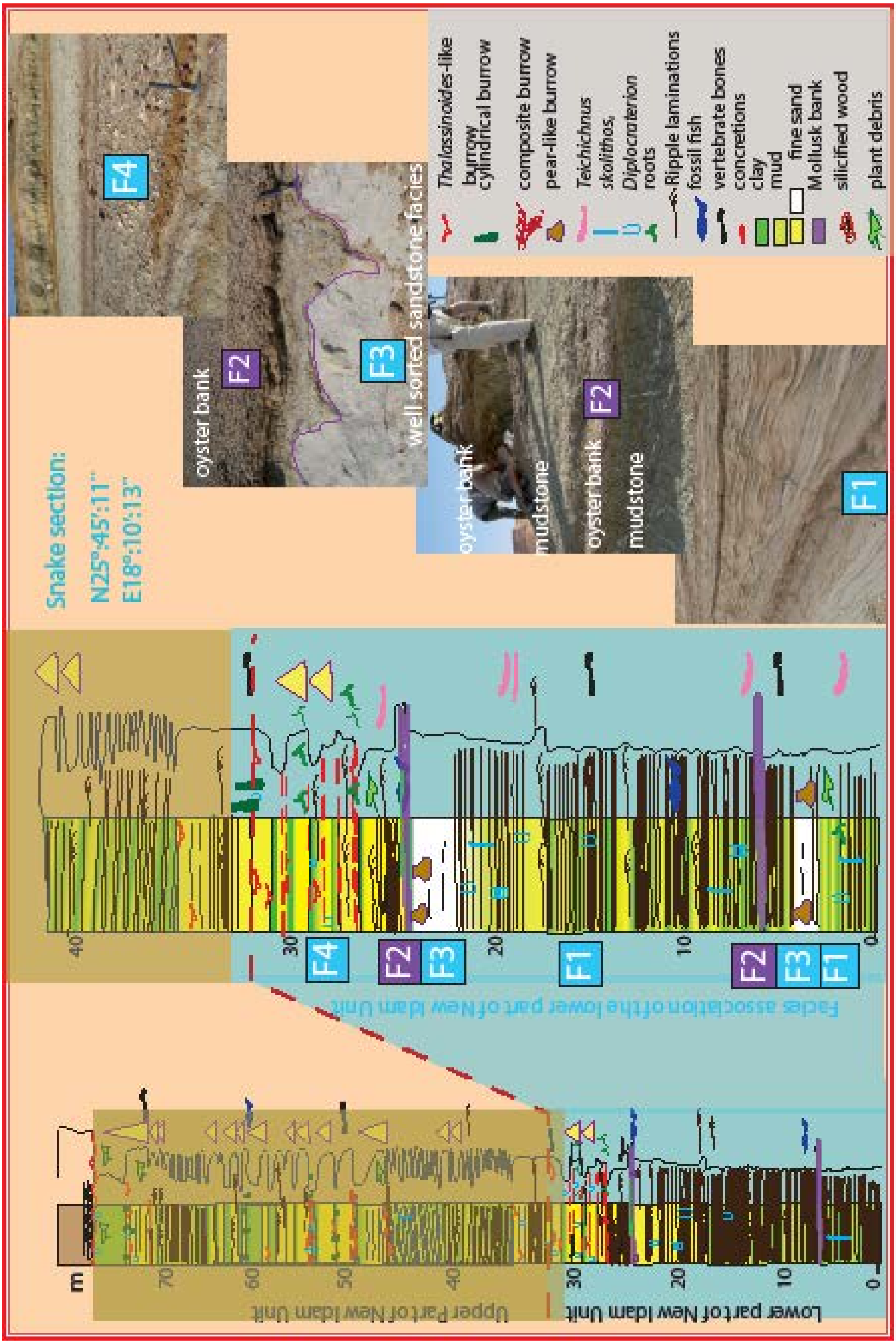


Fig. 3: shows the main facies composing the lower part of New Idam Unit and their general sequential organization. Recurrence of the facies can be noticed.

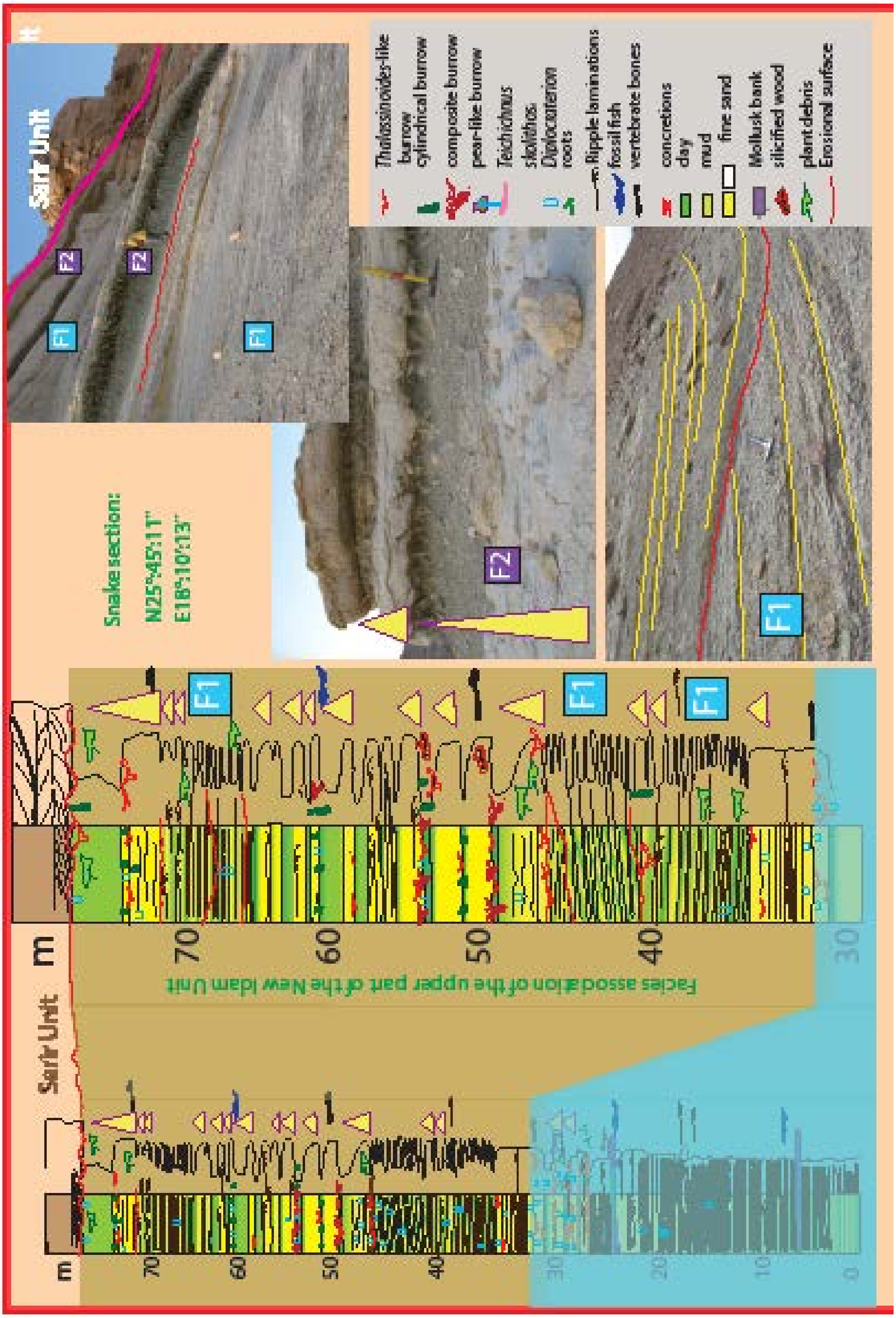


Fig. 4: Shows the facies encountered in the upper part of the New Idam Unit. Notice the absence of the mollusk banks and the frequent recurrence of the fining up parasequences.

2.1. Interlaminated sand/mud facies (FA1)

2.1.1. Facies description

This facies is exposed as a continuously thinly laminated sequence of very fine sand and mud alternations (Fig. 5A-F). One sequence may reach 9 m at its thickest part and it usually

Fig. 5A-F: Presents the characteristics of the interlaminated facies at the lower part of the New Idam Unit. A, B) show general view indicates high frequencies sand-mud interlamination with interpreted shallowing upward trend; C, D) general and detailed view of neap-spring-neap sequences; E, F) lenses of microconglomeratic lag interrupted the laminations, (D) shows the associated fossils.

shows lateral decreasing in thickness. The sand and mud layers composing these sequences are millimetric to centimetric in thickness; they show a trend of thickening upward (Fig. 5A, B). Typical tide-generated sedimentary structures are best recorded in this facies (Fig. 5C, D), compared to all other facies in the Unit. Lenses (cm-scale) of microconglomeratic lag are frequent. These later are found as intrabasinal accumulations of granules and pebbles, interrupting the sand and mud layers. These are composed mainly of rounded mudclasts and small fossil fragments (Fig. 5E, F). Sandstone rock fragments of cobble size are locally encountered. These are associated with small in situ roots and carbonaceous particles (Fig. 5G, H).

The tidal sedimentary structures recorded in this facies are the most striking aspect in the entire New Idam, upon which the whole unit has previously been interpreted as tide dominated unit (Abouessa et al., 2012). Among others, the most diagnostic are the neap-spring cycles that preserve mud drapes and double drapes. Small rhizoliths and pedogenic structures are generally noticed, specifically, at the top of this facies, these small fossil roots penetrate evident tidal laminations (Fig. 5I, J). Concerning relationship with the other facies, this one is certainly interbedded with beds of mollusk (oysters) and with the green mudstone. Both sharp and gradational contacts are observed between them.

2.1.2 Associated body fossils

Fossil occurrences in the interlaminated sand/mud facies are relatively uncommon. It mainly coexist with the microconglomeratic lag (Fig. 5E, F), and are limited to vertebrate bone fragments and shark teeth. Bones of large fishes are also frequently observed, in sediments thought to be equivalent to this facies. Moreover, Silurid catfish, lungfish and sawfish are reported from the lower part of New Idam Unit by Wight (1980), probably from this facies. Large bones of fishes, crocodiles, and other vertebrates found scattered on the surface where this facies is exposed, but these are not certainly in situ.

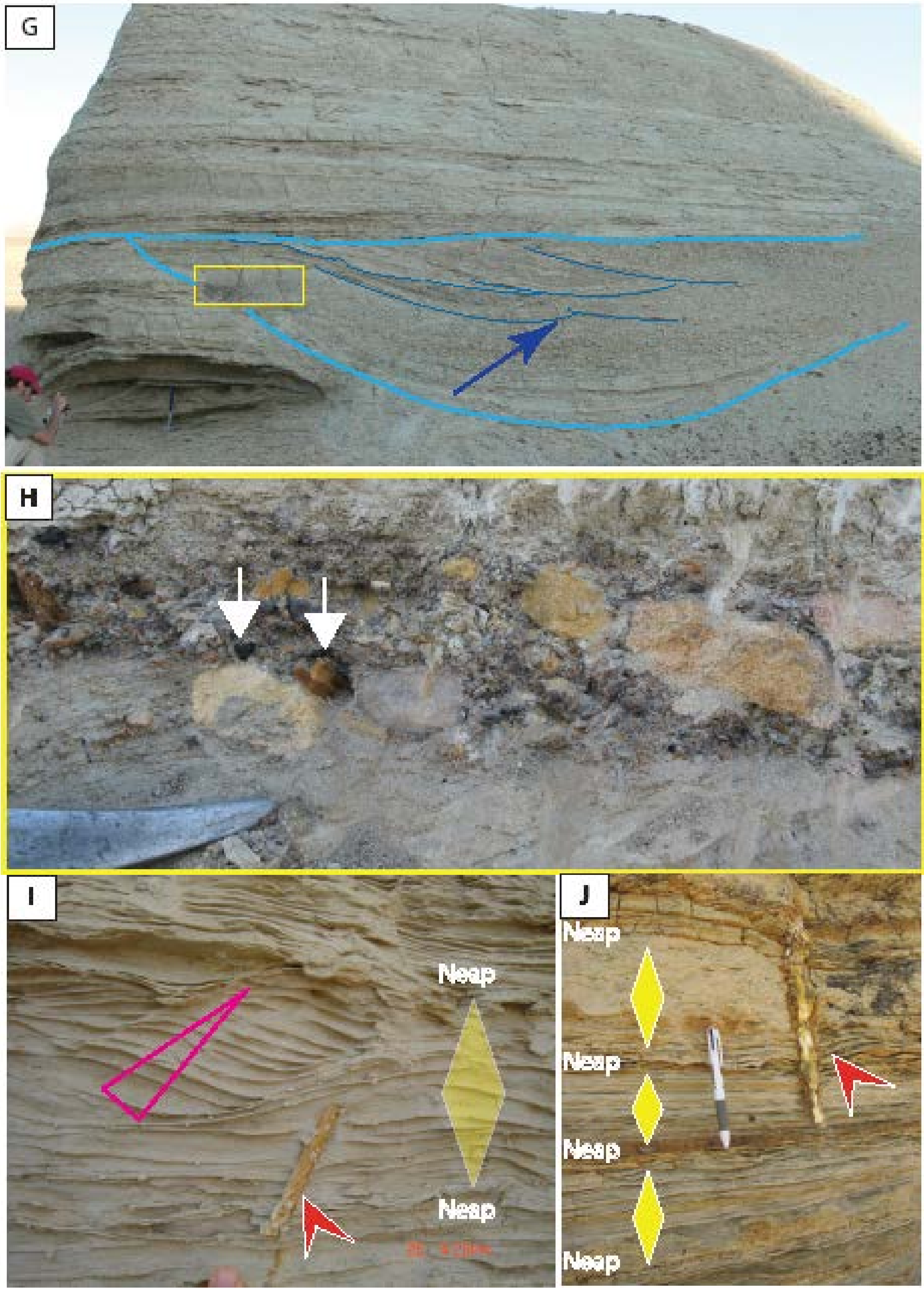


Fig. 5G-J: Characteristics of the interlaminated facies. G) this facies is channel forming facies the image shows small channel superposed by larger one; H) coarse lag with sandstone fragments and carbonaceous particles (white arrows) as well as mm scale roots. All points to terrestrial proximity; I, J) roots (the arrows head) penetrate tide organized layers. The oblique triangle in (I) points to the hierarchical thickness increase due to progressive increase in tidal energy.

2.1.3. Associated trace fossils

The most conspicuous trace fossil associated to this facies is Teichichnus isp. (Fig. 5K-P). It is well documented in Abouessa et al. (2012). Diplocraterion, Skolithos and Planolites ichnogenera are occasionally associated (Fig. 5L, O).
Teichichnus isp. are preserved in very fine grained sandstone as retrusive small-sized Spreiten structure of several cm up to 20 cm in high. They are built up as successive concave up tongues (or small elongate troughs ~ 2 cm in width, several tens of cm long (Fig. 5K). They are best observed in bedding plains where they appear as meandering flattened bodies up to 40 centimeters long. In the vertical section Teichichnus cuts across the laminated sandstone that display paired laminae of sand- mud (Fig. 5M, N), indicating their formation within the zone of tidal effect. Regardless of the burrow maker, Teichichnus is known to occur in shallow marine water deeper than that of Thalassinoides (Frey and Pemberton 1984; Taylor and Goldring, 1993). The retrusive Spreiten characterize well the close adaptation to daily tide deposition of sediments.

2.1.4. Interpretation

This facies represent the most abundant facies in the lower part. It has the greatest thickness (up to 9 m) and it preserve the best record of tidal dynamics in the whole New Idam Unit. Therefore, Inter- to subtidal setting could normally be suggested as a depositional setting. Supratidal environment is also partially suggested by the presence of root traces and pedogenic processes at the upper beds of this facies. Shallowing up ward of these tidalite sequences (from subtidal to supratidal) are indicated by the increasing of the roots intensity toward the top of the sequences. The frequent presence of lag deposits with coarse sandstone rock fragments refers to current energy capable to carry these fragments. Accordingly tidal channel can be proposed as a subenvironment. Channel morphology such as that illustrated in Figure (5G) as well as the presence of fossil fishes, ascertains this possibility. Tide dominated environment is supported by the trace fossils, Teichichnus and Diplocraterion. The small short-lived fossil roots (millimetric scale) culminating some sequences indicating channel shifting and filling of previously existed channel, followed at least a several month period of subaerial exposure.

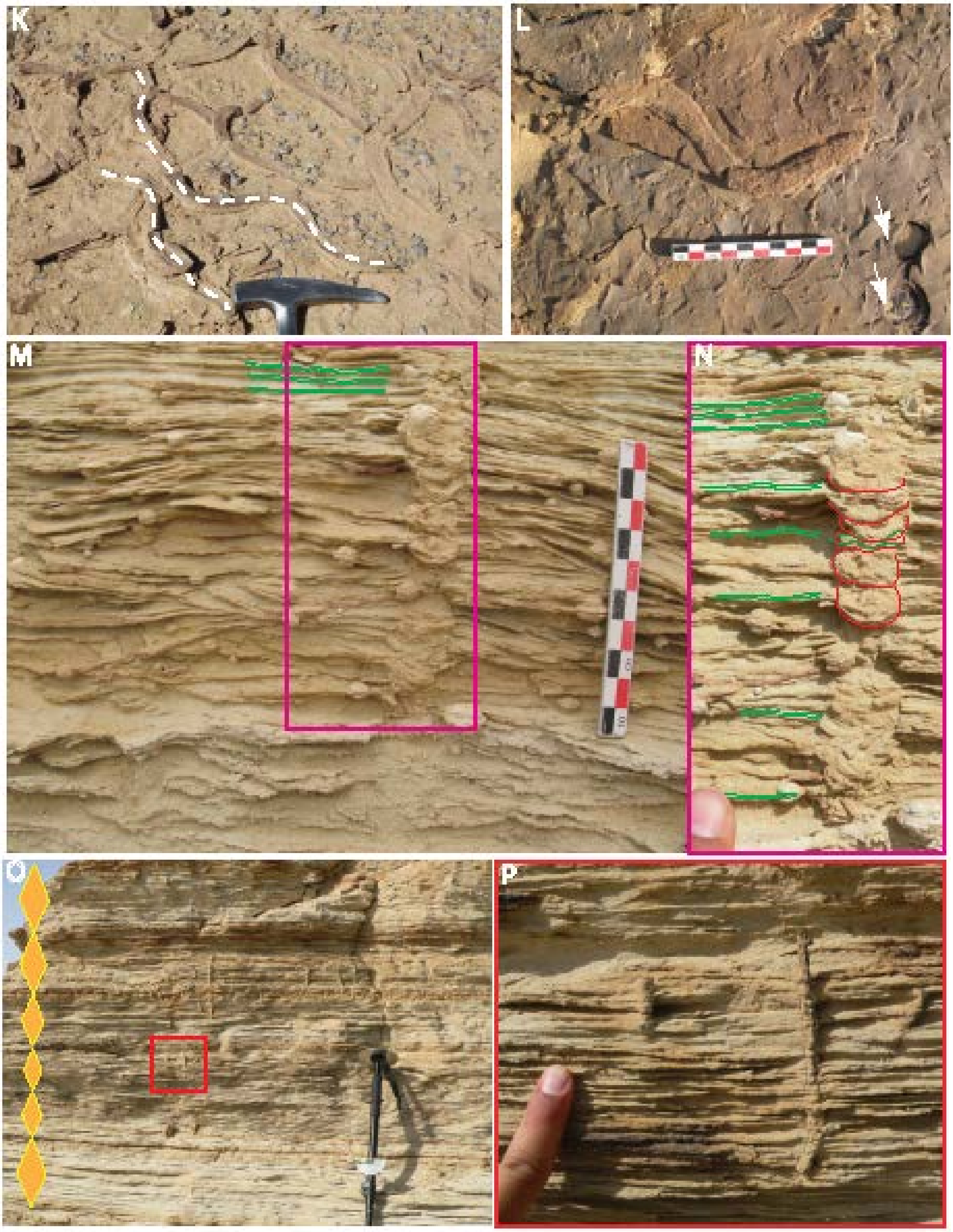


Fig. 5K-P: Trace fossils associated exclusively with interlaminated facies in the lower part of the New Idam Unit. K, L) bedding plain view of Teichichnus and Diplocraterion (white arrow in L); M-P) vertical view shows Teichichnus (interact with the tidal laminae; M, N). Skolithos and roots traces (in P) in O and B. Strong tidal signature are presented in all these locations

2.2. Oyster bank/mudstone alternation facies (FA2)

2.2.1. Facies description

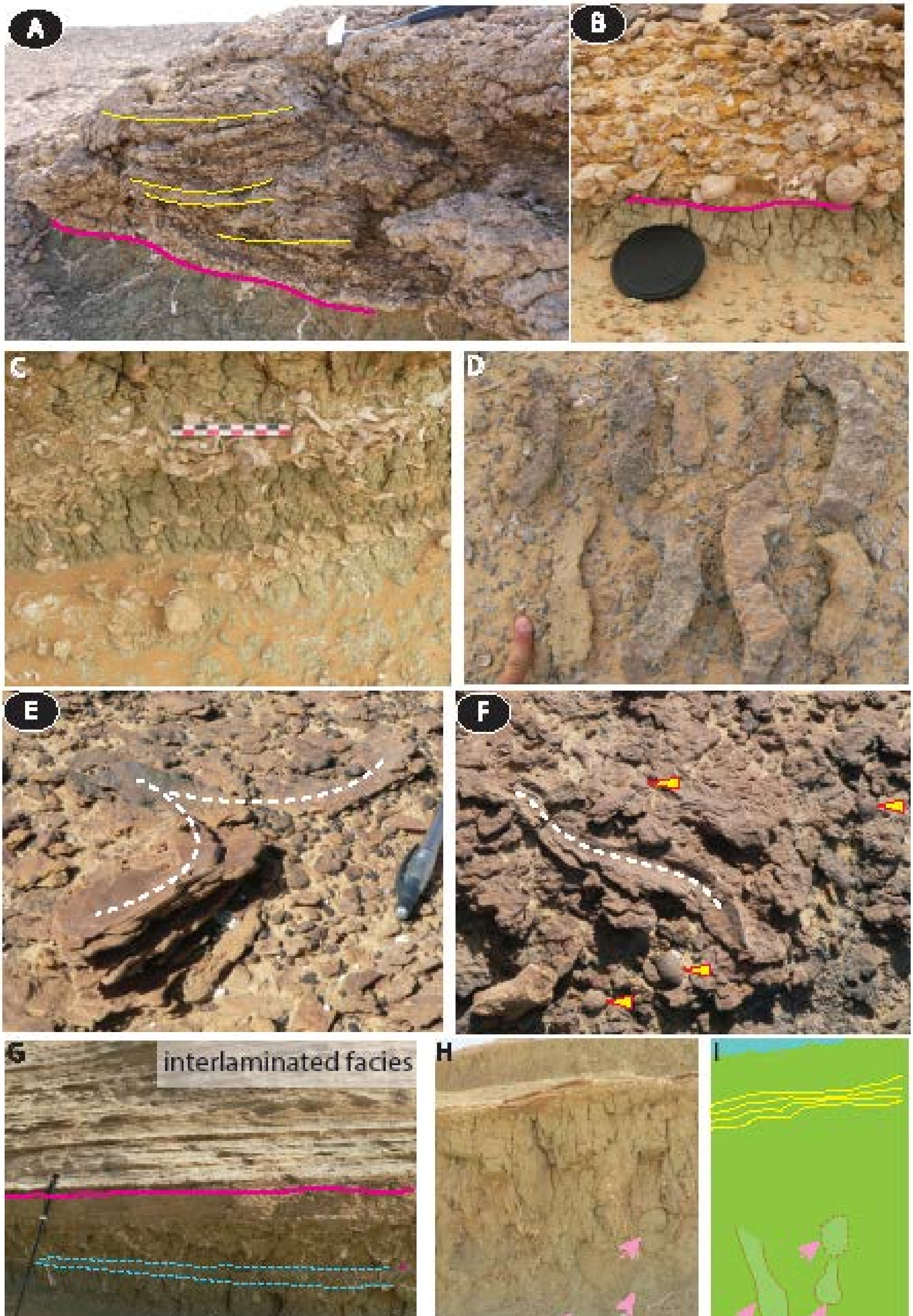
This facies occurs as widely extant lenticular beds (0-1 m thick, up to a few km lateral extensions) made up of marine mollusk shells, and is usually interbedded with green mud (Fig. 6A-C). The most frequent of these Mollusks are oyster (Savage, 1971; Wight, 1980; Abouessa et al., 2012). Scarce beds composed of gastropods and small pelecypods form local accumulation interbedded with the dominated oyster bank. After Vasic and Sherif (2007), they characterize marine to brackish water. At least 10 recurring banks of mollusks are encountered, sporadically punctuating the basal 35 m of the New Idam Unit. Many of the bands show indications of in situ growth. They are interbedded with green mudstone (Fig. 6A, C) as well as with the interlaminated sand-mud facies. Un-weathered mollusk facies normally exhibit a light bluish gray color. Notably, the topmost oyster beds are oxidized, preserving brown and dark brown colors, these are commonly thin and discontinuous. In general, Mollusk banks are structureless, massive beds. Though, very locally they provide low angle cross-bedding (Fig. 6A, J) observable in the relatively thicker beds. It is very possible that some of the mollusk banks are laterally represented by microconglomeratic beds of similar thickness and similar size of particles (Fig. 6B). These are composed dominantly of rounded granules and pebbles of mud rip-up clastic mixed with bone fragments.

The mudstones interbedding with the oyster banks are up to 2 m in thickness. It is usually green in color and is generally structureless, locally sandy and laminated at the top of the bed. The clay minerals forming of the mudstone are predominantly kaolinite with accessory chlorite and montmorillonite (Wight, 1980; Vasic and Sherif, 2007). The mud and the mollusk banks are closely associated. The latter are commonly pinch out inside the mudstone beds (Fig. 6G). In addition, shells imbedded inside the mud are common (Fig. 6C), indicating contemporaneous sedimentation. Instead of the mudstone the oyster banks are sometimes erosively overlies clean very fine to fine grained, well sorted sandstone (cf § 2.3).

2.2. 2. Associated body fossils

In addition to the mollusks themselves, as a fossil, remains of vertebrates are scantly observed. Wight (1980) reported the presence of marine species, notably whales, and sirenians in the lower part of New Idam Unit. In addition to the Ostrea clot-beyi, O. Cubitus described in Abouessa et al. (2012) as constituting the greatest part of the mollusk shells. Pelecypods (family Lucinidae and Glycmeridae were reported (Wight 1980; Vasic and Sherif 2007) but are rarely observed. Some mollusk banks are dominated by dwarfed helical gastropods (Turritelidae). The mud is occasionally containing small scattered remains of plants debris and crocodilian and possibly bones of small fish.

Fig. 6A-I (next page): Oyster bank/mudstone alternation facies. A) Uncommon cases where the shells accumulation shows signs of short transportation (cross bedding); B) conglomeratic lag lateral replace the shells; D) simultaneous sedimentation of the shells and the green mud; D-F) examples from different location of Teichichnus in association with the shell banks; G) this facies overlain by the tidal bedding of the interlaminated facies; H) cylindrical-shaped burrow rarely observed in the mudstone; I) simple sketch of (H), the arrows points to the burrow.


A
B
C
D
E
F
G
interlaminated facies
oyster bank-mudstone facies
H
30cm
I

2.2.3. Associated trace fossil

Two types of trace fossil are associated with the oyster bank facies:
The first type is Teichichnus ichnospecies are occasionally observed. These are particularly obvious in the banks of the oysters (Fig. 6D), and to a lesser extent associated with Lucinidae shells banks (Fig. 6E, F). Notably, in the latter case, the width of the trace is comparable with that of the body fossil of Lucinidae. The second type is rare, found as large tubular body characterized by bulb-like terminal chamber (Fig. 6G-I). This morphotype is observed only in the green mudstone. The observed case reaches one meter long and 10 cm in diameter with the inflated terminal chamber which reaches around 15 cm in diameter, showing generally smooth walls. Being filled with and hosted in the green mud makes it difficult to be distinguished. Comparable traces are described for the lungfish (Hasiotis et al., 1993; 2002). Basically because estivation burrows of the lungfish has a smooth wall and ends with enlarged terminal chamber, nearly twice the size of the burrow (Hembree et al., 2004; Marshall and Rogers, 2012). There is no strong argument about the burrow maker here. Other producers for this trace are possible.

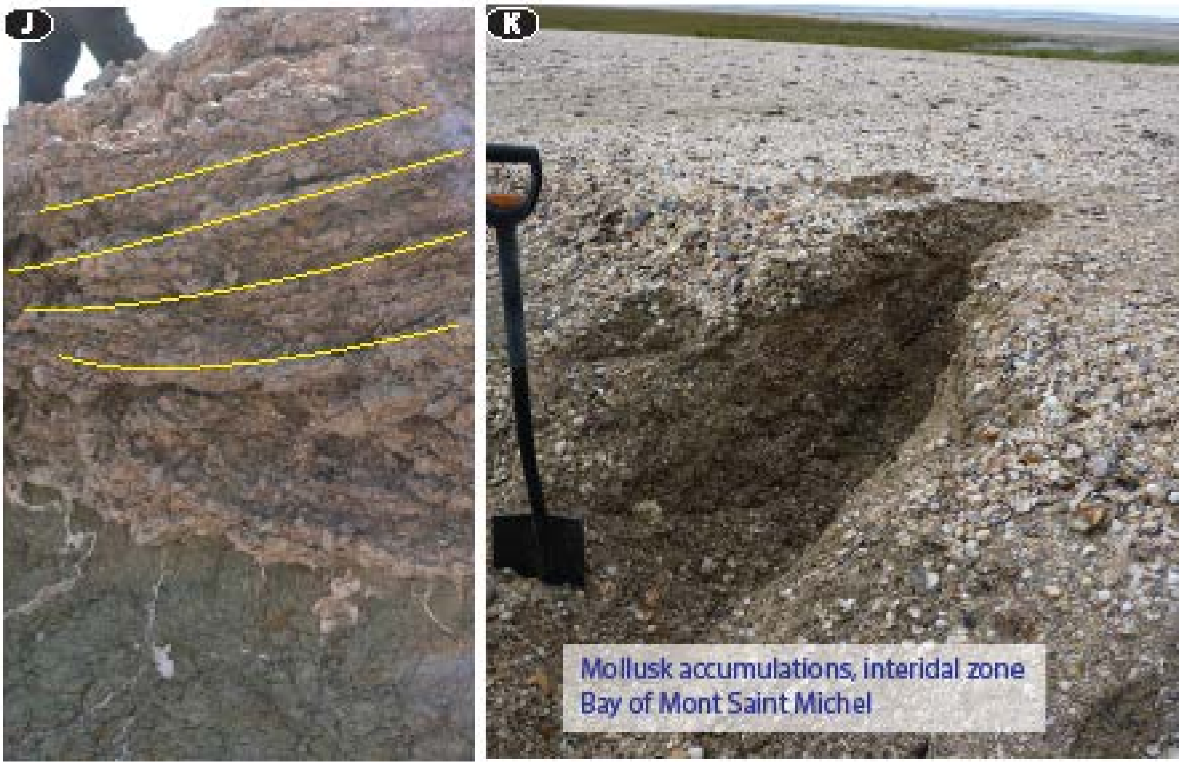


Fig. 6J, K: comparing the ancient mollusk bank from New Idam Unit with the modern ones from the Macrotidal bay of Mont Saint Michel.

2.2.4. Interpretation
The mollusk (mainly oysters) banks are of shallow marine origin as indicated by their content of fossil shells. Thanks to their two valves in connection and their close arrangement in live position, the oyster bank was interpreted as biostromal organization of the shells in a foreshore to backshore-lagoonal depositional environment in Abouessa et al. (2012). The observation of local cross-bedding indicated that the shells have occasionally experienced limited transportation (possibly over wash) during high tides. Similar mollusk shells growing are observed today in the intertidal (and supratidal) Bay Jade, northern Germany. Such shell banks are different to similar accumulation in the Mont Saint Michel supratidal zone where shell beds display obvious cross bed and where the bivalves are disconnected and accumulated after death (Fig.

6K). These accumulations are dominated by mollusk shells that are shortly transported by tidal currents before being accumulated. Thus, coastal environment are the best locations for shell bars accumulation; other modern examples are coast of, Virginia, Morocco, and Padare Island beaches in Texas (Watson, 1971). Texas and Mont Saint Michel examples are similar to that of New Idam Unit concerning the presence of the shells accumulation among terrigenous sediments.

2.3. Well sorted sandstone facies (FA3)

2.3.1 Facies description

This facies occurs as a few meter thick beds composed of very fine to fine grained well sorted, white sandstone (Fig. 7). It is locally and repeatedly exposed at the lower part of New Idam Unit, and alternates with the other facies (the oyster bank and the mudstones and the interlaminated sand/mud facies). This sandstone shows poorly preserved sedimentary structures, include faint laminations and low angle cross lamination. Some of the laminations are similar to the wind striations described by (Collinson and Thompson, 1982; Kocurek and Fielder, 1980). This characteristically clean and well sorted sandstone are erosively overlain by the mollusk banks (Fig. 7A, B). It also overlies and is overlain by the green mudstone (Fig. 7C). The upper contact of this sandstone is always marked by exclusive trace fossils that have unique morphology and largest size compared to all other burrows in the entire New Idam sequence.

Distinctively, this well sorted sandstone is in many locations colonized with oxidized plant remains and evident root marks with obvious conical morphology and dichotomy (Fig. 7E, F) (roots branching). According to their size (several cm diameter; several tens of cm length), many of these roots are suitable for medium size trees. These root traces are found at the interface zone with the overlaying beds. Moreover, several levels of millimetric scale traces of root horizons (short-lived roots of grass) are preserved intra-bed (Fig. 7F). As yet no fossil fauna is discovered in this sandstone.

2.3.2 Associated body fossils

There is no body fossils observed in this sandstone.

2.3.3 Associated trace fossils

Trace fossils here are of low diversity, low density, and exclusively large sized. Two common morphotypes exist (Fig. 7A-D):

(1): This (first) type is nearly rounded having pear- or kidney-like morphology, when best exposed. It is exceptionally large in size compared to all other burrows in the entire New Idam Unit. It has a nearly vertical long axis (up to 75 cm oriented) slightly larger than its width (reaches 50 cm; Fig. 7C, D). These unique burrows are observed only in this, clean well sorted sandstone facies. The filling materials of these burrows are from the overlying sediments, mud and muddy sand (Fig. 7C, D) and occasionally a mixture of both mud and oyster shells. This large burrow coexists with and intersects smaller elongate conical burrows.

(2): This time the burrow (Fig. 7A-D) is smaller with poorly defined shape (resembling roots). Many of the burrows have spindle-like (conical) structure, exceeds 35 cm long, several cm wide at the top terminated down to few cm. It is generally vertical, and occasionally terminates with a little curvature to left or to the right, but is in many cases straight downwards. The filling is always made with white sand of the hosting sandstone. There are some cases where the conical morphology are larger than normal and appear as v-down shaped conical-triangular morphology (Fig. 7B). These enlarged cases could be attributed to subsequent erosion.

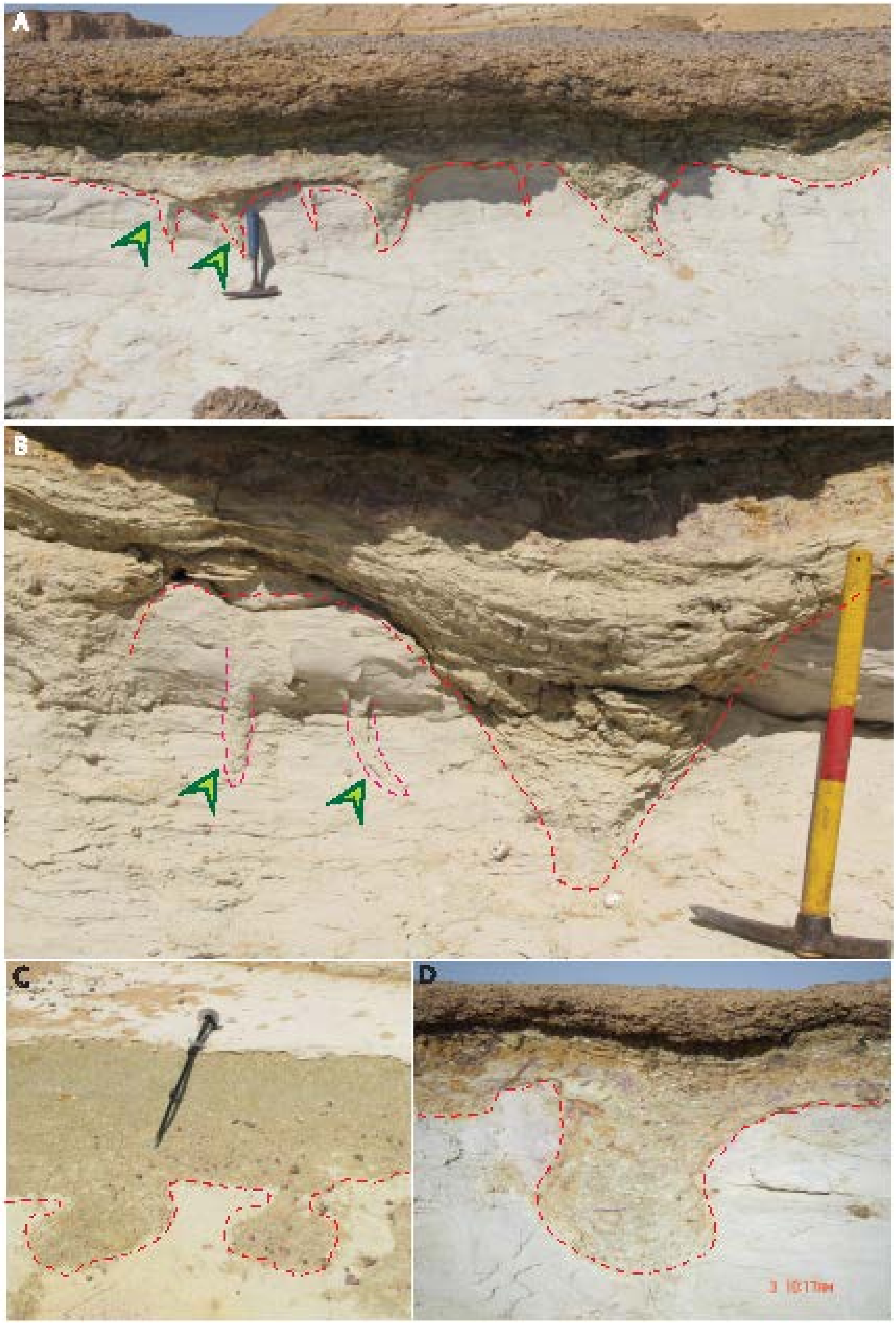


Fig. 7A-D: Shows the well sorted sandstone facies. A) White sandstone erosively overlain by oyster bank. Distinctive burrow types mark the contact, the arrow refers to the conical shape of some burrows; B) close view from (A); C) the white sandstone below and above the green mud; D) subvertical cross section of an exclusively large burrow.

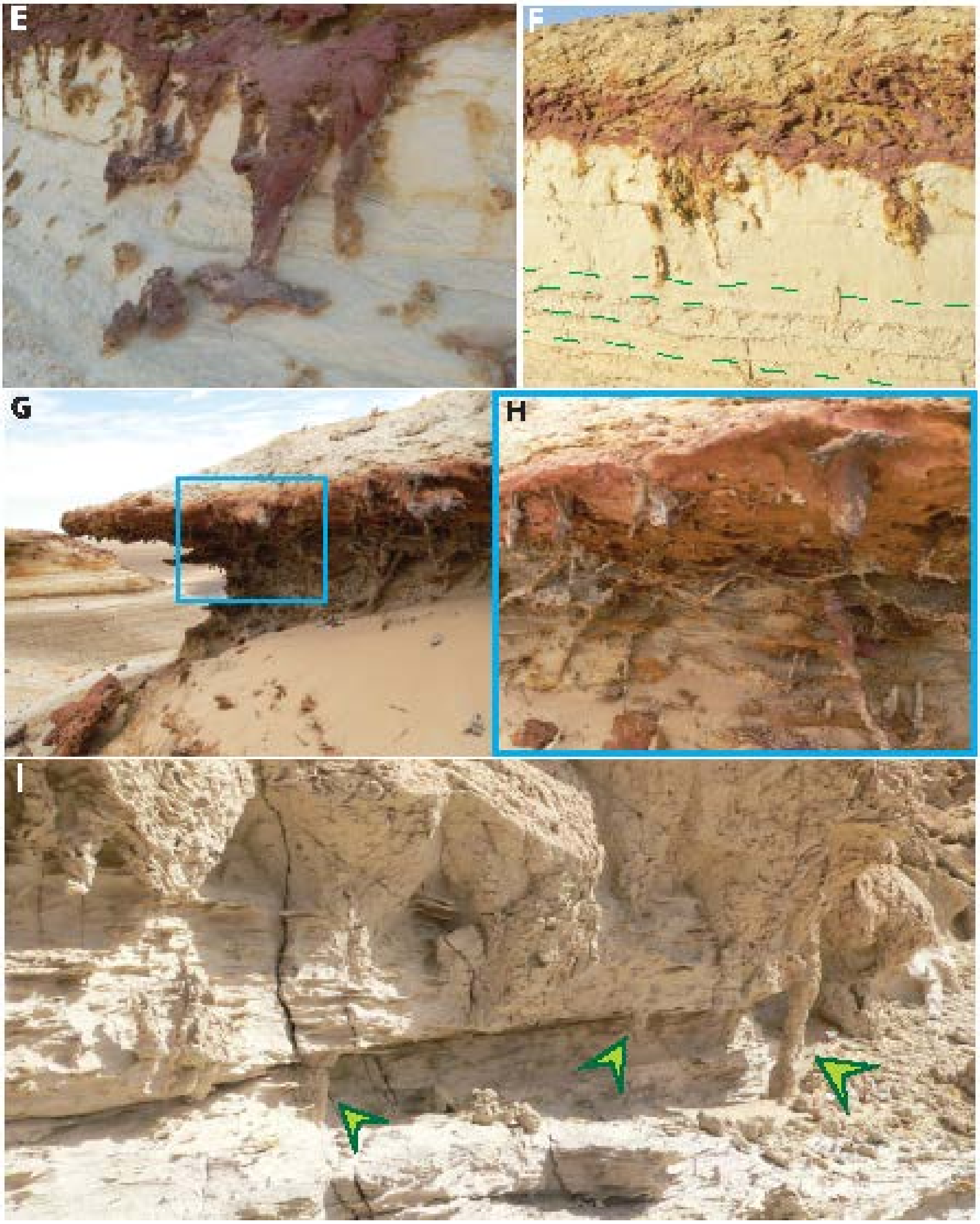


Fig. 7E-I: Root structures in the well sorted sandstone facies. E) Large roots; F) small roots truncated by the laminations; G, H) examples shows intensive root traces; I) large cylindrical and conical traces probably of roots origin (the arrow heads).

2.3.4. Interpretation

The white sandstone facies bears many characteristics suitable for wind-blown sand. Evidence for that is provided by: it's very good sorting, the presence of "wind striations structures", it is devoid of larger grains than the capability of wind transport. Being colonized by plants, and syndepositional roots (Fig. 7E, H) make it comparable with many coastal dunes around the world or blowing sand on supra/intertidal environments. All these features together with the lack of fossils propose wind as the only mechanism would produce this sandstone. The uniquely large burrow would support this proposition. The curved external perimeter as well as the large burrow size might suggest turtles, which lives today in many coastal plains, as a possible burrow maker. In particular, these burrows can be compared with that of "Gopher Tortoises" (Martin, 2013) who colonize densely such environments in coastal areas of Georgia (USA). Insects and rodents can be suggested as producer for the small conical traces. Both are reported from the sediments of New Idam Unit (Savage, 1971; Wight, 1980; Rasmussen et al., 2008). Due to their dimensions and conical morphology (Fig. 7E, I), traces of roots are strongly suggested by some outcrops. Being located subjacent to marine mollusks and tidal dominated sediments below and above, it is then suitable to ascribe this facies to backshore coastal wind accumulations.

2.4. Paleosoil facies (FA4)

2.4.1 Facies description

This facies (5-15 m thick, Fig. 8A, B) is exposed as interbedding of fine sandstone and mudstones to claystones, preserving paleosoil characteristics with lots of redoximorphic structures. Plenty of features described for instance by Retallack (1981), Kraus (1999) for pedogenically altered beds (horizons) are widely and frequently recurring in this interval, ending the lower part of the New Idam Unit. In the outcrop scale, this interval is characterized by several levels with continuous and discontinuous ferruginous crusts and concretions often associated to the paleosoils. The other pedogenic features are of small scale and include 1) roots-dominated (rhizoliths and rhizocretions) beds with bed thickness vary from several cm to several tens of cm, and the root traces here are of mm-scale (Fig. 8C-E). Continuously rooted horizons may exceed 3 m thick, superposed levels with roots are repeatedly terminated by laminations. Larger size roots cannot be excluded in local outcrops; 2) predominance of variegated color or color mottling (grey, brown, purple to light greenish grey) that shows some difference from one level to the other; 3) poorly preserved desiccation cracks; 4) various forms of pedoturbation including patchy lithological alterations and large cylindrical-shaped, well defined trace fossils (section 2.4.3 below) mixed with root marks and petrified plant remains. Discontinuous laminae of gypsum crystals are also widely observed along and across this interval.

This paleosoil facies is widely observed at the same horizontal level for several tens of kilometres. Worth considering is that the first appearance of this thick paleosoil is following the disappearance of oyster facies, with no visible regional discontinuity. In some outcrops patchy remnants of oxidized oysters found embedded at the base of paleosoil interval. Discontinuity is absent also in places where the paleosoil is underlain by the (tide dominate) interlaminated sand/mud facies. In these outcrops, the top of the interlaminated facies are colonized by millimetric scale roots showing upward increase in intensity, and a gradual continuity with the paleosoil facies.

The beds composing this paleosoil facies are nearly flat (Fig. 8A, E) in the east-west cross-section, low angle inclined heterolithic stratifications (IHS) are occasionally preserved within or in-between the flat sets. The later shows a component of lateral accretion (Fig. 8F). Worth mentioning is that pedogenic alterations is better displayed by the flat than the inclined beds. In addition to this prominent interval of paleosoil pedogenically altered beds are also found frequently in the upper part of New Idam Unit. Compared with this interval those in the upper part are differently and apparently less well developed. For instance iron crust and concretions are not as common and laterally continuous as in this interval.

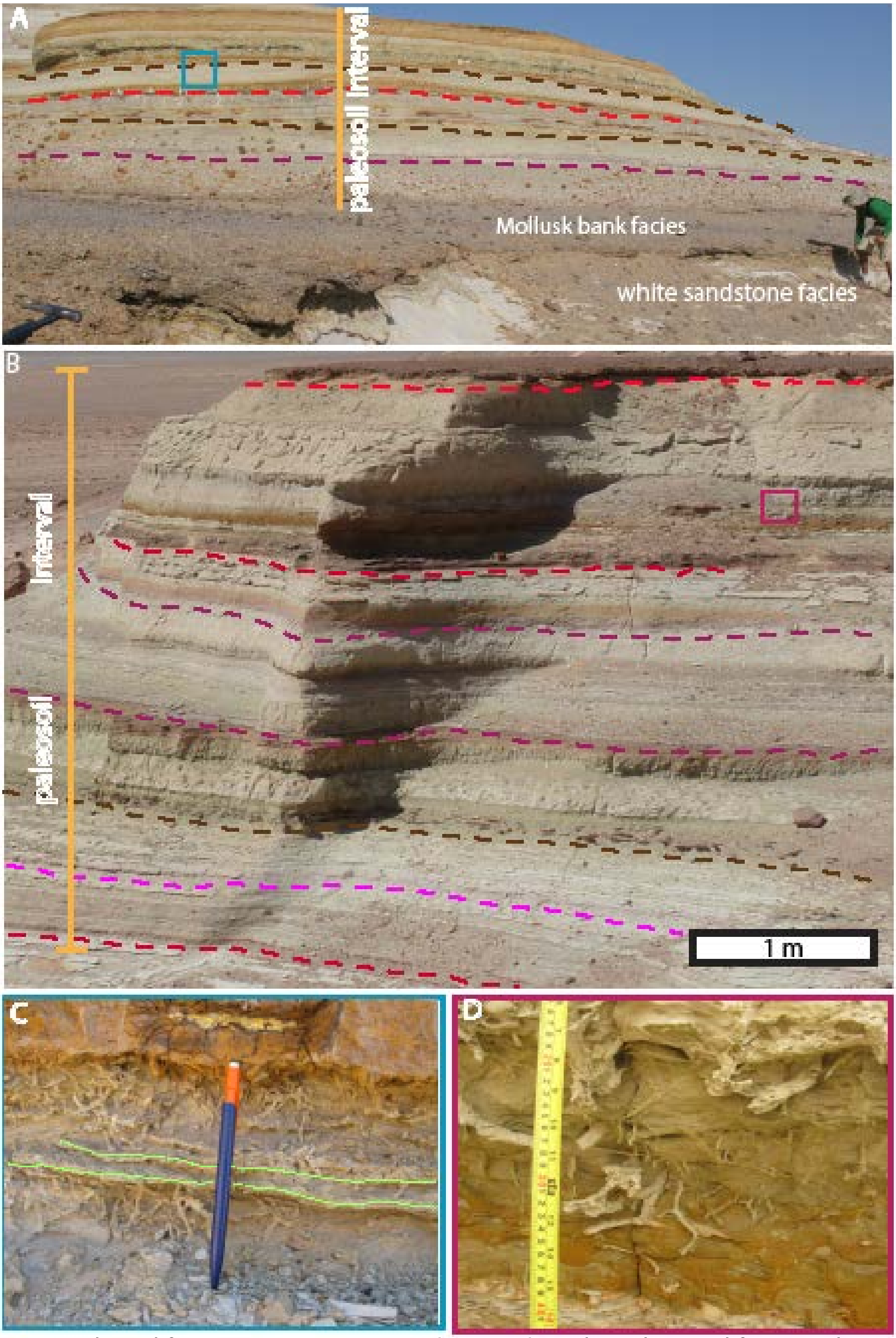


Fig. 8A-D: Paleosoil facies: A, B) Outcrop view showing the paleosoil interval from two locations 5 Km apart; C) Small roots repeatedly truncated by the lamination; D) Other example of roots and plant traces.

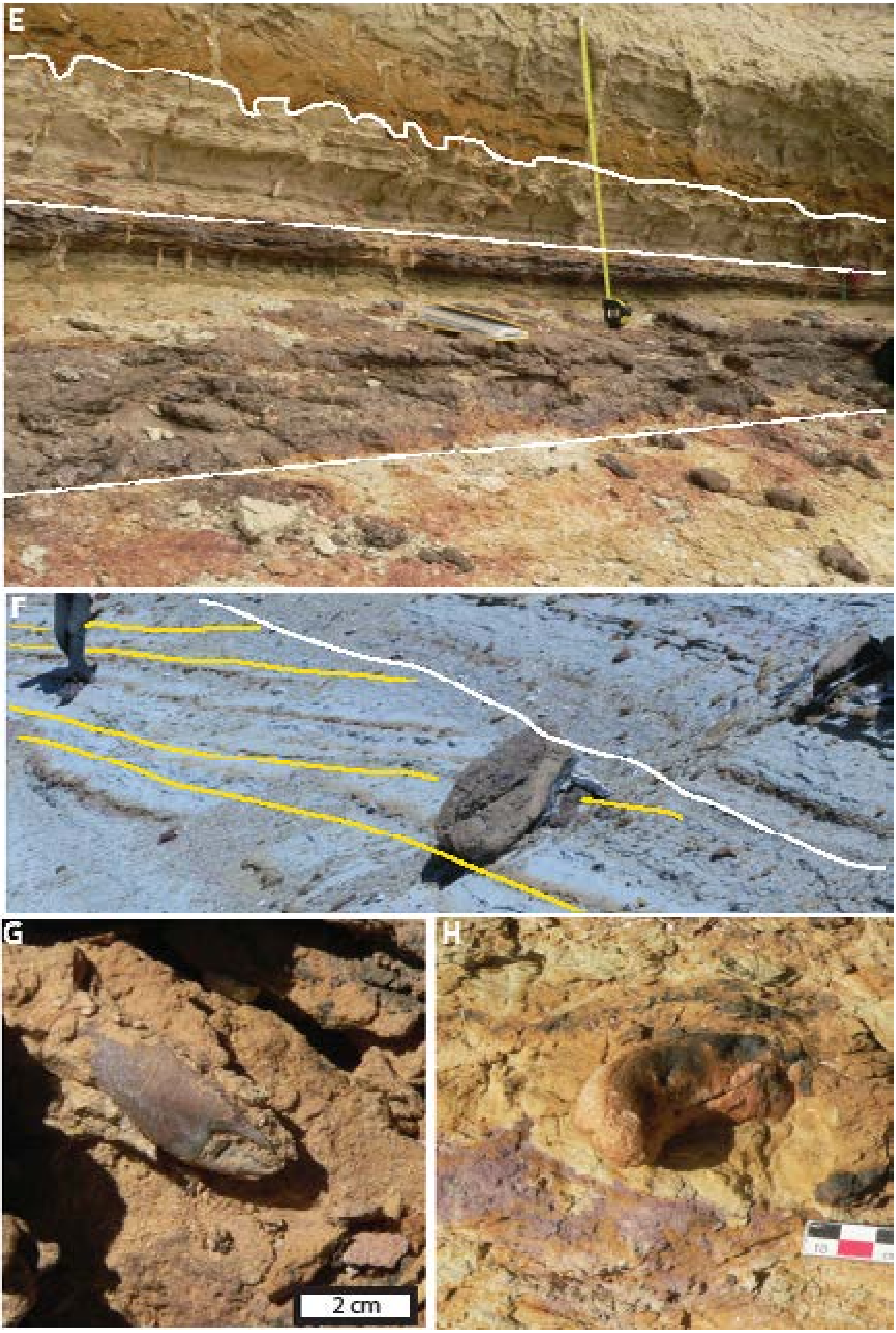


Fig. 8E-H: Paleosoil facies: E) Close view showing ferruginous layers, color mottling and frequent roots; F) Inclined heterolithic stratification intersecting with the paleosoil horizons; G) Single fossil claw of decapod crustacean found close to the top of the paleosoil interval; H) Remains of crocodile.

2.4.2 Associated body fossils

Very unique concerning the body fossil here is the discovery of one claw of decapod crustacean (Fig. 8G), found preserved in a sandstone bed near the top of this facies. Notable, the shape and size of this claw is comparable with that of the modern crab and fresh water crayfish. Coprolites of crocodile (Fig. 8H) are frequently observed, other fossil remains of undifferentiated vertebrates (probably crocodilian remains) are scattered throughout this facies.

2.4.3 Associated trace fossils.

Besides the rhizoliths and undifferentiated pedoturbation features, this paleosoil facies record the probably first obvious appearance of cylindrical morphology and large (decimetric-size) trace fossils in the New Idam Unit (Fig. 8I-O). This morphotype are preserved as irregularly cylindrical tubes (5-10 cm in diameter, mostly 20-35 cm long) with circular to oval cross sectional area. The burrow orientations are commonly vertical to subvertical with or without slight curvature at the base (J-shaped). The burrow spacing (intensity or Bioturbation index) is few cm to several tens of cm apart, though exposed bedding plains are sometimes completely churned (BI=6). The bedding planes are ornamented with a pattern of adjacent circles; plenty of these circles are intersected, indicating repeated burrowing and filling. Limited outcrops provide observing a full burrow casts emanating above the exposed bedding surface for up to 20 cm (Fig. 8K-M). These are exposed as a result of the differential erosion. In fact, the burrows are more cemented than the surrounding sediments. The external surface of the burrows is uneven and scratched (Fig. 8J, K). Scratches appear as subparallel (sometimes curved and oblique) groves. Some of the groves are parallel others are oblique to the long axis of the burrow. Remnants of few cm wide irregular rims are attached to the emanating casts, and are circumferentially surrounding them (Fig. 8L, M). Comparing the overall morphology and size of the described burrows with similar modern and ancient counterparts, this burrow can be ascribed to few candidates. Even if lungfish or amphibian, as well as traces of roots can make similar burrows, decapod crustacean, including freshwater crayfish could also be the trace maker. Further discussion concerning the burrow maker will be given later in this chapter, because the same morphotype is preserved (in this unit) in the overlaying facies.

2.4.4. Interpretation.

The recurrence of rhizoliths, plant remains and iron crusts as well as other features of pedogenic alteration suggested relatively prolonged and intermittent subaerial exposure of these sediments. This (paleosoil) facies has a wide lateral continuity across the escarpment, in this, it is similar to the underneath mollusk bank facies, which also extending laterally for at least 100 km. The presence of patchy remnant of mollusks embedded at the base of the paleosoil beds suggests gradational contact between both facies. This means that these two facies were deposited in a more or less flat area. It also suggests that the sediments composing the paleosoil interval are deposited in a marine proximity roughly flat zone. This inference came from the evident origin of the mollusk banks as of (foreshore-backshore) shallow marine environment. The paleosoil interval is in places (gradually) overlies the tide dominated sand/mud interlaminated facies (FA1) and it commonly overlain by similar (probably tide influenced) sediments (facies 3.1; below). In most locations, the strata underneath the paleosoil facies is end up with frequently rooted beds. I.e. in the locations where the paleosoil facies overlies the interlaminated facies, roots show gradual increase upward, with no visible discontinuity in between.

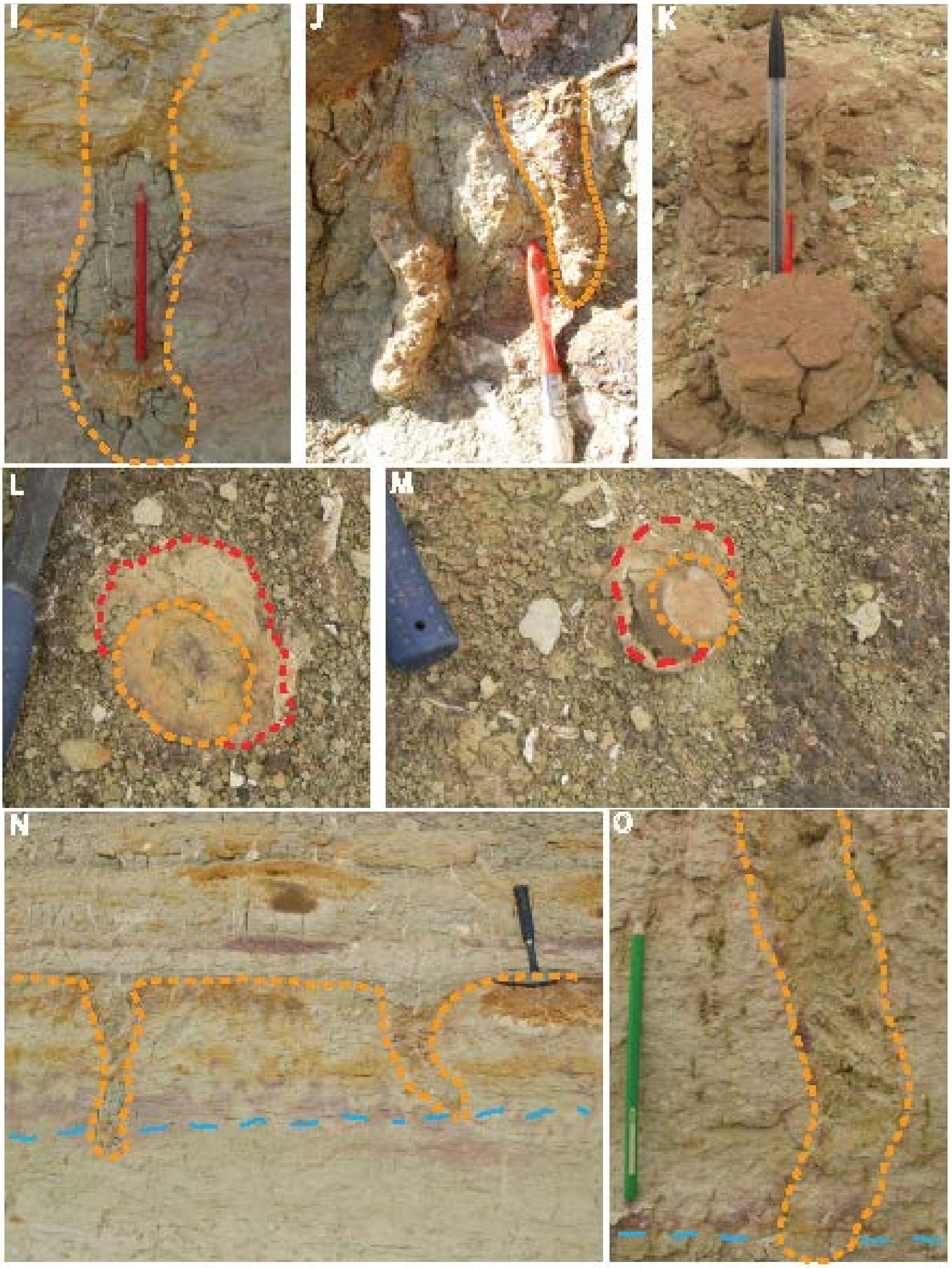


Fig. 8I-O: special characteristics of the paleosoil facies: I) Cross-section of cylindrical burrow full by mud (dashed line outline the burrow); J) Slightly helical curvature; K) Emerged cast (or chimney) of the burrow; L) Cross-section of the burrow surrounded by outer rim, imitating the chimney morphology of modern crayfish burrow; M) Vertical cross section of cylindrical burrow nearly terminated at the same (mottled) horizontal line (probably the paleo water table); O) Smooth J-shaped cylinder show internal oblique back filling (or groves) surrounded by mm-scale roots.

Because intertidal environment is proved in the sand/mud interlaminated facies, supratidal environment can, accordingly, be suggested for the paleosoil (5-15 m) interval. Such environment suits deltaic/estuarine flood plains; this is mainly attributed to the flat bedding and the parallel laminations.
The inclined heterolithic stratification (Fig. 8F) intervening between the flat paleosoil intervals reminds meandering channel. The sand/mud layers organization in these pedogenically altered strata can be correlated with the neap-spring fluctuation of the tidal energy (e.g. Thomas, 1987; Ashley, 1990; Féniès et al., 1999; personal observation, Mont St. Michel Bay). Finally the domination and reoccurrence of small root traces, combined with the existence of crocodilian remains, fishes, marine fossils and tidal sedimentary structures at the base, mud cracks, and the presence of laterally accreted beds carrying tidal signature, all together suggest coastal estuarine plain (supratidal zone) as a depositional environment to the paleosoil interval.
In overall sediments of the lower part of New Idam Unit represented nearshore tide-dominated environment. Subenvironments are intertidal channels, coastal dune (aeolian sand), and extensive intertidal-supratidal flat. These subenvironments constitute nearly East-West trending coastal strip.

3. Facies composing the upper part of New Idam Unit.

This part of New Idam Unit (Fig. 4) is composed of siliciclastic rocks, of generally the same texture and composition of their counterpart in the Lower Part of the unit. Fine sand and mud is predominating here as well. Principle exception, contrary to the lower part of New Idam Unit is that this part devoid of shell fossils. Despite this fact, vertebrates are common, these are mostly of terrestrial mammals, and are observed in many locations across and along this (the upper) part of the New Idam Unit. This fact, moreover, had also been reported for this part of the Dur At Talah sequence (Wight, 1980). Worth mentioning here is that the tidal sedimentary structures are only locally observed in this part of the New Idam Unit and are not as diagnostic compared to that in the lower part of the unit.
Based on the available information, the upper part of the New Idam Unit is built up by metric-scale alternations of two main facies associations (Fig. 4). These are: (i) The interlaminated sand/mud facies (which is apparently similar to the same facies, FA1, in the Lower Part) and (ii) interbedded sand to mud facies (parasequences). The two facies are similar in terms of lithology and are different in the thickness of encountered stratification and sedimentary structures. The two are principally different in the types and the intensity of the bioturbation, and they are spatially interplaying.

3.1 Interlaminated sand/mud facies
3.1.1. Facies description

This facies occurs as sequences of laminated, very fine sand thinly alternating with silt and mud. One sequence has thickness of few to several meters, with individual layers varies from thin lamina to thin beds (Fig. 9). Several cm thick beds are laminated and showing fining upward trend. Channeling is a common outcrop feature constituting this facies (Figs. 9A, B). Individual sequence is showing perceptible increase in the number of channels toward its top. The channels are frequently commenced (and interrupted) by lenses of fossiliferous microconglomeratic intraformational lag (Fig. 9D). Despite the rhythmicity and the obvious parallel and subparallel stratification displayed by this facies, tidal sedimentary structure is not as striking

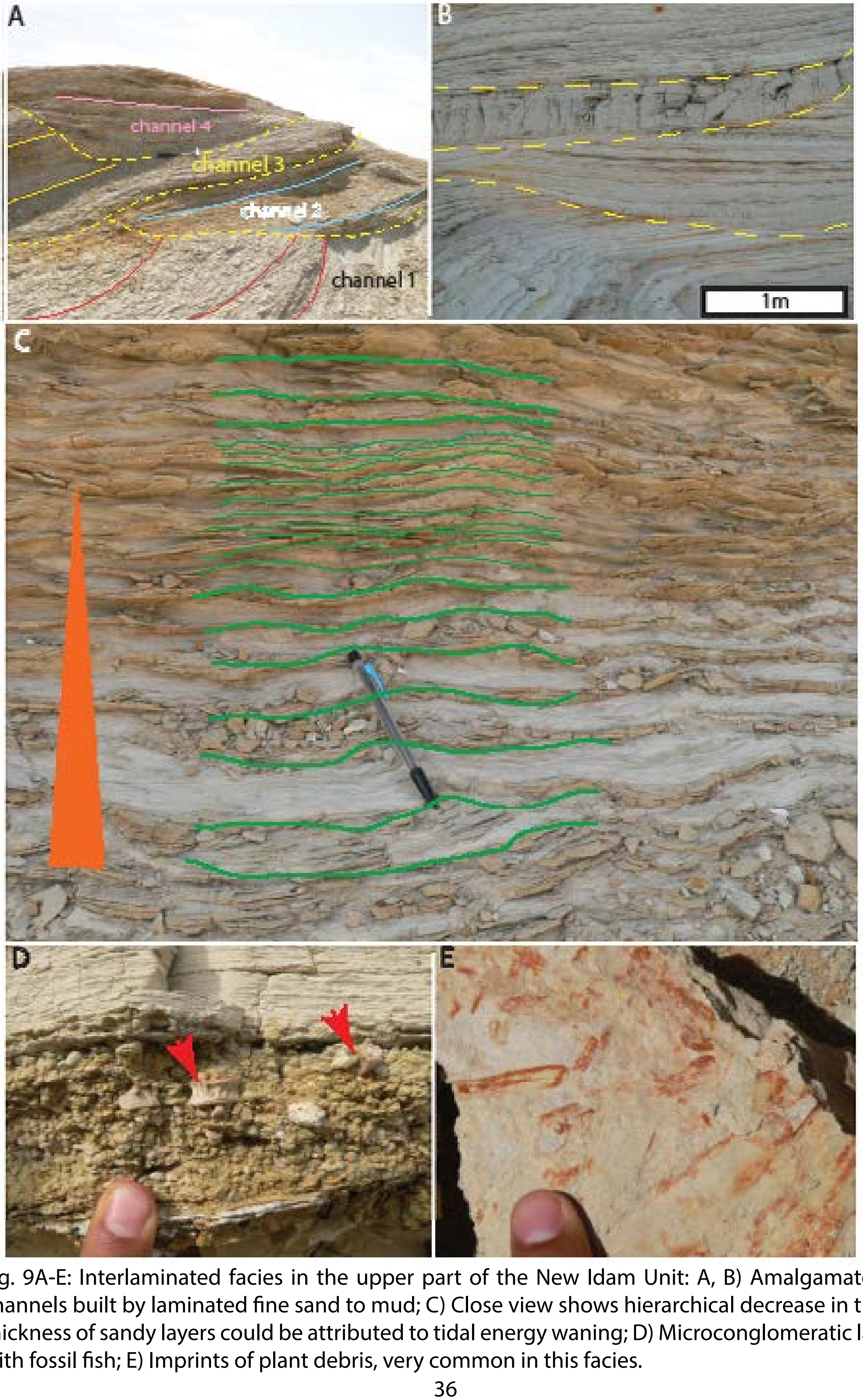


Fig. 9A-E: Interlaminated facies in the upper part of the New Idam Unit: A, B) Amalgamated channels built by laminated fine sand to mud; C) Close view shows hierarchical decrease in the thickness of sandy layers could be attributed to tidal energy waning; D) Microconglomeratic lag with fossil fish; E) Imprints of plant debris, very common in this facies.

and well-developed as in the same facies in the lower part of the New Idam Unit. It is expressed for instance, as a local poorly organized bedload-suspended load sedimentation, which could occur in many other subaqueous environments (e.g., Reineck, Singh, 1980; Scott et al., 2002; Zavala et al., 2006).

It is important to highlight that the interlaminated sand/mud facies is in general light gray to white in color, and frequently contain ubiquitous but small fossil fragments of plant debris (Fig. 9E). This is not always the case, in some outcrops interlaminated sequence are locally dark gray to dark brown and pink in color (Fig. 9F), and are very rich in plant debris and leaves. These plant remains are dominating (Fig. 9G, H) in many outcrops, and probably imbue the sediments with the dark color. Outcrop showing this trait have wide lateral extent (decametric to kilometric scale). Leaves imprinted in these deposits are of various species of plants.

3.1.2. Associated body fossil

Teeth, fragments and intact bones of crocodile and proboscidean (Fig. 9I, J) are sparsely observed embedded in the thinly laminated facies. Rasmussen et al. (2008) and Wight (1980) reported the same from similar sediments in the upper part of New Idam Unit. This is considered in addition to the small bones and teeth (of fish vertebrate and other undifferentiated bones) associated with the microconglomeratic lag punctuating finer layers of this facies.

3.1.3 Associated trace fossils

Termite burrows associated with fungus comb chambers are observed in specific levels of this facies. It is restricted only to the top of some channels morphology (Fig. 9K-M). Termite burrow are rounded, to subrounded in cross sectional (few to several cm wide; Fig. 9L, M), and are linked with several cm to few tens of cm long horizontal and subhorizantal tubes (galleries). Remain of fungus comb chambers similar to those described by Duringer et al. (2007) are scattered within the burrows. Moreover, internal concentric structure of the termite nest could still be recognized. The termite traces are preferably positioned at the top of channels where the strata tend to become horizontal. They are associated with mm-scale irregular tubes with nodes, these tubes are very much resembling plant rootlets (Fig. 9M).
Other type of burrows of smaller size (few cm long, less than 1-2 cm diameter) and irregular shape exist at more or less certain levels. This time the overall trace architecture (Fig. 9K, N) are slightly similar to Thalassinoides, but their internal meniscate structure (Fig. 9O) and smaller size make them more closely comparable with Naktodemasis Bowni trace described by Smith et al. (2008) as made by a larva of insect beetle. Apart from the morphological and architectural features, upward increase (Fig. 9K, N) in the bioturbation index (BI; Droser and Bottjer, 1986) is remarkable. It gives impression that the burrow maker started digging from exposed surface and decreasingly penetrated down into the sediments. BI increases upward from one to six as the strata attain its horizontal position.
It is worth mentioning, as a matter of comparison that the trace fossils Teichichnus, Diplocraterion and Skolithos which are common in the lower part of New Idam Unit are not observed in this interlaminated sand/mud facies and in upper part of New Idam Unit in general.

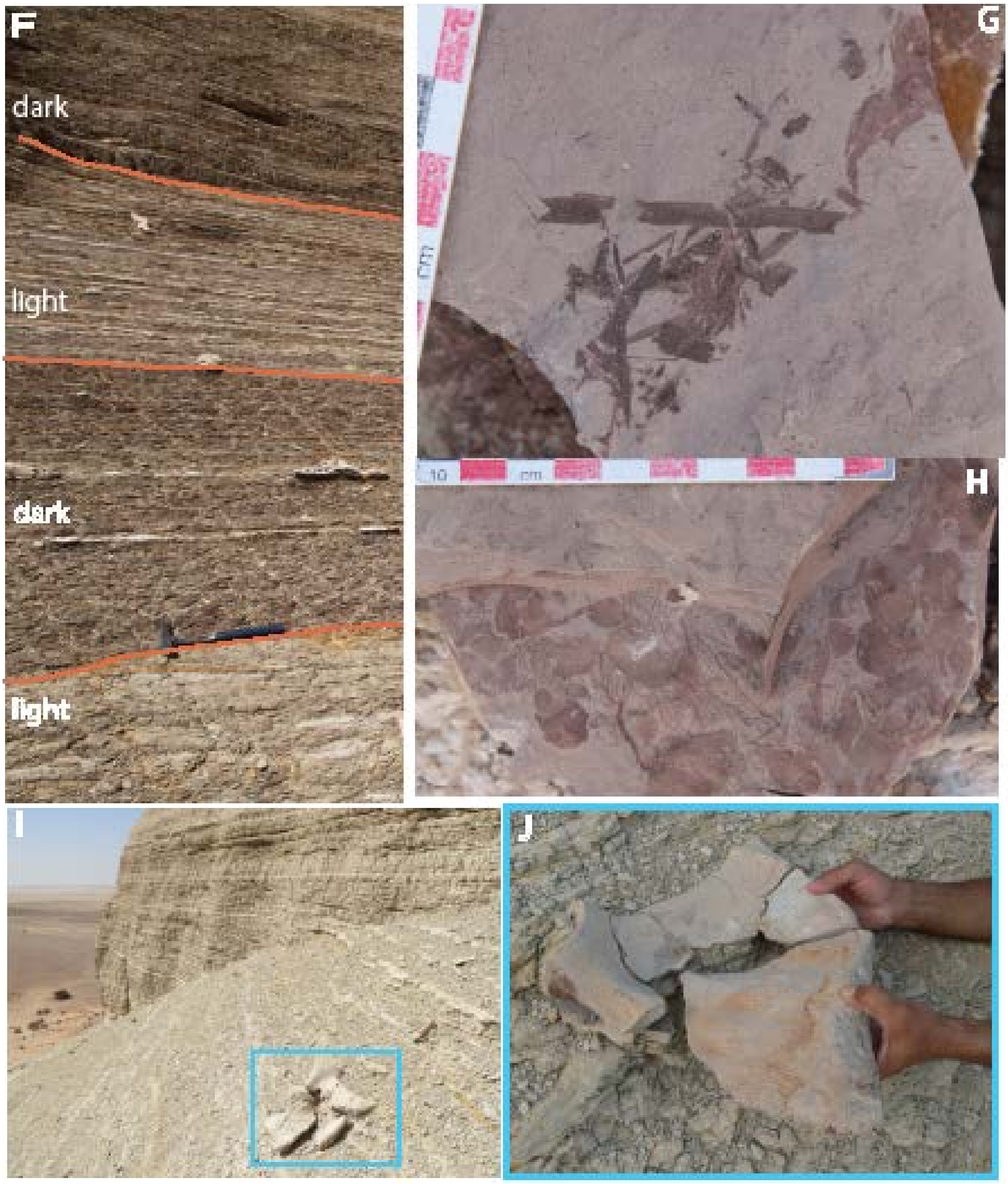


Fig. 9F-J: Interlaminated facies: F) Interbedding of dark and light intervals attributed to the domination of organic debris; G,H) Imprints of leaves of different plants; I, J) General and close views of proboscidean bones.

3.1.4. Interpretation.

The fine interlayering of the two lithologies, fine sand and mud, composing this facies can occur in a variety of environments. In this facies they are commonly built up as variable dimensions channeled architecture. This fact beside the other described aspects, such as the microconglomeratic lag and the shallowing up trend, supports two reliable possibilities, tidal or fluvial channels. Tidal sedimentary structures are reported by Pelletier (2012), and cannot be excluded according to our observations (Fig. 9C). Therefore, there are many indications suggesting that these channels are neither entirely tidal nor entirely fluvial. They are more likely a tide-modulated fluvial channels, rather than shallow marine tidal channels. In the present days, many tidal influenced rivers extend for several tens to hundreds of kilometer inland from the shore line (references in Dalrymple, 1992; Dalrymple and Choi, 2007). Similar cases in the geological record are described by, for example, Clifton (1982) and Shanley (1992). What makes this interpretation reliable is simply because the fluvial (terrestrial) indicators in these channels are much greater than that of the tidal signature. The wide lateral extent and the domination of plant debris presented by some outcrops made lacustrine environment possible for some dark-colored sediments of this facies. Further investigation is required to enhance this assumption

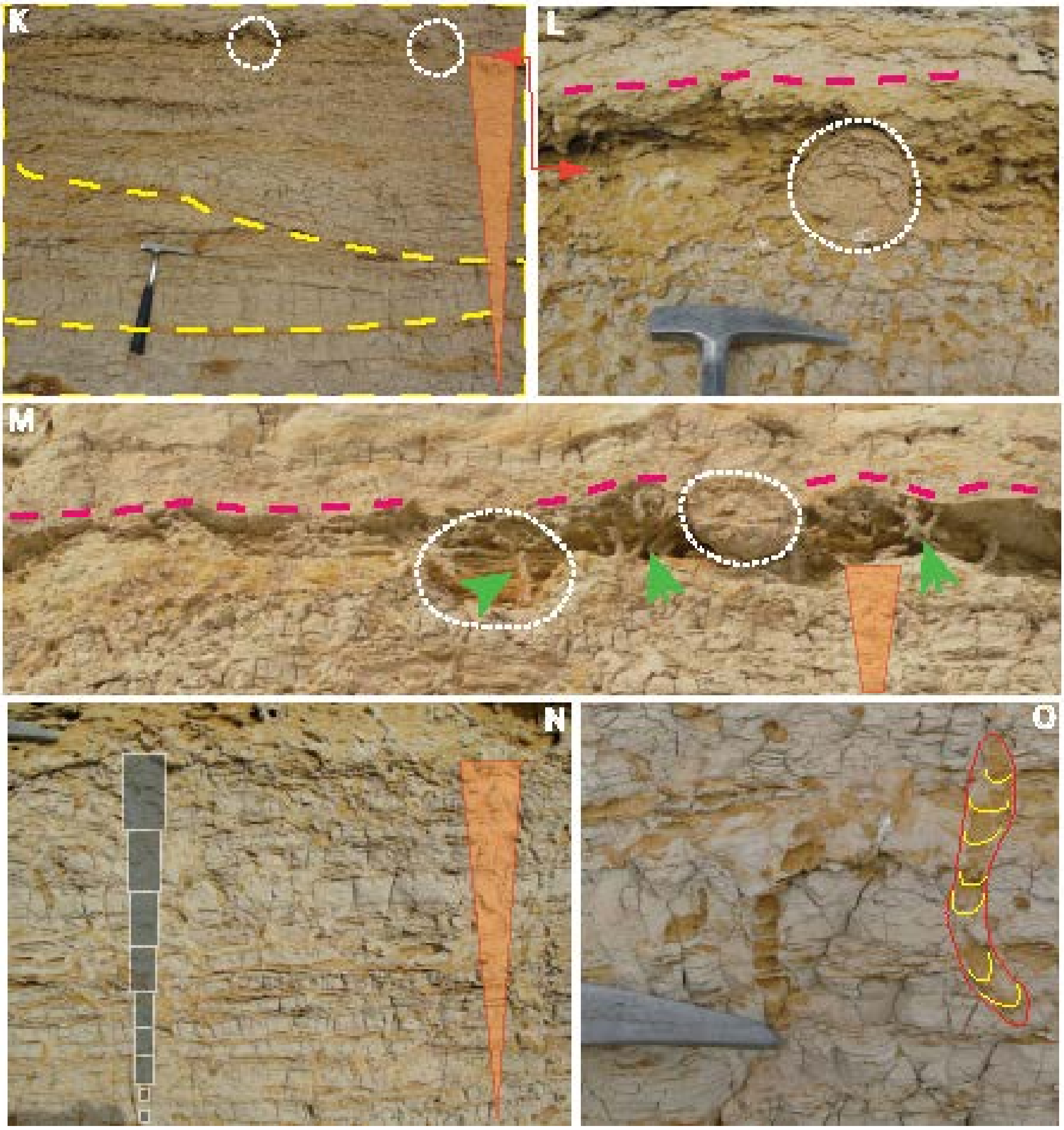


Fig 9K-O: Trace fossils in the interlaminated facies. K) Shallowing up channel, known by upward increase in roots and terrestrial burrows; L, M) Termites (dashed circle) and roots (green arrows); N) illustrates upward increase in burrows and roots; O) Possible trace of insect, probably beetle.

because domination of sediments with such plant debris could occur also in shallow marine environment.

3.2 Interbedding sand-to-mud facies (parasequences)

3.2.1. Facies description

This facies consists of short parasequences composed of fine sandstone to mudstone. The majority of these parasequences begins with sand, gradually grades up to mud and clay (Fig. 10A, B), with commonly erosive contact separating the sand and the underlying mud. Light green and gray is the color dominating the mudstone beds and gray, yellow, and grayish white dominate the sandstone. Color mottling is locally preserved in many horizons in both the sand and the mud; gray, purple are common, pale yellow, red and brown are occasional, all these colors are lies within the light spectrum. There are two distinctive geological features characterizing this facies. The dominance of distinctively large burrow casts (Fig. 10B), and the frequent local occurrence of fossil plants, and vertebrates. Levels with centimetric and sometimes millimetric (hear-like) scale roots are frequent, especially in the sandy beds.
In general, this facies is interbedding and laterally interplaying (amalgamated) with the interlaminated facies (section 4.1 above). Sedimentary structures preserved in this facies are not prominent. The sandstone shows faint lamination. The mud is commonly structureless and sometimes faintly laminated. Fortunately, excavated outcrops (Fig. 10C) reveals well developed mud cracks, observed at the interface between muddy and sandy beds. These cracks (Fig. 10D, H) appear as a few cm to several tens of centimetre deep V-shaped structures, preserving their sharp outlines. Possible root traces coexist with the mud cracks.
The erosive surface described between the sand and the mud is occasionally mantled with microconglomeratic lag followed by the fine sand. Intrabasinal mudclasts are the common constituents of such lag, associated with lots of vertebrate fragments.

3.2.2. Associated body fossil

Undifferentiated fragments of vertebrate bones are frequent in this facies. These are mostly observed in association with the sandstone beds. Large skeletons and bones of proboscideans, for instance Figure (10E-G) are commonly scattered throughout the beds of this facies. Barytherium and Moeritherium (known for terrestrial aquatic environment similar to extant hippopotamus) are, as well, reported from the upper part of the unit (Wight, 1980; Rasmussen, 2008). Furthermore, small bones and teeth of rodents are reported in microconglomeratic layers (Wight, 1980) and rodents and primates (Jaeger et al., 2010a, b), in addition to other mammalian remains. Of significant importance is that these microfossils are found sometimes filling the mud cracks (the most famous site explored by the team of J.J. Jaeger was located over such well-developed mud cracks (Fig. 10H). Also in the upper part of New Idam Unit, Savage (1971) and Wight (1980) reported fragments of rodents and Hyracoidea occurrences as well as freshwater fish (catfish). Recently, Grohé et al (2012) described Apterodontinae (Hyaenodontidae) which is one species of a terrestrial carnivore.

Apart from the mentioned fauna, this facies is laden with different species of fossil flora, both are notably coexisting in many outcrops, fossil remains of different plants (Fig. 10I-L) are very remarkable in frequent outcrop. Their exposure seems to be controlled by the outcrop conditions. These plant remains are very remarkable in many exposed sandy bedding plains,

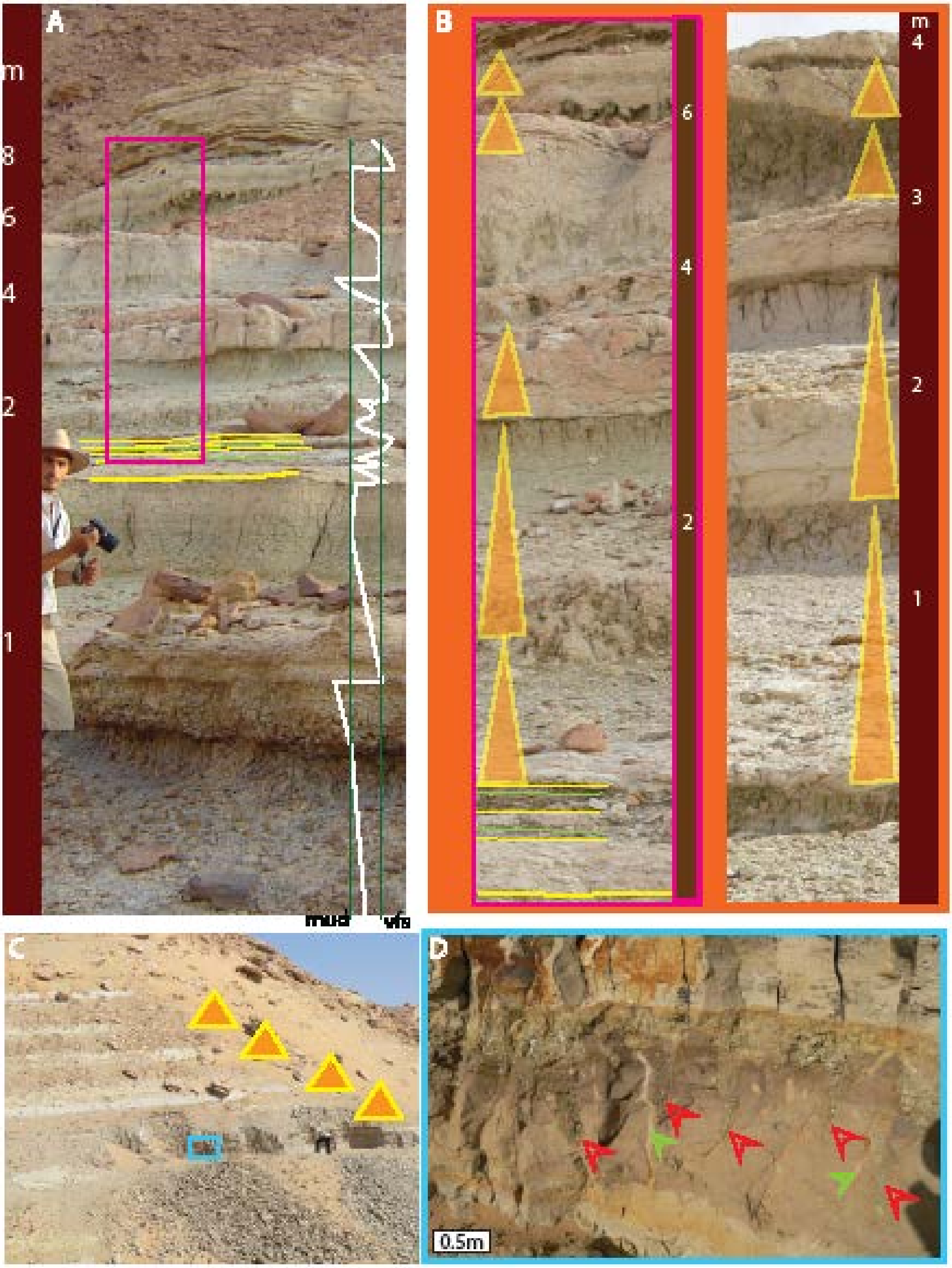


Fig. 10A-D: Interbedding sand-to-mud-facies (parasequences) from different outcrops in in different scales. A) Stacked parasequences, possibly interrupted by interlaminated facies (yellow and green horizontal lines); B) The first sequence is close view from A) (the red rectangle), and the second sequence is nearly a horizontal equivalent with 10 Km apart, both are bioturbated with the same traces but in a variable degree; C) Parasequences (fining up) in outcrop scale (man for scale); D) Close view from excavated outcrop (Blue Square in (c) shows roots (green arrow) in association with mud cracks (green arrow).

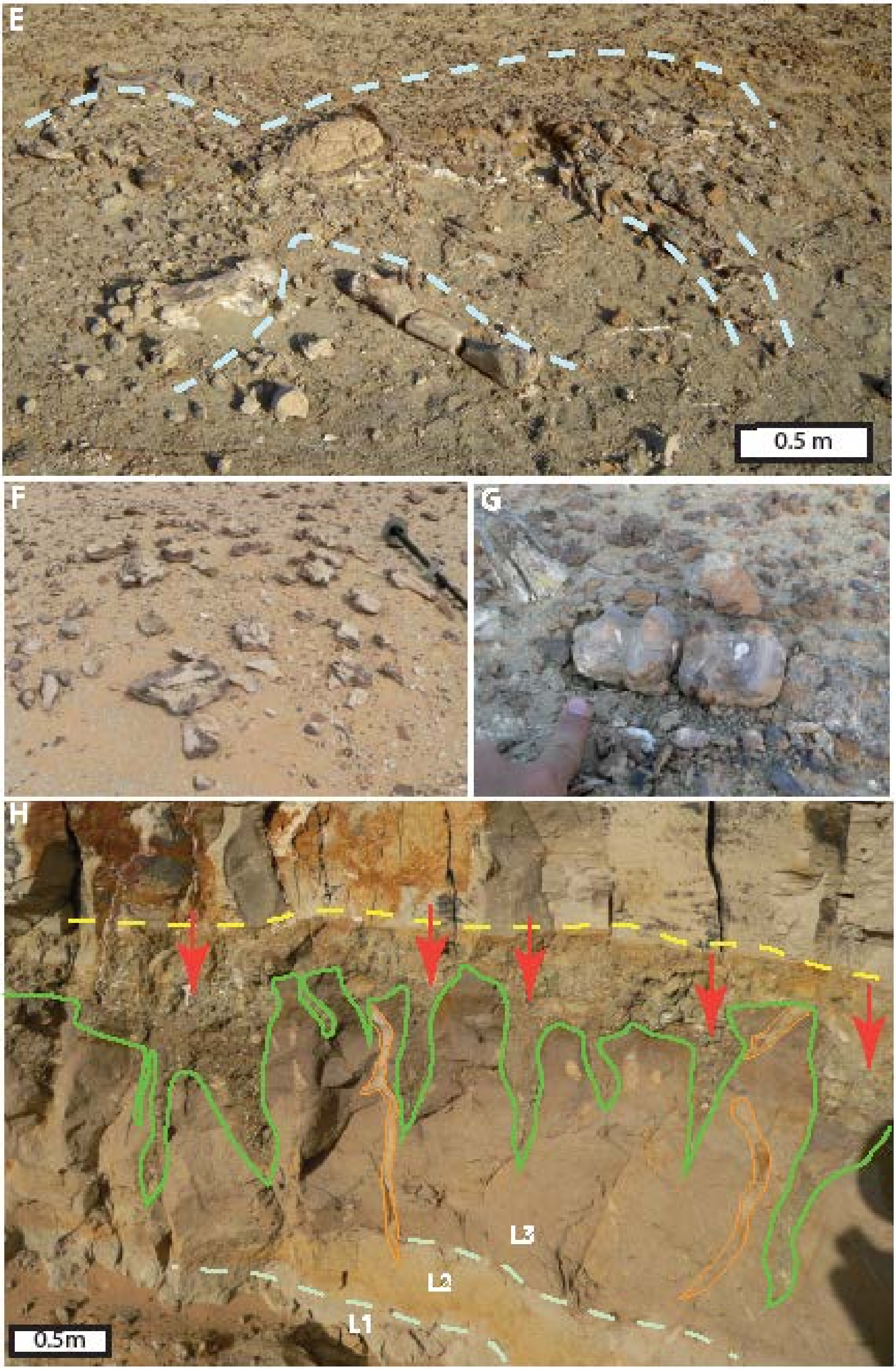


Fig. 10E-H: Sedimentary features in sand mud parasequences. E) Nearly complete skull of large terrestrial mammal (dashed line trace the animal body); F) Scattered bones probably of vertebrate animal; G) Large teeth of proboscidean; H) Shows that the mud crack and the burrow are filled with microfossils and are associated with paleosoil zones (magnification and illustration of Fig. 10D).

where they appear as a petrified roots, stumps and large tree trunks. Fossil fruits of different species are very common as well especially Pandanus fruits. Many of these have been recently reported (Abouessa et al, 2012; Pelletier, 2012). Among other species, water lily fruits have been frequently observed and documented (Wight, 1980). All these are indicators of aquatic terrestrial environments.

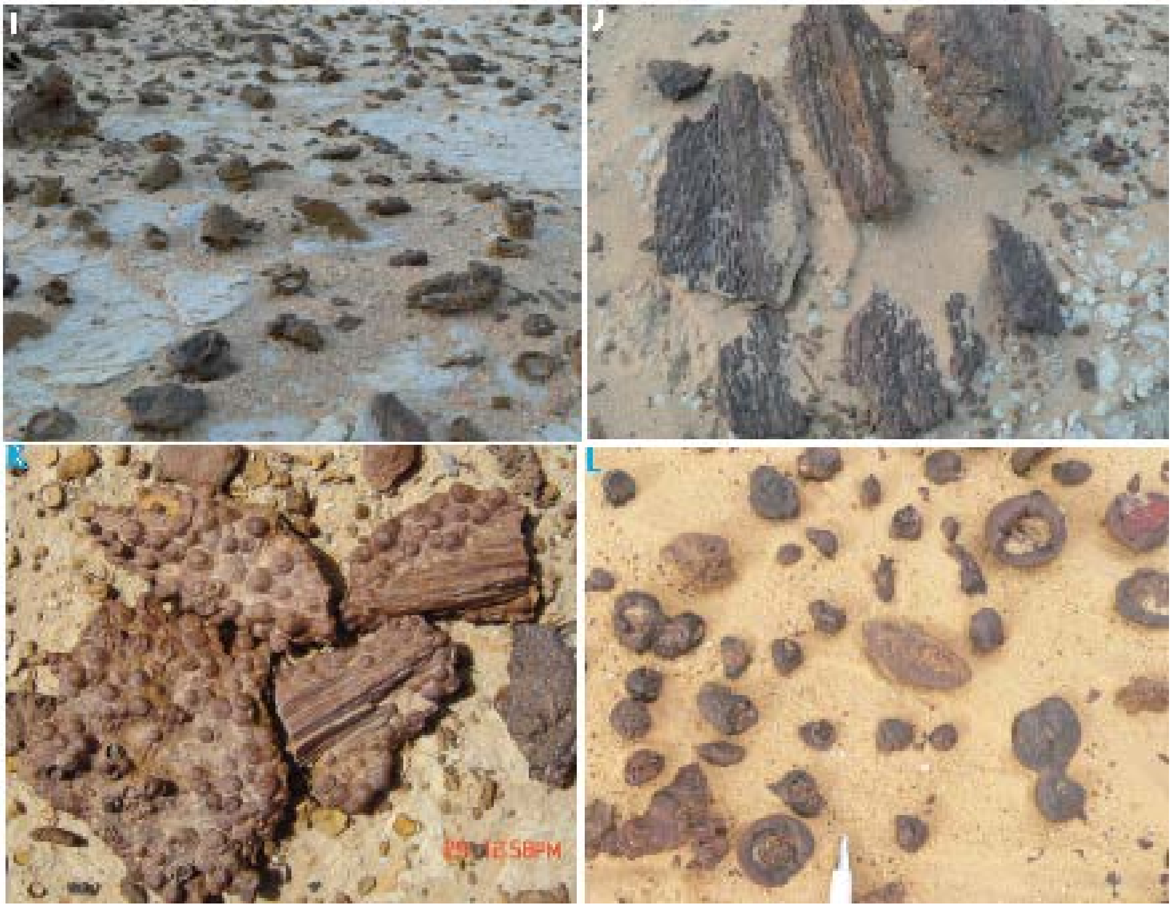


Fig. 10I-L: Various expressions of fossil vegetation. I) Shows vertical stumps and trunks of medium-sized plants; J, K) Chunks of different trees; L) Different fossil of fruits, dominant in the upper part of the New Idam Unit. All are probably associated with the sand-mud parasequences but are certainly common in the upper part of the New Idam Unit. These are good indicators of vegetated flood plains and interfluve areas.

3.2.3 Associated trace fossils.

The interbedded sand/mud (parasequences) facies are marked exclusively by the predominance of two commonly co-existed trace morphotypes. These are Thalassinoides-like burrows and (associated with) cylindrical burrows. Their coexistence together seems to produce a morphotype composite between the two.

Type (i): Thalassinoides-like traces

This type of trace fossil can be described as three-dimensional web-like galleries made of small, irregular, fingers-like tubes (Fig. 11A-C). It occurs in most of the parasequences, displaying variable intensity.

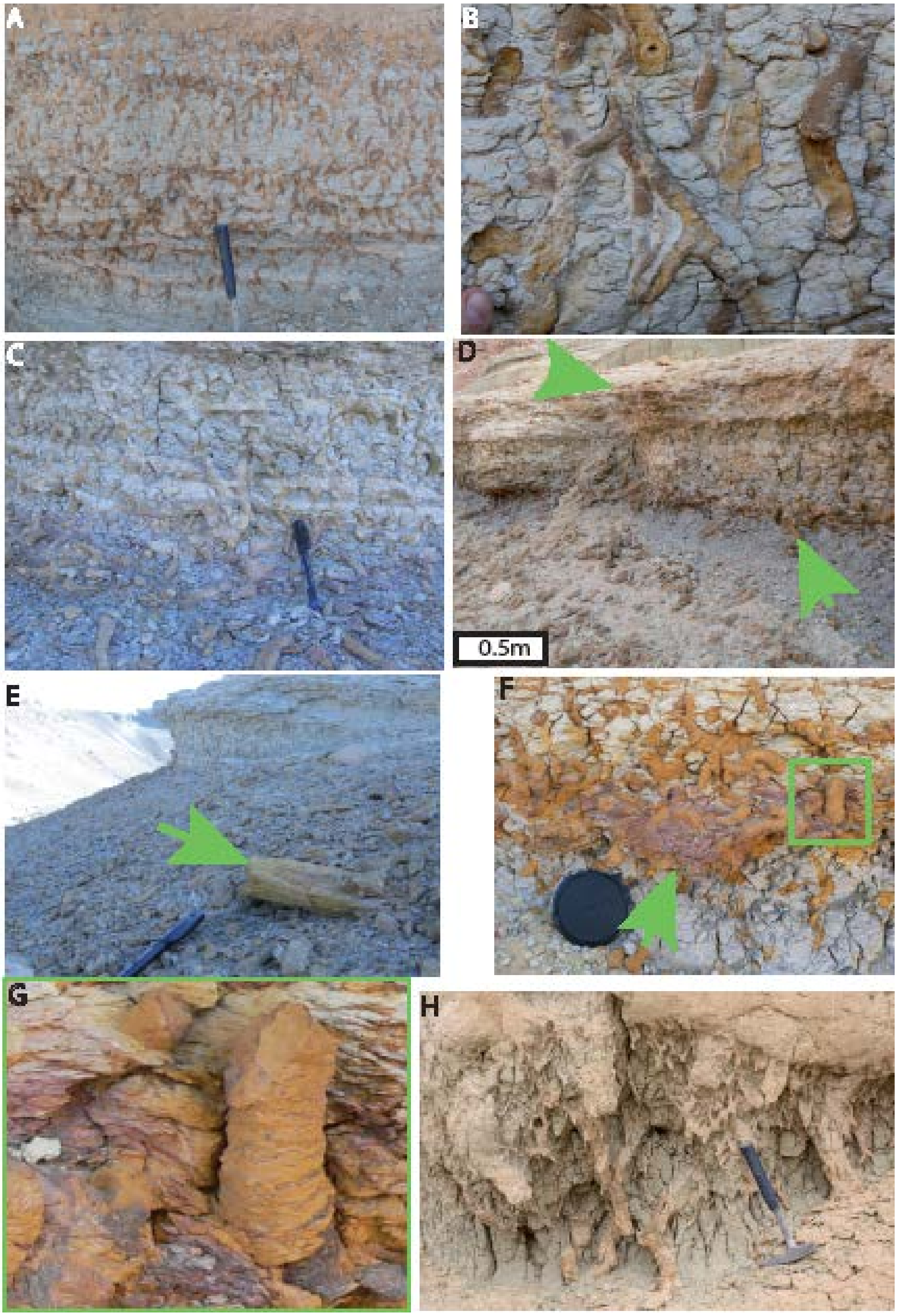


Fig. 11A-H: Thalassinoide-like burrows in the sand-mud interbedding facies. A) General view of the burrow network; B) Thalassinoide tubes size and morphology; C) Thalassinoide network from other location; D-F) Thalassinoides coexist with fossil plants (the green arrow); G) Close view from F (the green square) showing crescent-shaped surface ornamentations; H) Composite burrow architecture (oriented Thalassinoides) .

They are better developed in the sandy beds, where they are characteristically associated with petrified wood chunks (Fig. 8D-F) and with different types of fossil fruits including, Pandanus. Their intensity exhibit slight downward decreasing, into the mud beds. The burrow architecture of this type is (in terms of size and morphology) comparable with or corresponds to Thalassinoides paradoxicus (described by e.g. Kennedy, 1967; Rice and Chapman, 1971; Bromley and Frey, 1974; Bromley and Ekdale, 1984; Martin, 2008). The burrows network are built up of randomly interconnected tunnels and shafts with diameters vary between 1-3 cm and the length before any bending or curvature may reach 15 cm. Swollen or enlarged area at the burrows junction (characteristic for Thalassinoides) occurs at the intersections and bending points of the tubes. Y-shape, inverted Y and J- and L-shapes all are common. Cross section of the burrow is commonly circular, and some of them are penetrated by narrower (few mm diameter) open tube-like burrow in this aspect they are similar to Lunulichnus tuberosus ichnospecies described by Zonneveld et al. (2006) as Arthropod-constructed trace, associated with alluvial firmgrounds.
The filling of the Thalassinoides-like burrows is massive. But many of them preserve laminated (meniscate) structure. In this aspect, the Thalassinoides here resemble the trace Naktodemasis Bowni of Smith et al. (2008). The outer surface of the Thalassinoides-like burrow is generally smooth, though, in some forms the outer surface are ornamented, preserving a subcircular crescent shaped wall texture (Fig. 11G). With this ornamentations in mind as well as the other aspects of size and general morphology, make these burrows comparable to the Lunulichnus tuberosus trace fossil. In many beds of these parasequences the artwork of the Thalassinoides are intermixed (intersected and intersect) with a larger cylindrical burrow, result in a third (composite) morphotype (Fig. 11H).

Interpretation of Thalassinoides-like burrows

The paleoenvironmental distribution of Thalassinoides is commonly marine (e.g., Howard and Frey, 1975; Myrow, 1995). Nonetheless, Thalassinoides paradoxicus and T. suevicus have been recently recorded in the nonmarine floodplain environments (e. g., Kem et al., 2002; Martin et al., 2008). However, Thalassinoides are not a direct indicator of water depth and quality, but are mainly related to other ecologic and sedimentological factors especially the substrate characters (Ekdale, 1992). In these sediments (parasequences) this trace is closely associated with plant remains and fossil fruits of various species. In addition, it is also associated with vertebrate fossils of fully terrestrial and aquatic terrestrial vertebrates. Accordingly, the recurrence of this trace fossil with such fauna and flora suggests that the trace maker could be entirely freshwater (adapted) organism.

Type (ii): Cylindrical morphotype burrows

This burrow is predominantly preserved as sand- and/or mudstone casts and molds of cylindrical shape. Their general morphology is similar to the ones described above in the paleosoil facies (Fig. 8I-O). But this time, burrows are, in average, slightly larger (Fig. 11I-M). Cylinders here are longer (up to 200 cm long) with generally circular to subcircular cross sections. The burrow diameters (4-25 cm, average 10 cm) are, to a great extent, uniform from its top to bottom. Roughly, the length to width ratio is variable from one parasequence to the other (1:4, for thin to 1:15 for thick parasequences). In addition to their overall vertical-subhorizantal simple morphology, cylinders show also composite morphology with different orientations, other than simple cylinder. Sinuous and Y-shaped cylinder (Fig. 11K), concave up cylinders (Fig. 11L),

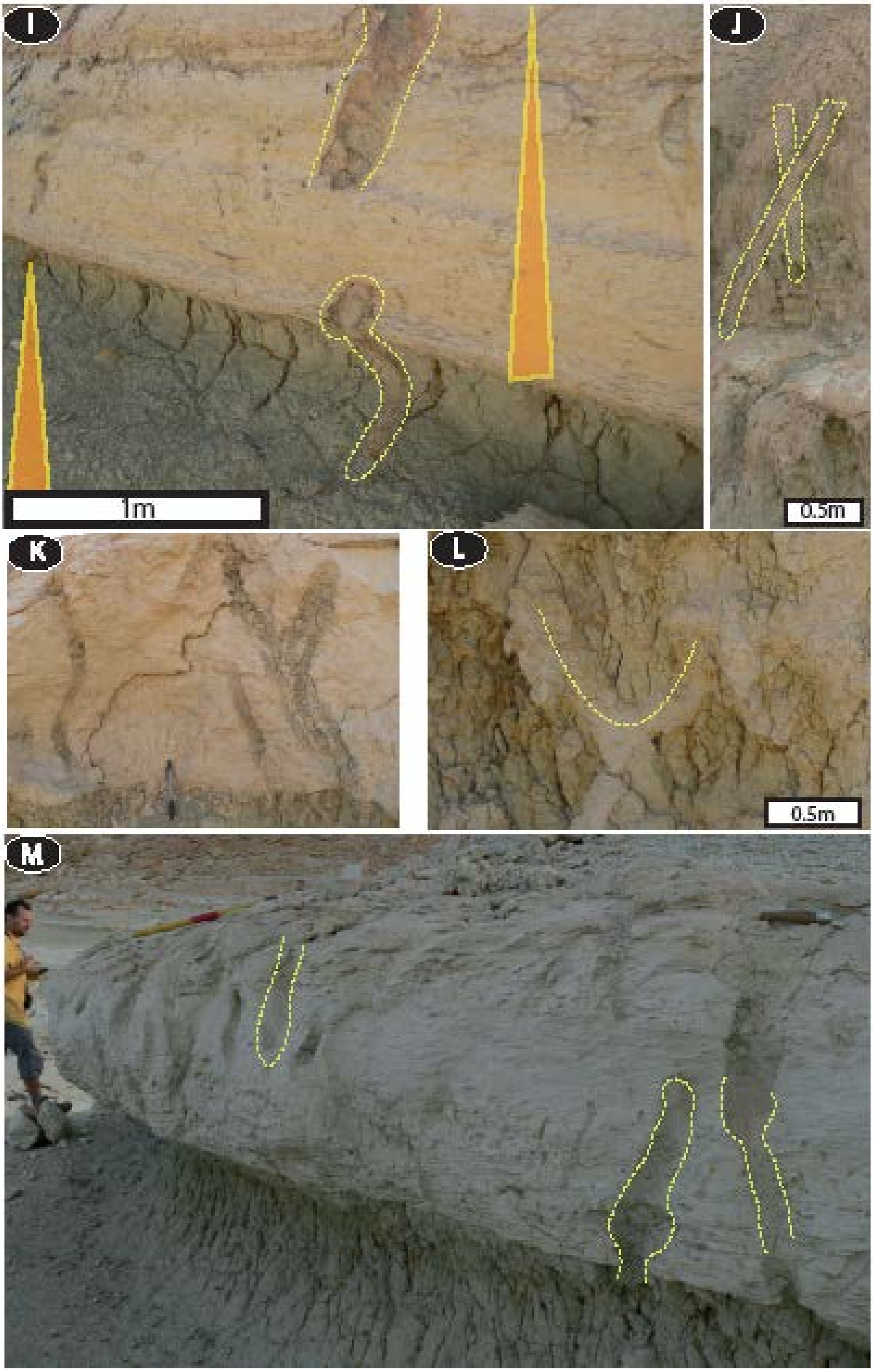


Fig. 11I-M: show the different morphological aspects of the cylindrical burrow.

vertical cylinders with component of vertical curvature, all are common.
Many cylinders seemed to be initiated in the sandstones and dig down into the underlying mudstones. Regardless of this, it seems that longer burrows are associated with thicker beds. Continuity of the same type of burrow is recorded by the superimposed parasequences.
The diameter of some longer borrows decreases slightly downward, many of these having an enlarged chamber at some points along its long axes (Fig. 11M). Many burrows show slight change in their orientations at the point of enlargement, and of particular interest is that adjacent burrows, in some outcrops, show the enlargement (and or diversion) at approximately the same vertical level. Again, in this aspect, these burrows are typically similar to those cylindrical burrow described in the underneath paleosoil facies.
This cylindrical burrow type exists in almost all the parasequences; their density changes laterally from one place to the other, even in the same bed. Differential erosion among the sand and the mud has important role in exposing their casts and molds. Of particular significance is that some cylindrical burrows are filled with microconglomeratic mud clasts mixed with broken fossil vertebrates (Fig. 11N). Rodents and primates described by Jaeger et al. (2010b) are retrieved from this microconglomerate.
In addition to the granular filling, burrows sometimes show segmented (or layered) backfill, composed of fine sand and mud (Fig. 11O), each segment is few cm thick. Such cases could probably reflecting episodic (seasonal) passive backfilling of the burrow. Close to the neck of some burrows some scratch-like marks (of several mm wide and few to several cm long can be faintly observed, these exist in the burrows and also (similarly) in the adjacent hosting rock (Fig. 11P, Q). The shape and size of some of these scratch-like marks reminds the fossil root traces of small plants. Apart from the burrow filling, some surface ornamentation are still preserved, as poorly defined scratches and inclined and curved groves preserved on the outer surface of the casts and, less likely the inner surface of the molds.
The two main burrow types (cylindrical burrow and Thalassinoides-like) dominating the sand-to-mud facies usually exist together. Large cylinders are commonly intersected and are intersected (or occupied) with the smaller Thalassinoide tubes (Fig. 11R, S). In some levels their combination produces a distinctive composite burrow structure: the morphology and the orientation of this new structure are in overall similar to the cylindrical burrow and sometimes exhibit overall conical outlines. Moreover, the small Thalassinoides tubes appear selectively oriented inside the cylindrical burrow. The Thalassinoides occur as a regular stringy tubes, that extend (helically; Fig. 11R) up the cylindrical body. Those tubes developed inside the cylindrical body (forming the composite burrow architecture), and they diverge and radiate as they attain the top of the cylinder (Fig. 11T), i.e. the top of hosting bed. Cross sectional outcrop view of the composite cylinders displaying diagenetic redoximorphic rings shown by individual tubes (Fig. 11U). Worth mentioning in this situation, is that many of these composite burrows preserve semi conical morphology, and with their general orientation involved, they typically resemble that of the roots network (Fig. 11V). Occasionally, the upper bedding plains (when exposed) of the beds hosting those conical cylinders are dominated by chunks and stumps of petrified trees. Section (4.1, below) will illustrate that roots are not the only candidate for the cylindrical burrow.

4. Interpretation of The sand to mud (parasequences) facies.

Sand-mud fining up parasequences are one of the known criteria of channel-abandoned channel in fluvial (e.g., Cant and Walker, 1976; Mail, 2002; Selley, 1992; Allen, 1983; Thomas, 1987) and in tidal (e.g., Thomas, 1987; Dalrymple and Choi, 2006; Van den Berg et al. 2007) depo-

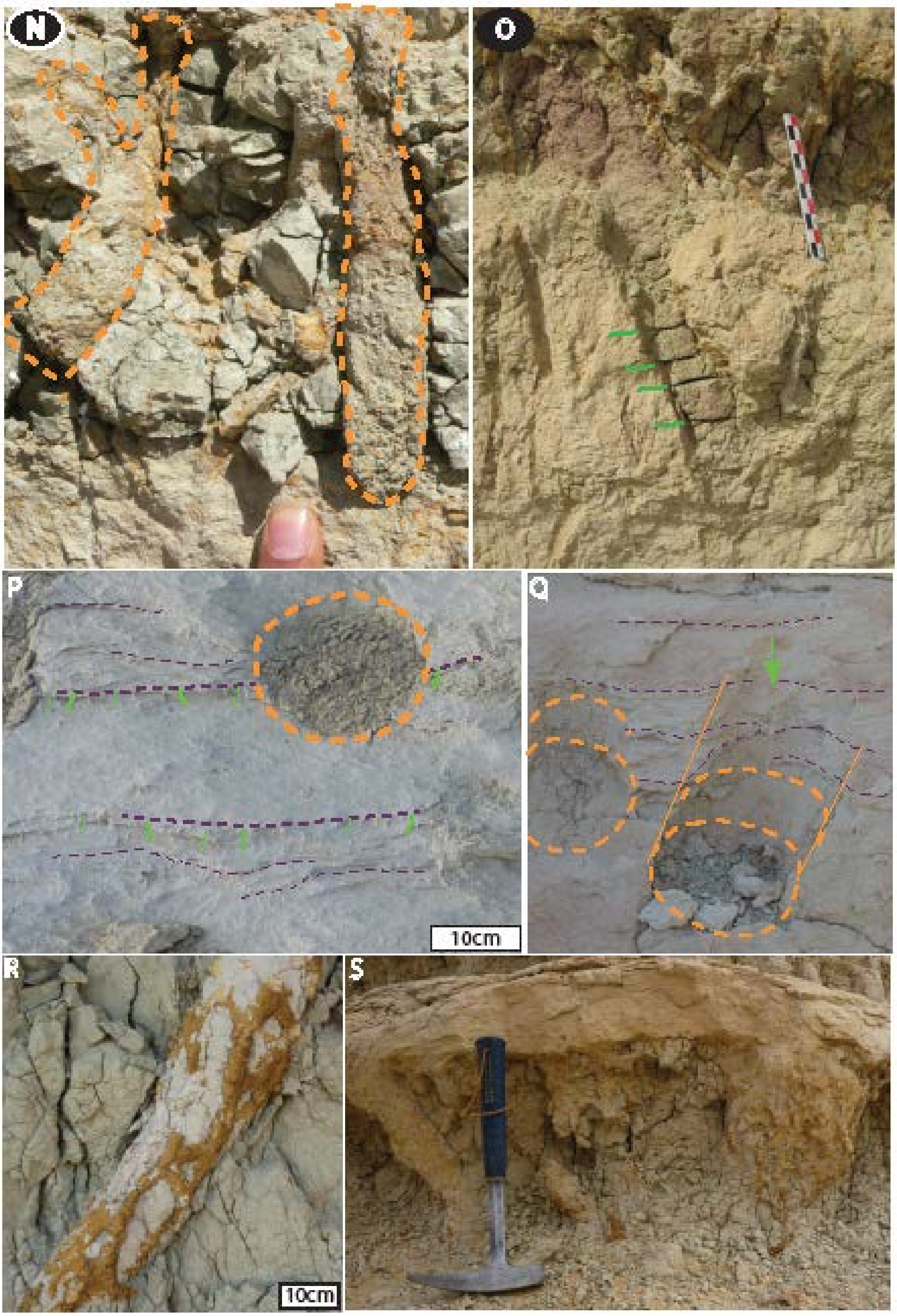


Fig. 11N-S: characteristic aspects of cylindrical burrow in the interbedding sand-mud facies. N) Burrows filled with aggregated fossil fragments; O) Segmented back fill; P,O) Cylindrical burrow associated with subtle millimetric roots; R) Thalassinoides-oriented into the cylinder morphology; S) Large cylinder reoccupied by small burrow tubes.

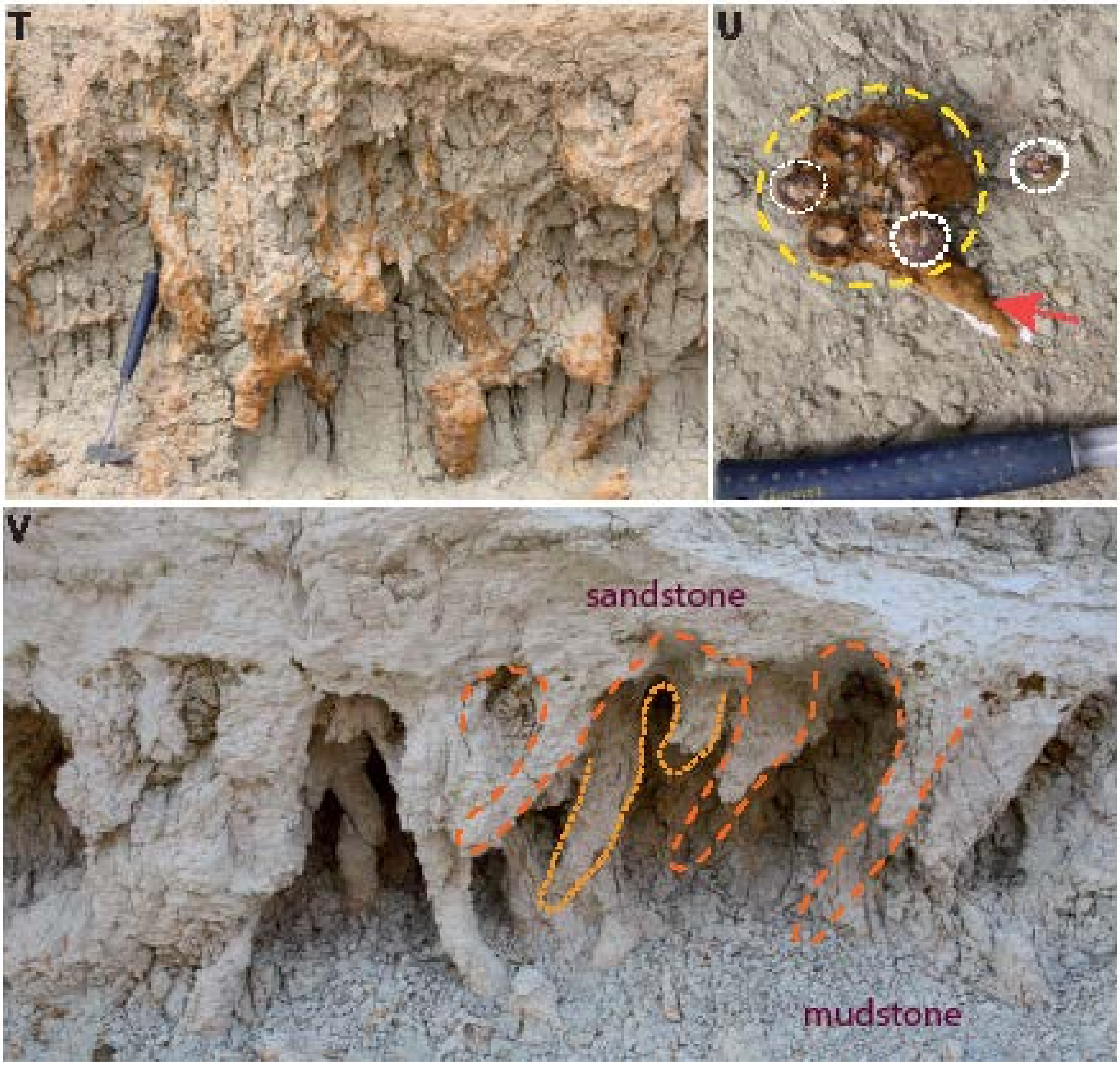


Fig. 11T-V : Composite bioturbation. T) Thalassinoide-like burrow closely associated with cylindrical burrows; U) Transversal cross section of biogenetically altered composite burrow; V) Cylindrical/composite burrow imitating net-work of medium plant roots (in 3D).

sitional environments. Fining up sequences can occur in many other depositional settings, e.g. turbidites and lots of others. In addition to their distinctive bioturbations, the fining up facies in the upper part of New Idam Unit shows three main nonneigligable aspects,: 1- high frequency of sand/mud alternation, 2) ubiquity of fossil flora and fauna, of specifically aquatic terrestrial vertebrates in conjunction with the absence of marine shells, 3) the intermittent occurrences of emersion surfaces indicators, such as: beds with hair-like root marks, color mottling, and desiccation cracks, large bones of terrestrial animals. The first aspect is also known for many environments concerned with rapid fluctuation in energy level, which is also a characteristic for tidal (estuarine and delta) as well as fluvial (streams and lakes). The second and third aspects are to a variable extent, applicable for the entire upper part of the New Idam Unit. All these features have been reported in a variety of fluvial subenvironments such as flood plain, crevasse splay and abandoned channel and channel bars. An attempt to interpreting the origin of the cylindrical bioturbation would provide a supportive evidence of which environment is most reliable?

4.1 Origin of the cylindrical burrow (discussion)

Two exclusively predominant types of traces are described, the small Thalassinoides-like burrows and the large cylindrical morphotype burrows. Both are widely spreaded throughout the entire outcrop of the upper part of the New Idam Unit. In fact, the obvious observation of the cylindrical burrow as a distinctively dominated burrows type commenced at nearly the middle of New Idam Unit in the paleosoil facies. Respecting this fact, the first glance that appear in mind is the relative absence of the Teichichnus, Diplocraterion and Skolithos which are common in similar lithofacies in the lower (tide dominated) part of the New Idam Unit. This precludes that the environment of the deposition of sand-mud parasequences is far (inland) from being of pure shallow marine environment. Then, what about the bioturbations?

Trace fossils of cylindrical morphology are commonly documented in the literature. They can be produced after the decay of roots and stumps of small trees (Bown, 1982; Kraus, 1988; Tanner and Lucas, 2007), aestivation burrows of lungfish (Dubiel et al, 1987; McAllister, 1988; Hasiotis et al. 1993) or amphibian (Reno et al., 1972; Hembree et al., 2004), crustaceans in shallow marine environment (Frey et al. 1984; Rodriguez-Tovar et al, 2008). And in terrestrial inhabitats similar cylindrical burrows can be produced by freshwater crayfish (e.g. Hobbs, 1981; Lucas et al., 1999; Welch and Eversole, 2006; Hasiotis and Mitchell, 1989; Tanner and Lucas, 2007), and freshwater crabs (Cumberlidge 1986; Dopson, 2004; Melchor et al., 2010). Identification of the trace maker would help in recognizing the depositional environment. This is the case here because of the repeatability of the same burrow in the same lithology. What makes the identification of the trace maker difficult is the presence of many features in common between the different makers of the same trace. The few coming paragraphs will discuss the possible trace maker for the bioturbations encountered in the sand-mud parasequences, the upper part of the New Idam Unit.

The morphology and the size of trace fossils as well as the surface ornamentations, are the most significant recognizable criteria to identifying their burrower (Seilacher, 1967; Bromley, 1996). Literature review (e.g. Hobbs and Whitman, 1991; Hasiotis and Mitchell, 1993; Bridge, 2003; Tanner and Lucas, 2007) of the most common burrow similar to the described here as a cylindrical burrow suggests that the candidate burrow maker is the decapod crustacean. These small organisms (decapod crustaceans) are known to excavate burrows several orders of magnitude larger than their size. Traces of roots, lungfishes and amphibians cannot be totally excluded, because of the similar morphological and dimensional features with, at least, some of the encountered burrow. The presence in the cylindrical burrows of scratch marks and groves as well as some behavioral features (described in e. g. Hasiotis and Mitchell, 1993; Tanner and Lucas, 2007; Bedatou et al., 2008; Martin, 2013) points to the fresh water (crayfish or crab) decapod crustaceans.

4.1.1 Comparing the cylindrical burrows with recent burrows of decapods

For the purpose of comparing the cylindrical burrows of New Idam sediments with recent burrows of decapods, wax molding has been performed, for a decapod crabs excavating their burrows in the supratidal and intertidal area on the Kampot delta, south Cambodia. In principle, two sizes of tubular burrows are obtained: 1) small size burrows (Fig. 12A-C) made by relatively smaller crabs (12B). The wax molds of these burrows are closely comparable (Fig. 12C, D) to the Thalassinoides (compare also Fig. 11A-H) morphology in the sand-mud parasequences. It has been monitored that these modern burrows are made by small crabs in the upper intertidal

Fig. 12A-D: Wax molding of modern burrows (A1, A2) made by small crabs (B1, B2); C, D) comparing branched galleries of modern with ancient (thalassinoides-like structure) from upper part of New Idam Unit.

zone; 2) larger type burrows (Fig. 12E-H) retrieved from the supratidal zone, inside the mangrove forest with shallow ground water. These are made by larger crabs (fiddler crab). This time, the wax molds are typically comparable to the larger cylindrical burrows of the sand-mud parasequences (previously illustrated in Figs. (11I-M, 8I-O). The burrow architecture, dimensions and orientations are, to a great degree similar. These recent burrows and the described cylindrical burrows are closely comparable in terms of diameter, length (and length: width ratios) as well as the presence of scratch marks and the mid-way enlargement chamber (Fig. 12G). Differently, the numerous

Fig. 12E-J: modern burrow of large crabs. E) pouring the molten wax into the burrow via the burrow chimney; B) The molded burrow morphology, top view; G) The enlarged chamber, notice the serrated end of the burrow; H) Another burrow from adjacent place, notice the many branchings and bifurcations; I, J) Shows the external morphology of the burrow chimney and the difference between the external and the internal diameter of the chimney (the dashed circles).

branching in the wax molding (Fig. 12G-H) seem to more branch than that of the fossil. The explanation for this difference could be attributed to the outcrop nature. The outcrops where cylindrical burrow observed is only a two dimensional cross section, meanwhile the wax

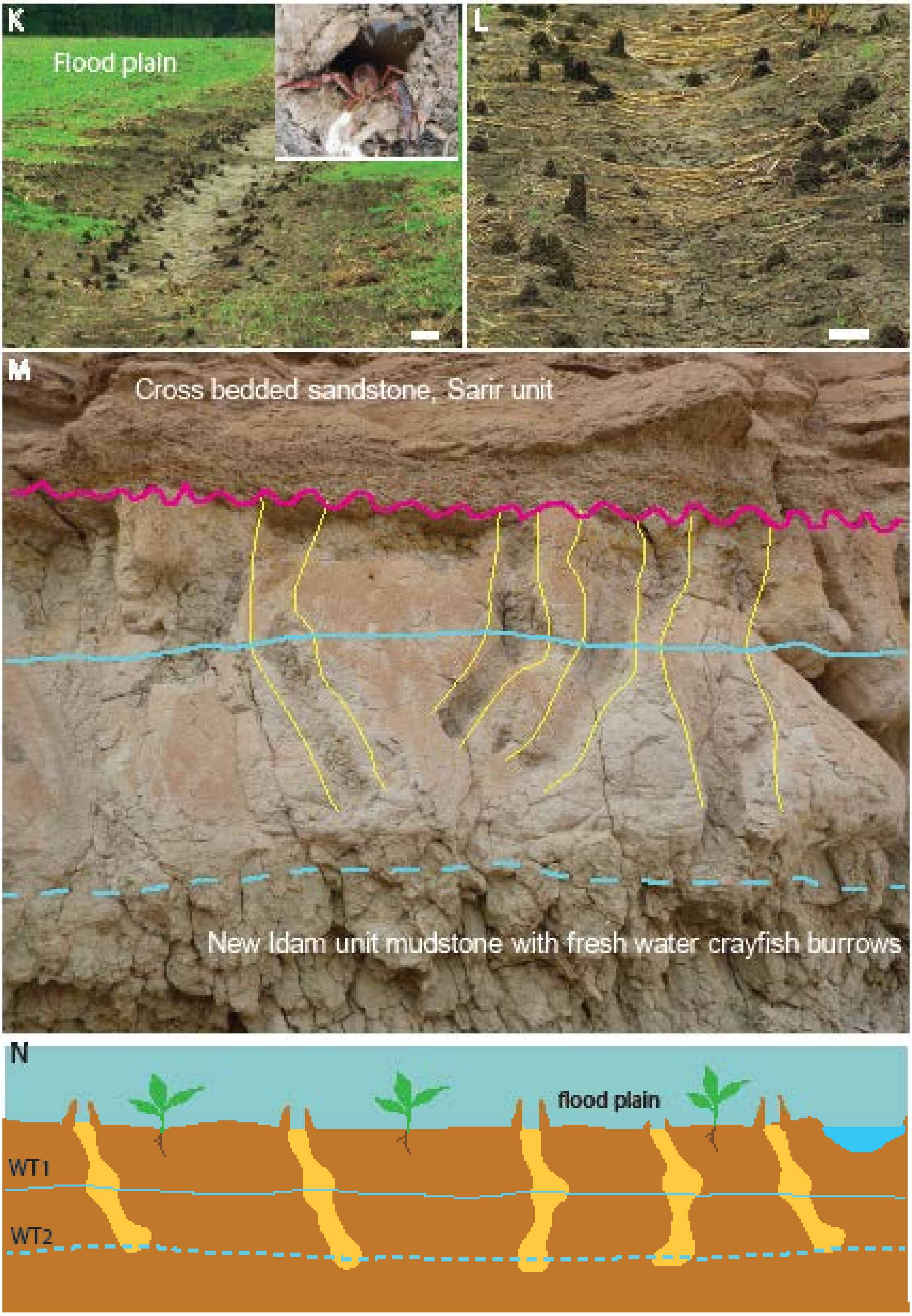


Fig.12K-N: Fresh water crayfish burrow, the modern ones, and the fossil in New Idam Unit; K) Chimneys of crayfish living in fluvial flood plain (Louisiana, USA; Google); L) Close view from (K) to show the chimney dimensions (scale bars 20 cm). In (K) the inset photo is for a living crayfish; M) Adjacent burrows of crayfish reoriented themselves at nearly the same level (notice the horizontal level of the enlargement chambers); this level (the blue line) is probably represents the paleo water table; N) simplified model for crayfish in the flood plain (the blue solid line for the precedent water table, the dashed one for the next water table during dry season.

molding casts the entire burrow network made by the crab. One more aspect related to the slight difference in the length of the wax molds and the ancient cylindrical burrow. The obtained molded recent burrow is slightly shorter. This is attributed to the shallow ground water in the molding area.
This similarity between the recent crab burrow and the cylindrical burrow in the upper part of New Idam Unit is not the only features in common. An exclusive criterion for the crab excavating in the emerged supratidal zone is that they build up an external chimney. This chimney has an internal diameter equal to that of the attached burrow (Fig. 12I, J). The chimney may extend for up to 25 cm above the ground surface. Back to our fossil cylindrical burrows, the morphology and size of this modern chimney is typically resembles the emanating fossil casts (Fig. 8K, M) exposed in some bedding plains at the middle of New Idam Unit.
Fossil burrow of the crabs of freshwater habitat are numerously documented from the ancient rock record. Nonetheless, almost the same morphological and dimensional burrow features of the crab are produced by the freshwater crayfish, from Triassic (e. g. Hasiotis, 2002; Bedatou et al., 2008; Martin et al, 2008) to recent. Present day crayfish are also able to build chimneys in flood plains (Fig. 12K, L). Crayfish is living today in many humid tropical areas around the world in shallow fluvial streams, river banks, flood plains as well as terrestrial wet forests and grass lands (e.g. Hobbs, 1942, 1981; Horwitz et al., 1985; Hasiotis et al., 2004; Millar, 2007; Martin et al, 2008; Schultz et al, 2009; Martin, 2013) and they are unable to survive in sea water salinity (Wheatly and McMahon, 1983; Holdich et al., 1997) due to the adverse effects of saline water on egg development and hatching.

As a matter of comparison all the cylindrical burrow criteria exhibited by the cylindrical burrow of the New Idam Unit are comparable with the present day burrows of the freshwater crayfish. Remarkably, there is another criteria match between our burrow and that of the crayfish. This criterion is linked to the style of living of the crayfish. A special behavioral aspect known specifically for the freshwater crayfish burrow is their basic need to freshwater. The essential reason for the crayfish to burrowing is to seek the moisture, i.e. the ground water (Hobbs, 1942, 1981; Horwitz and Richardson, 1986; Hasiotis and Mitchell, 1993; Hasiotis et al., 2004; Bedatou et al, 2008; Martin, 2013), for foraging, breeding and protection from predators. Their need to water leads them to dig until they reach the water table, rest in the enlarged chamber, and then continue digging during the dry periods following the drop in the water table (e. g., Hasiotis and Dubiel, 2005; Helfrich et al, 2009; Martin, 2013). This behavioral aspect is registered in the cylindrical burrow in the sand-mud parasequences, expressed by four features:

(i) The adjacent burrows in the same outcrop shows changing in their orientation in the same horizontal level (Fig. 12M), this level is supposed to be the paleo groundwater level during the time of burrowing (Fig. 12N).
(ii) The presence of mid-way enlargement chamber (Fig. 12O, P). The horizontal level of these chambers is the initial water table, the rainy season. The continual burrowing beyond this chamber is probably due to the drop in the water table.
(iii) Many burrows are terminated at a suspected paleo water table, such cases is illustrated in figure (Fig. 8N, O).
(iv) The longer burrows are mostly associated with the thicker sandy beds, and the shorter ones are associated with thinner beds. Explanation for this could be given by the relatively faster water percolation in the thicker beds of sand. Shorter burrows may be attributed to the interbedding with the mud beds which are able to retain water in and above them.
In this context, taking into consideration the ubiquity of the terrestrial fossils in the upper part of New Idam Unit, and absence of typical tidal sedimentary structures and marine fossils, the fi-

ningupparasequencesofsandtomudisdepositedinentirelycontinentalaquaticenvironment. Theirflathorizontalbeddingandwidedistributionconcomitantwithfrequentlydominantroots remindchannel-fillandabandonedchanneldepositswhichiscommonly,commencewithsand and grades up to mud (Walker and Cant, 1984; Bridge, 2003). The rooted beds with fossil plant thensuggestingvegetatedinterfluvesandybars,largeislandformedbycoalescedbarsandover bank deposits; Figure (12P) proposes a simplified model. Comparable cases are reported from both rock record (e.g. Hasiotis and Mitchell 1989, 1993; Babcock et al., 1998; Tuner and Lucas, 2007; Bedatou et al, 2008) and modern sediments (e.g., Richardson, 1983; Guan, 1994; Hamr and Richardson, 1994; Hasiotis and Mitchell, 1993; Buckup, 1999; Noro and Buckup, 2010).

5. Interpretation of the upper part of New Idam Unit (summary)

The typical shallow marine environment, assigned for the lower 35 m of New Idam Unit, could reasonably be excluded from this part of new Idam unit. This is suggested by the ubiquity, diversity and wide spatial and temporal distribution of vegetated land with fully terrestrial fauna, freshwater trace fossil concomitant with the frequent presence of emer-

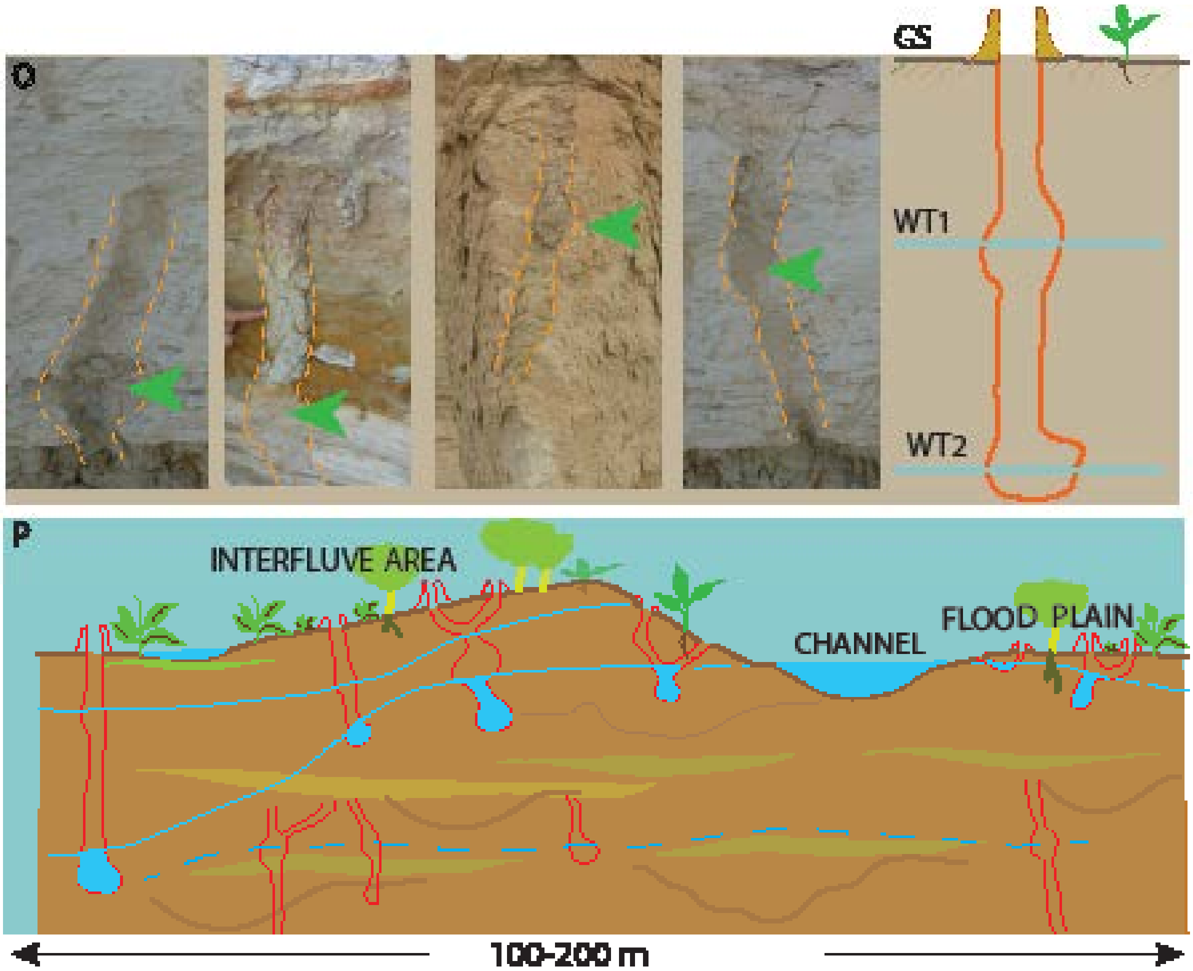


Fig. 12O-P: O): The cylindrical (crayfish) burrow from different places in the upper part of the New Idam Unit, the midway enlargement chamber is a common criterion. The sketch to the right demonstrate the possible interaction of the burrow maker with the lowering water table; O) rough sketch models a small interfluves area, within the inner estuarine environment proposed for the upper part of New Idam Unit. The longest crayfish burrow could exceed 3 m long (modified after Hobbs 1976).

sion surfaces. The emersions surfaces are presented for instance by mud cracks and burrows that are uniquely filled with various species of terrestrial fossils, and by recurring pedogenically altered beds. In the other hand, the channel facies represented by the sand/mud interlamination are also end at its top with emersion features such as the roots and termites fungus comb and galleries that prove at least a several months to year's exposure.

Fluvial interpretation upstream from a tidal dominated estuary for these channels becomes the reasonable conclusion, especially if one takes into consideration the repeated microconglomeratic lags containing continental fossils. Nonetheless, possible tide modulation is suggested in some channels by regular alternation of sand and mud associated with flaser bedding, (similar structures are reported by Pelletier, 2012). Further research is required to decipher the specific distribution of subenvironments. For instance, local small-sized lacustrine environments in backshore area cannot be entirely excluded from this part of New Idam Units. The richness of thick dark colored sand/mud interlaminated succession with a variety of fine plant debris and leaves can be regarded as a witness for lacustrine setting (e. g., Smith, 2008; Paik et al, 2012). Admitting that the upper Part of the New Idam Unit is composed of several fluvial subenvironments is to a great extent similar to that of Wight (1980) how stated that "the upper 35 m of NIU is rhythmical alternation of white sandstone, green silt and claystones represents fluviatile channel, point bars and over bank deposits". The essential difference with Wight is that this chapter suggests possible existence of lake deposits and that channels here are sometimes tidal influenced. This kind of environments is geographically located several km to several hundreds of km inland (upstream) from the shore lines (Dalrymple, 1984, 1992; Shanley et al., 1992; Reading, 1996; Dalrymple and Choi; 2007; Van den Berg; 2007).

6. Conclusions

New Idam Unit is composed of a succession of clay and very fine grained siliciclastic rock. There is enough sedimentary structures and shallow marine fossil to assign the basal (35-45 m) of this succession to coastal tide dominated estuarine (outer estuarine) environment. This part of New Idam unit is separated from the upper part by the well-developed paleosoil facies (5-15 m) which also preserve evident but local shallow marine indicators, compared to the underlying sediments. The paleosoil sediments at the middle of the unit are interpreted as a supratidal flat experienced long time of emersion and intersected by tide dominated channels. The contact between the lower tide dominated section of New Idam Unit and the upper (45-55 m) tide influenced part goes gradationally through this paleosoil zone. The upper part is characterized by the domination of fluvial (fossil and trace fossil) features rather than tidal features. Fluvial domination is supported by the absolute absence of marine fossils and trace fossils. This evidences make inner estuarine the most rational interpretation for the upper part of New Idam Unit.

The overall sequential pattern of New Idam Unit (outer estuarine gradually superposed by inner estuarine) suggests retrogradational shore line trajectory (estuarine filling). The individual parasequences constructing the unit expressing pulses of sea level fluctuations within an overall decreasing rate of sea level rising.

CHAPTER THREE

The sedimentary geology of the Sarir Unit: an abrupt change from shallow marine to fluvial systems

1. General introduction

This chapter will deal with the description and illustration of the sedimentary facies composing the Sarir Unit, aiming at interpreting their depositional environments. Emphasize is given to the nature of the contact between the lower and upper parts of this unit. This chapter is complementary to the next chapter (4) which focuses on the tidal sedimentary structures distinguishing the lower part of this unit. Results of the two chapters well lead to realize that of great stratigraphic significance subdividing the Sarir Unit into two independent parts (two different stratigraphic units), the lower and upper Sarir Units. Concerning the lower part itself sedimentary features allowed its roughly splitting into two parts. The lower lower Sarir (LLS) and upper lower Sarir (ULS), the boundary between these two parts is gradational and arbitrary. Despite the sedimentary features in common between the lower (including LLS and ULS) and the upper Sarir, it is obvious that the two intervals are completely different in terms of environments of deposition. Lower Sarir Unit proved deposition in shallow marine tide-dominated environment (LLS), with evidences of gradual upward decreasing in the tide signature compensated by increasing in fluvial signature (ULS). In contrast, the upper part of the Sarir Unit sandstone is entirely fluvial. In addition to the stratigraphic aspects, this chapter provides evidences that the lower and the upper Sarir are unconformable, with obvious erosional contact separating the two intervals. The coarse fluvial rocks above the contact cut down into variable sandstones facies and paleosoils of tidal dominated (LLS) and mixed tidal-fluvial sandstones (ULS).

1A. Introduction to the Sarir Unit

Sarir Unit is composed of dominantly fine-medium grained to microconglomeratic sandstones, measures approximately 50 m in thickness and occupies the top of Dur At Talah escarpment. Because of erosion, the complete sequence of this unit (Fig. 1) crops out only locally, at the western side of the escarpment. It constitutes the well exposed subvertical cliff (20-30 m) and extends above onto the attached plateau (up to 30 m), where it is only locally exposed, as discontinuous hills and small isolated mesas. This unit is composed of siliciclastic rock, much coarser than that of the underlying New Idam Unit which is made of fine sandstone and mudstones. In particular, Sarir unit sediments are represented by fine to medium grained sandstone with subordinate layers of mudstones, these grade toward the top into very coarse to microconglomeratic sandstones (Fig. 1). Overall variations in the grain size and texture, sedimentary and biogenic structures allowed subdividing the Sarir Unit into two stratigraphic levels, the lower and the upper Sarir. The lower Sarir (20-30 m) started from the sharp contact with the underlying, highly bioturbated New Idam Unit and extends up until the upper reaches of the cliff. The upper Sarir (around 30 m) occupies the remaining part of the escarpment including the isolated hills distributed over several kilometers to the North. Good and continuous outcrop is provided by the cliff for the lower Sarir, and very scattered and discontinuous exposures are available for the upper part of the Sarir. In general, good outcrops occur in the western 100 km of the cliff. Channelization of variable horizontal scale (decametric to hectometric) is one of the most prominent features of the Sarir Unit. This is especially very obvious in the lower Sarir.
The division of the entire Sarir Unit into lower (20-30 m) and upper (around 30 m) Sarir is

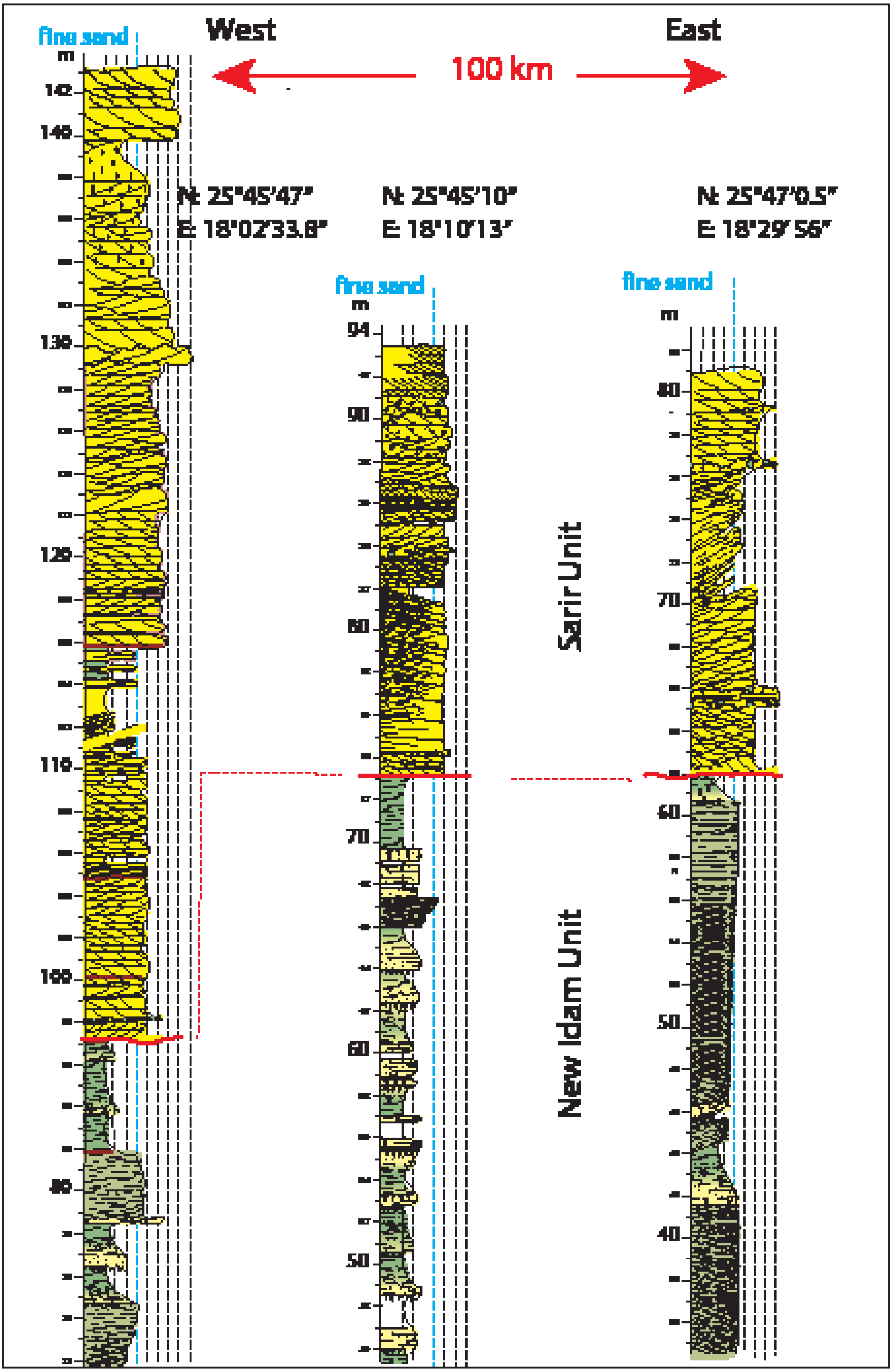


Fig. 1: Lithological log shows the medium to very coarse cross bedded sandstone of the Sarir Unit from three locations, within the western 100 km of the studied escarpment. Completely sequence of the unit is available only in the western side of the study area. The grain size contrast with the underlaying New Idam Unit is obvious.

based on following criteria:
1) The lower Sarir Unit is characterized by fine to medium sandstone while upper Sarir Unit displays obvious medium to very coarse sandstone with place to place microconglomeratic facies occurrences.
2) Paleosoils as well fossil roots and termite fossil traces are very seldom and only locally preserved in the lower Sarir. Contrary, these are very intensive and ubiquitous in the upper Sarir. Paleosoils are especially obvious at the contact zone between the two units. In addition, silicified wood is in general common in lower part of Sarir and absent in the upper Sarir.
3) Poly directional palaeocurrents structures characterize lower Sarir (Fig. 2), these are tending to be unidirectional, commonly to the North, towards the upper Sarir. Palaeocurrents are displayed by cross bedding of variable scales.
4) The cross-bedding in the lower Sarir display thinner foresets than that in the upper Sarir.
5) Soft sediment deformation as convolute bedding and overturned cross-beds are obvious in the lower Sarir but very seldom in the upper Sarir.
6) Above all, tidal sedimentary structures are evident in the lower Sarir and completely absent in the upper Sarir.
In addition to the aforementioned outcrop scale aspects, sediments of entire Sarir Unit exhibit many other small scale sedimentary structures. Both large aspects and smaller structures led to differentiate several different sedimentary facies. In sum, facies of the Sarir Unit are grouped into three depositional facies: tide dominated facies occupy the base (LLS), followed by mixed (tidal-fluvial) at the middle (ULS) and finally by fluvial facies belong to Upper Sarir.

2. Facies composing the Sarir Unit

This section describes the facies encountered in the entire Sarir Unit starting from its sharp base with the New Idam Unit ending up with the exposed top of the Sarir far on the plateau. 14 facies are described and interpreted. Facies are amalgamated and exchanging locations within a lateral distance of few to several hundred meters. Sedimentary bodies (different facies) truncating each other are prevailing feature in lower Sarir. Volumetrically, cross bedded sandstones are the dominating component of this facies sequence. Therefore cross bedding sandstone is not considered as an independent facies. Another aspect to be considered is that this facies are frequently repeatable laterally and vertically, and they show some subtle variation in their characteristic features. For instance facies (2.1, 2.2) exist at the base and at the top of the Lower Sarir. But they show variability in the ubiquity of tidal/fluvial sedimentary structures and features.

2.1 Cross-bedded thinning/fining up sandstone facies

This facies is composed dominantly of fine to medium, occasionally, coarse grained, moderately to well-sorted cross-bedded sandstones, with yellow-grayish yellow as the dominating colors. Sets are few cm to several tens of cm thick. Cross-sets are commonly organized as a thinning up sets (Fig. 3 A-C). Thick trough cross sets at the base grade upward to a thinner trough and tabular cross sets, and occasionally terminate with plane parallel and lenticular bedding. The thinning up trend is commonly easy to distinguish, coupled with slight fining up in grain size, and is expressed by sequences range in thickness from few to several meters (Fig. 3A), can be traced laterally for few hundred metres. Thinner sequences are incomplete, truncated by an abrupt (local) erosional surface (Fig. 3B). Many of the basal erosional surfaces of this facies are mantled with blocky greenish mud clasts of variable sizes and shapes (Fig. 3D), sometimes associated with petrified wood (Fig. 3E). Petrified wood logs show variable abundance and size depending on the position of this facies in the sequence. They are smaller (several cm) and less common at lower positions; more frequent and

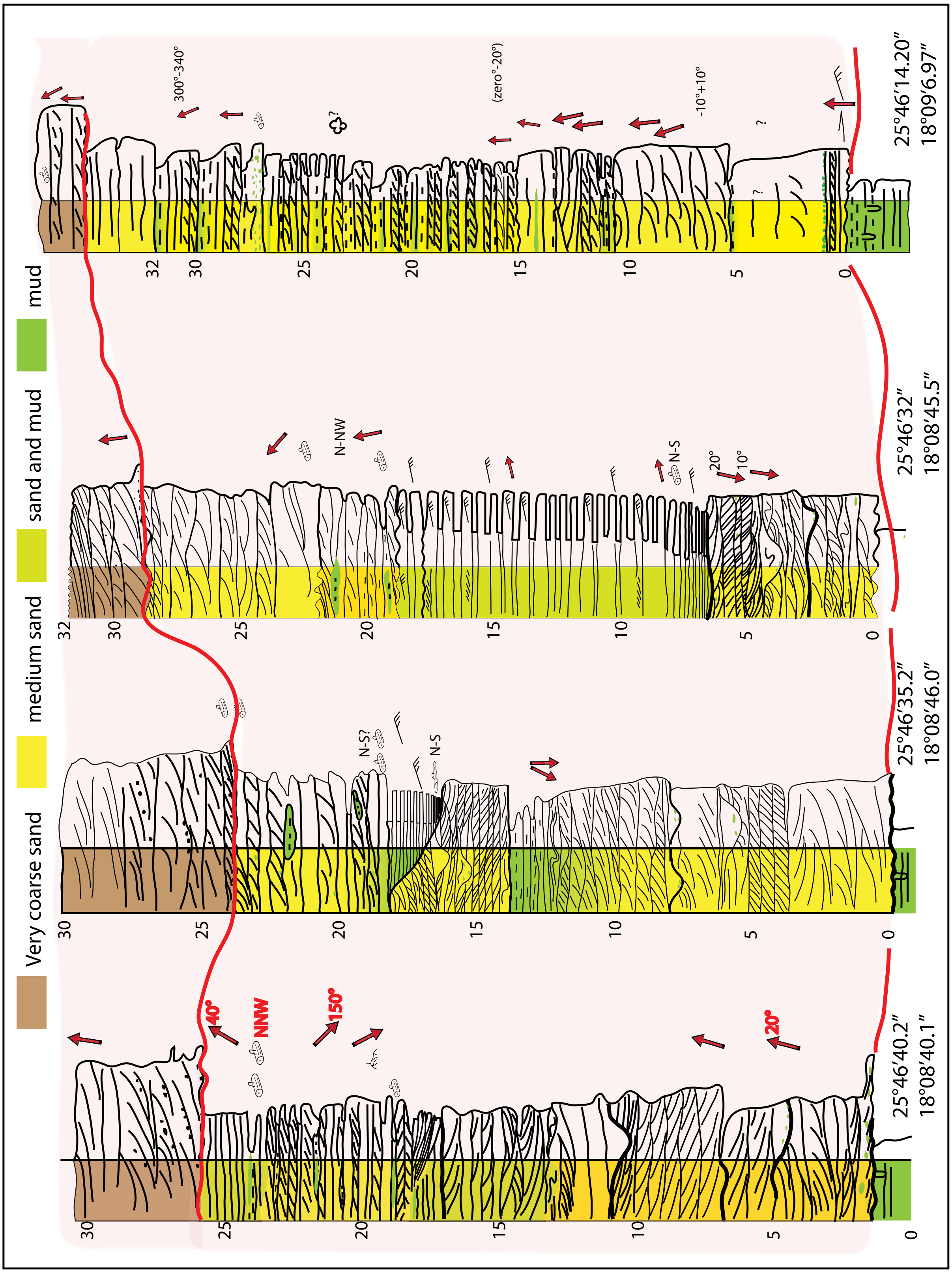


Fig. 2: Correlates the lower Sarir Unit (between the red line boundaries) in four adjacent locations. Notice the variability in the paleocurrent directions (the red arrows), which tend to be unidirectional at the upper Sarir (the brown color).

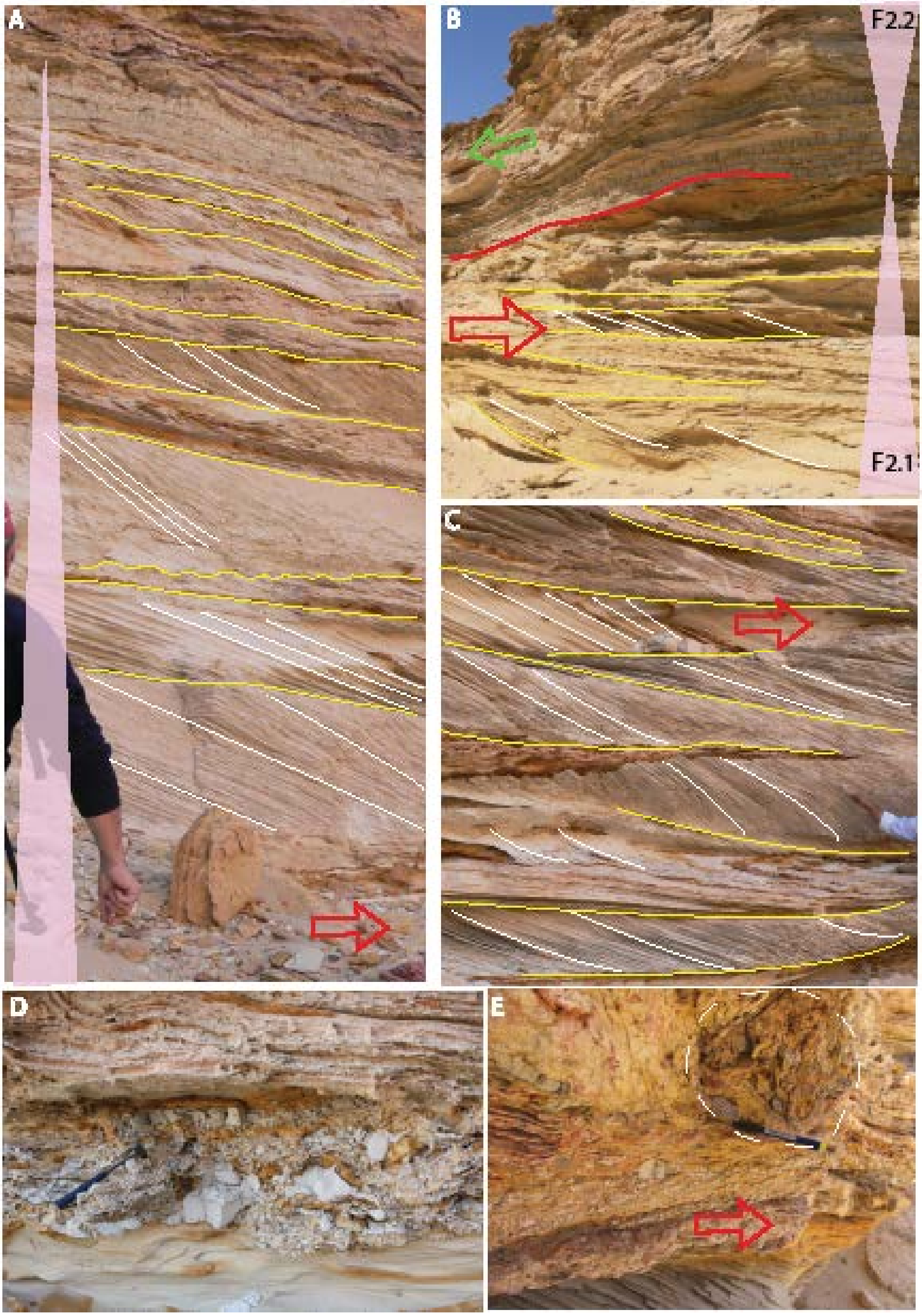


Fig. 3A-E: Cross bedded thinning/fining up sandstone facies. A) Cross bedding fining up sequence; B) Fining up facies erosively overlain by thickening up facies; C) Trough cross bedding showing southerly oriented paleocurrent; D) Blocky conglomeratic clasts at the base of channel; E) Silicified wood at the base of the thinning/fining facies, it exist also at other position but is less dominant.

larger (few to several tens of cm) at upper positions, petrified wood are generally randomly oriented (commonly parallel to the cross-sets direction of progradation). Northerly-southerly oriented silicified wood is more frequently observed than the other directions.
The palaeocurrents recorded by the cross bedding shows great variability from one location to the other, though, southerly direction (landwards) appear to be overwhelming, especially at the basal part of the Lower Sarir. Northerly oriented palaeocurrents led to the local preservation of herringbone cross bedding (Fig. 3F-H) associated with other tidal sedimentary structures,

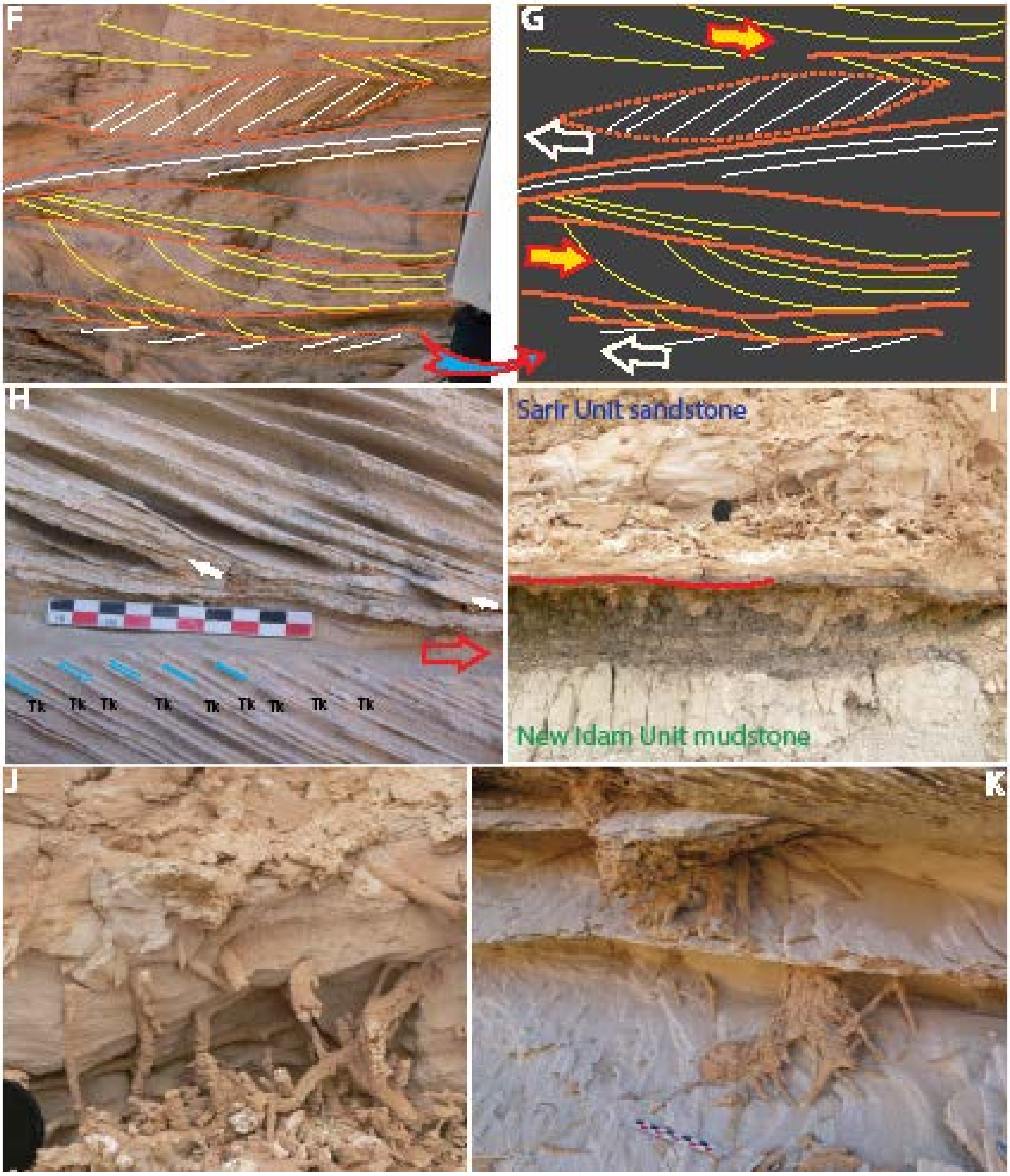


Fig. 3F-K: F) Herringbone cross bedding in the fining up facies; G) Schematic presentation of (F) indicates the opposite palaeocurrents; H) Cross-bed sets display sinusoidal thick-thin alternations attributable to the semidiurnal tidal regime. The above set shows mud draped fore-sets associated with small reversed ripples (red arrows); I) Ophiomorpha trace fossil in the sandstone of lower Sarir; J) Closes view of (I); K) Termite fungus comb and the connecting conducts (shafts and galleries).

especially the typically tidal mud drapes. Moreover, the cross-sets of this facies involve centimetric scale sedimentary structures characteristic of tidal processes. Mud double drapes, current ripples oppositely climbing on the prograding foresets, current ripples perpendicular to the forests (draining or climbing ripples described by Van den Berg et al., 2007) are well preserved in many cross-sets (illustrated in chapter 4). The mud drapes are the most ubiquitous figures of tidal structures in this facies. It is in many occasions associated with other diagnostic tidal structures. Most typical of these are the daily tidal bundles (Boersma, 1969) and the fortnightly tidal cycles. Some of the cycles exhibit hierarchical changes in their thickness, indicating longer (semi-annual) tidal cycles. In scant occasions, successive bundles sequence display a systematic sinusoidal pattern of changing thickness (thick-thin-thick, Fig. 3H). This sort of bundles arrangement is reported from semidiurnal tidal regime due to the combined effect of both daily and fortnightly tidal cycles (neap/spring; Kvale et al, 1999). Details of these aspects are given in chapter 4.

Bioturbations in this facies are uncommon and generally absent in many locations. Bioturbation index (Droser and Bottjer, 1986) rarely exceeds 4, reached by scares Ophiomorpha ichnospecies (Lundgren, 1891) (Fig. 3I, J). Rhizoliths of centimetric scale are also but rarely observed in few levels of this facies, those, again these are more frequent towards the top of the unit. In terms of size and morphology some traces are sometimes similar to Psilonichnus ichnospecies. However, in reason of presence of subtle small nodes and side branches of these tubes the occurrence of Psilonichnus has not been proven. Instead, roots are the possible alternative. In some exposures, termite burrows mainly gallery and, sometimes, preserved fungus comb chamber) are associated with the roots. Termites occur as irregular circular and oval ball-like morphotype, of few to several centimeters in radius, sometimes with a planar base. These bodies are linked together with randomly oriented tubes/galleries (Fig. 3K). The termite nests and galleries (less than 1 to 3 cm wide) and elongate conduits having circular and rounded tubular and flattened cross sections connecting the larger usually rounded chambers. Some of the balls preserve concentric pattern of filling, others are apparently structureless. Identically similar structures, in the literature and in modern environments were attributed to termites trace maker (Duringer, 2007 for details). The galleries and balls are penetrated into the hosting sandstone, indicating the occupation probably shortly after the deposition, and before the consolidation. Similar structure attributed also to termite activities has been described in the Qatrani formation from Fayum depression in Egypt (Bown and Kraus, 1988) what is the stratigraphic equivalent of DAT formation.

2.1.1 Interpretation of the cross-bedded thinning/fining up sandstone facies

Sediments of the cross-bedded sandstones facies are mostly bedload transported. They require flowing currents able to carry sands with mud blocks and silicified trunks. It is known in this area that the main source of siliciclastic sediments is, in general, from the south (Selley, 1968; Benfield and Wright, 1980) and the essential transporting mechanism is fluvial streams. In spite of this, well preserved, unequivocal tidal sedimentary structures indicate that tidal current where acting during the deposition of this facies. Arrangements and dimensions of cross-sets composing this facies, starting with thick trough cross-beds followed with thin planner cross-bed, and ending sometimes with muddy parallel laminated beds, are criteria indicative of shallowing water depth (Swift, 1975; Van den Berg, 1987; Selley, 1992). In Dalrymple et al. (1992) and Dalrymple and Choi (2007) such succession is also attributed to tidal processes in a tide dominated shallow marine environment.
Large sets with double mud drapes are commonly indicative of subtidal and the upper plane

laminated beds are deposited in the intertidal zone as the channel is approaching its filling stage (e.g. Dalrymple et al., 2003). The occasional presence of petrified wood indicates fluvial/terrestrial proximity and the development of roots associated with termites trace are signs of ephemeral emersions which are also required for the wood settlement. Therefore, sediments of this facies suggested deposition in tidal channels that are slightly fluvially influenced. The southerly oriented cross-bedding sets preserved by some of the channel deposits are indicative of flood domination in those channels.

2.2. Cross-bedded thickening/coarsening up sandstone facies

This facies is composed of very fine to coarse grained, variably cross-bedded sandstones characterized by local abundance of silicified trunks. Opposite to facies (2.1 above), sediments of this facies occur as coarsening up (Fig. 4A-C) packages that may exceed 7 m in thickness extends laterally

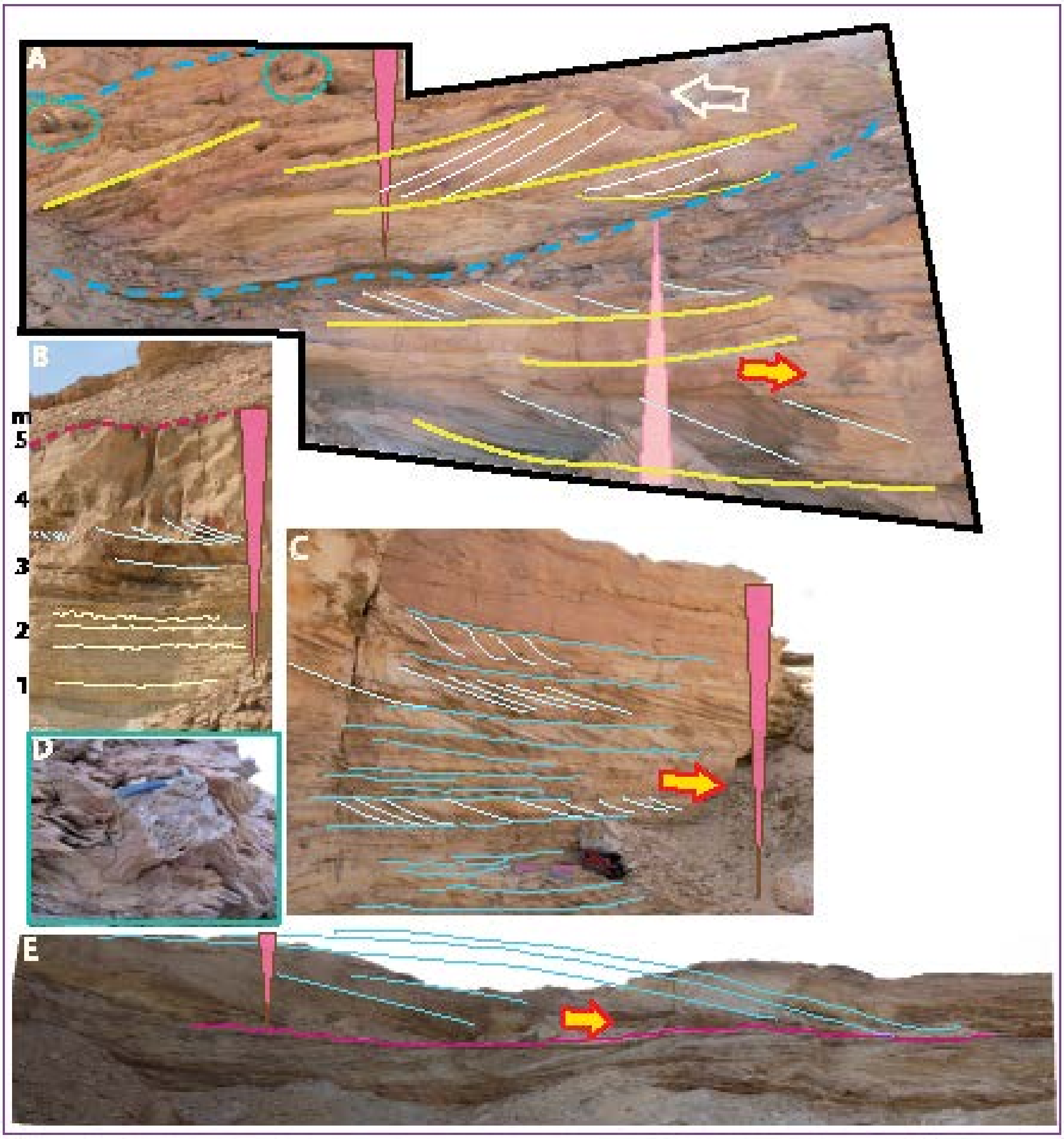


Fig. 4A-E: Shows the thickening/coarsening up facies. A) Cross bedded coarsening up facies erosively overlaying fining up facies, notice the opposite paleocurrent directions below and above the erosional surface (dashed line at the middle of the photo); B) Other example of coarsening/

thickening up facies showing lenticular bedding at the base; C) Coarsening up at the upper reaches of the cliff; D) Silicified wood shown in (A) above, inside the dashed circle; E) Outcrop view shows northward prograding clinoforms.

up to 2 hundreds of metres and possibly more. The complete succession of this sandstone begins with very fine sandstone and mudstone that present lenticular and wavy bedding (Fig. 4B), grading up into cross-bedded coarse sandstone. This facies is more frequently observed as approaching the top of the escarpment. At this position, a panoramic cross sectional view shows concave-down clinoforms-like, northerly inclined (basin ward) master beds (Fig. 4E). The internal cross-sets display palaeocurrents, oriented commonly in the same direction as the master beds inclination (i.e. to the North, seawards).

Dominating color of this facies is dark brown, pinkish and reddish brown. Cross-bedding is variable in dimensions and architecture, but dominated by trough and to lesser extent planner tabular as well as sigmoidal cross bedding.

Bed (set) thickness incorporated in this facies sequence increases from few cm at the base to several tens of cm towards the top. Larger individual cross-sets (thickness up to 2.5 m.) are encountered in some sequences, observed especially at the southern reaches of north-south oriented traverses. The architecture and geometry of compound dunes (Ashley, 1990; Berné et al., 1993; Dalrymple and Rhodes, 1995) are preserved in some of these large sets, for instance (Fig. 4F-J). It contains smaller subsets of cross-beds that are differently oriented in a direction inclined or even opposite to that of the hosting master sets (Fig. 4G, H). Subtle mud drapes are poorly developed in few locations (Fig. 4I). Sigmoidal beds (diagnostic of subtidal setting, Kreisa and Moiola, 1986; Nio and Yang, 1991) of metric size (Fig. 4J) are also formed locally as large clean sets. Some of them present internally bundled foresets (chapter 4 presents more details).

Beside these large structures, tidal signatures in these coarsening up sequences are preserved sporadically in smaller cross-sets as single and paired drapes (Fig. 4K-M), daily bundles, and fortnightly cycles (Fig. 4N). Notably tidal structures can be said of as gradually disappearing towards the upper locations of this facies. At these reaches large silicified tree trunks are more frequent than at the lower locations of this facies (Fig. 4O). What is more, some of the silicified wood trunks are associated with small fossil roots below the trunk (Fig. 4P, Q), and other having their stump in vertical position (living habitus) (Fig. 4R-U).

Bioturbations are relatively rare and absent in outcrops with largest cross-bed sets. Similar to facies (2.1; the fining up sandstones) termite traces are occasionally observed showing increasing upward. Some cross-sets preserve termites together with tidal sedimentary structures, mud drapes and tidal bundles.

2.2.1 Interpretation of cross-bedded thickening/coarsening up sandstone facies

The coarsening up tide influenced cross-bedded sandstone is known as a shoaling mouth bars (e.g. Wright et al., 1986, Schumacher, 2010). Mouth bar succession commonly begins with lenticular and wavy beds of tidal flats superposed by the cross-bedded sandstones as the bar prograde toward the basin (e.g., Reading and Collinsion, 1996; Bhattacharya, 2006). Progradational sand bodies similar to the one presented by this facies and preserved tidal signature have been attributed to (or defined as) delta topset (Galloway, W.E., 1975; Wright, 1977; Harris et al., 1993; Fielding et al., 2005). Northerly oriented, inclined clinoforms with internal cross-bedding showing palaeocurrents directions coinciding with that of the clinoforms can be regarded as the frontal parts of prograding mouth bars. Most of the sediments of this facies are due to bedload transport, subordinate component (the mud layers) is due to suspended load settlement. Thus sediments are mostly transported by a unidirectional most probably riverine current. This is suggested by the increasing influx of large petrified wood as well as the upward coarseness cosets. The concave up morphology are attributed to the prograding sand waves. Such typical mouth bar characteristics are known to form the basin wards side of prograding delta lobes (e.g. Frazier, 1967; Schumacher et al., 2010). Sedimentary structures preserved in this coarsening up sequences indicate their depositional bathymetry fluctuating from shallow subtidal (indicated by large compound and sigmoidal cross bedding) to nearshore fluvial (sandstone colonized by large and small plants).

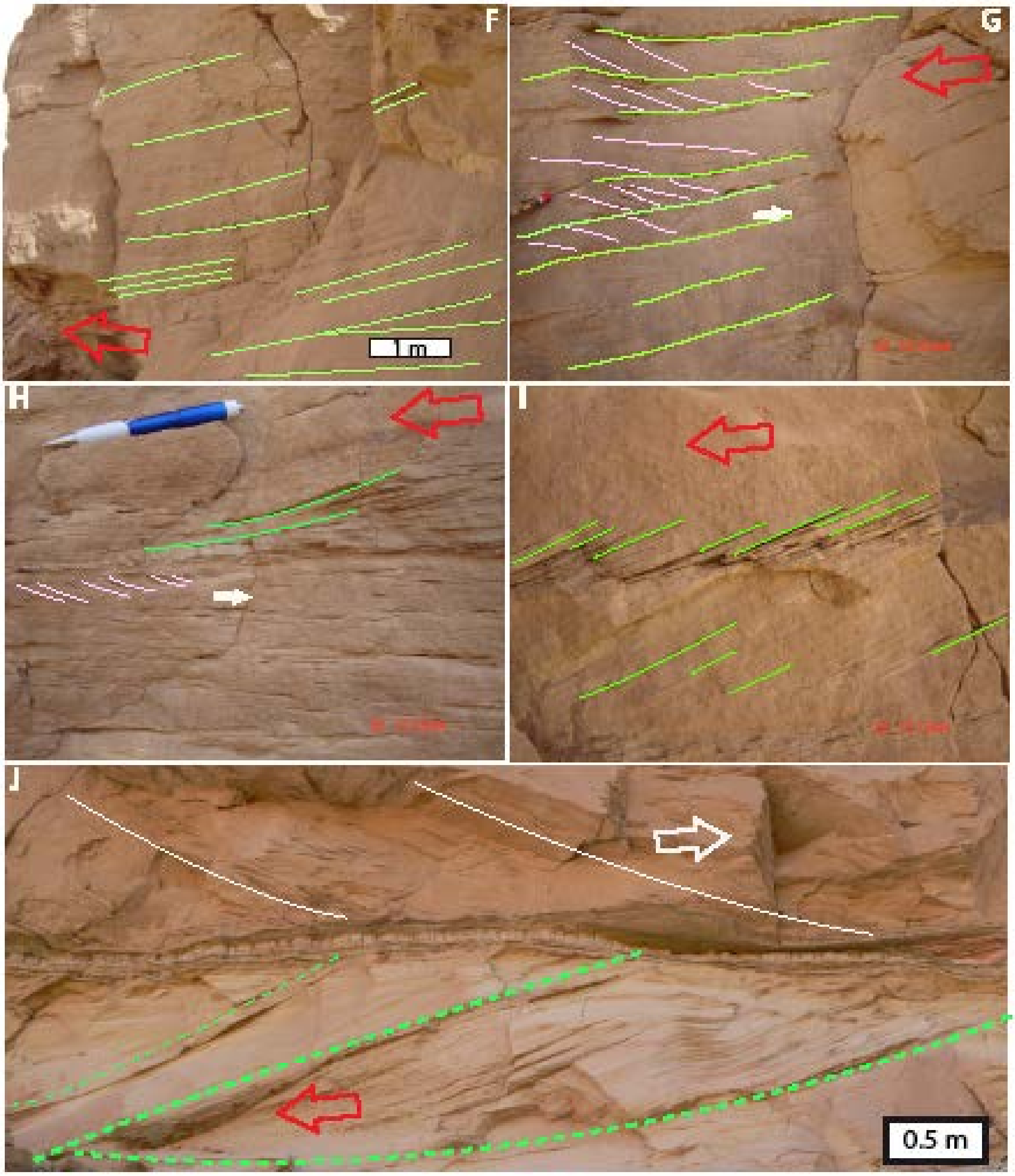


Fig. 4F-J: Tidal sedimentary structures in the coarsening facies; F) Large compound cross bedding; G) Master beds of the compound dune with the internal foresets oriented oppositely (white arrow); H) Other example of oppositely oriented cross set; I) Mud drapes in the compound dunes; J) Subtidal sigmoidal cross beds. Similar structures in modern environment are reported to occur in subtidal environments.

Fig. 4K-N: Tidal sedimentary structures in the Coarsening up facies; K) Coarsening thickening up tidal sequence with diagnostic tidal structures (colored rectangles); L) Mud drapes between coupled foresets of sand; M) Side view of thick set with paired laminae; N) Successive bundled foresets display neap (n) spring (s) cycles.

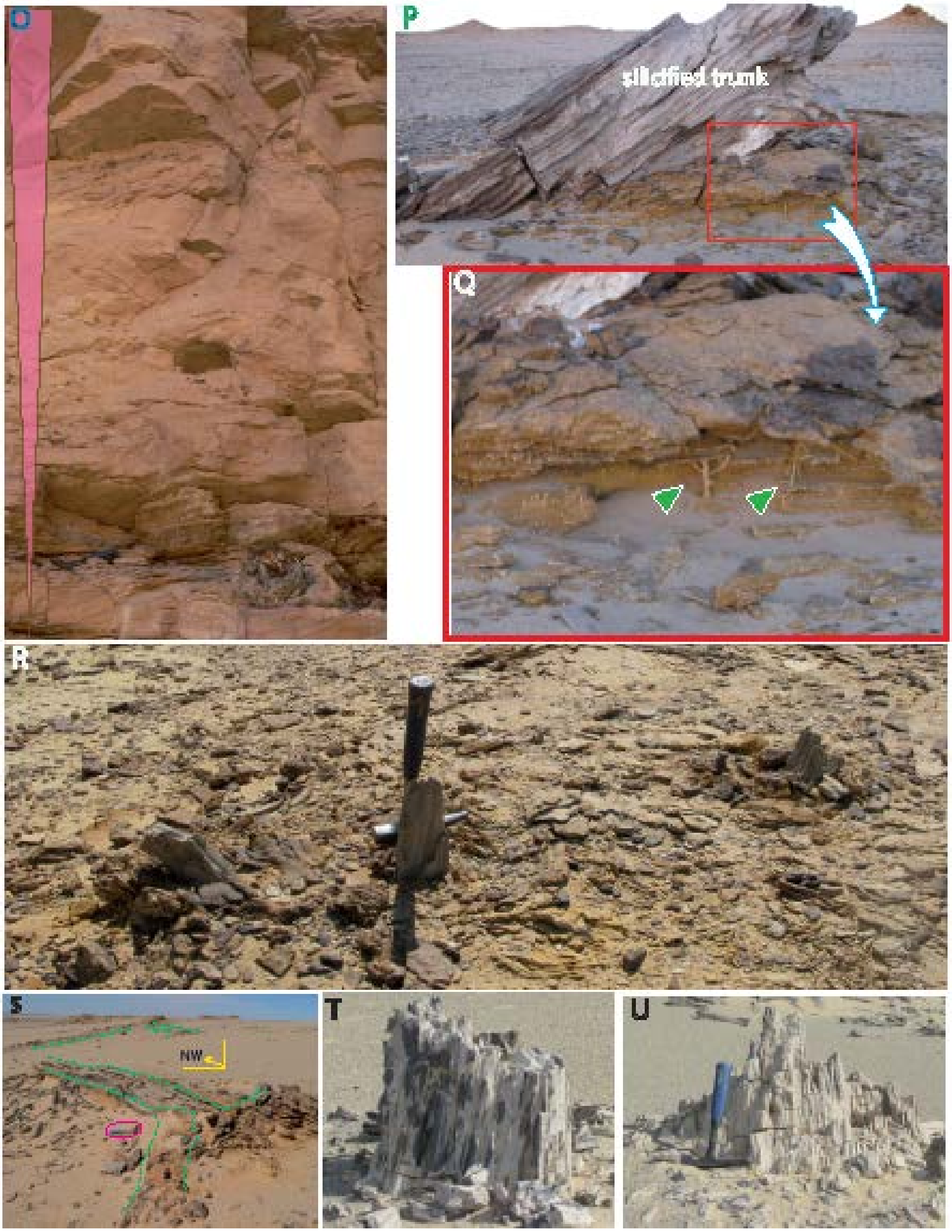


Fig. 4O-U: O) Coarsening up facies with silicified wood at the base; P) petrified wood associa-ted with fossil roots (indicating subaerial exposure),; R) Wood in vertical position. The position of (P, R) is close to the top of cliff; S,T and U) are examples of petrified wood in living position from different places of nearly the same horizontal level (the top of Lower Sarir).

2.3 Laminated mud-siltstone alternation facies

This facies constitute sediments of the finest grain size in the Sarir Unit. It is composed of (few to several metres thick) interbedding succession of laminated beds of siltstone to mudstone, with intercalations of very fine grained cross bedded sandstone cosets (Fig. 5A). When exposed in the southern reaches of the escarpment, this facies is generally thinner (few metres). These fine deposits are particularly well exposed towards the northern sides (distal) of the escarpment. In general, beds are horizontal to subhorizantal in east-west traverse and inclined to the North in the northerly-southerly traverse. Angle of inclination of master beds is around or less than 15°. The greatest thickness of succession composed of this facies is exposed in the northern side of North-South trending cliff. In these reaches, this facies are directly superposed on the similarly (fine) sediments of the New Idam Unit (Fig. 5B). Because of the similarity in lithology, the contact between the two lithologies is difficult to distinguish. Nevertheless, thanks to the existence of bioturbation and the lack of sedimentary structures in the New Idam Unit. This made the differentiating of the disconformity between the two units possible (Fig. 5B).
Parallel laminations and climbing current ripples (Fig. 5C) are the most recognizable sedimentary structures expressed by the beds of this facies. Individual bed reaches 30 cm in thickness. Remarkably, some beds record subtle fining upward sequences starting with graded bed, following by plane bed and ended with current ripples and parallel laminations (Fig. 5C), in this aspect some of these beds are comparable to Bouma sequence. Convolution and other forms of synsedimentary deformations are common in the scale of a bed and laminae (Fig. 5D, E). Apart from the silt-sand alternation, evident tidal structures are uncommon in this facies. Tidal signature is locally observed in some beds of this facies, preserved as vertically accreted rhythmicity in convoluted layers (Fig. 5D, E). In other small outcrops, beds thought to belong to this facies, displays sequential increase followed by decrease in the thickness of the successive beds (Fig. 5F, G). Concerning the lateral facies changes, it has been often observed that the fine grained sediments of this facies are in landwards direction equivalent to the coarse cross bedded sandstones of facies (2.1, 2.2 fining up and coarsening up facies respectively), which is the dominating in the same cliff few kilometers to the south (Fig. 5H).

2.3.1 Interpretation of the laminated mud-siltstone alternation facies

Characteristic grain (very fine sand to mud) size and sedimentary structure of this lithofacies suggest suspension fall out, resulted in the deposition of mud layers, and lower flow regime (Simons et al., 1966) plane bed resulted in the deposition of silt and fine very fine laminated and current rippled silt and sand. Being more exposed in the northern proximity of a south-north traverse and the basin ward inclination of the beds made this facies appear as a foresets (clinoforms) and bottom sets. Thus, these foresets representing the northward (basin wards) facies change equivalent to the coarser cross-bedded sandstone in the south (Fig. 5H). Based on this consideration, it is best being explained as representing the distal expression of the deltaic mouth bar (prodeltaic environment). The preservation of Bouma-like sequences and the presence of convoluted bed carrying tidal expressions suggested that they are deposited within the deeper parts of the subtidal zone, distal side of the prograding mouth bars clinoforms (shingled turbidites).

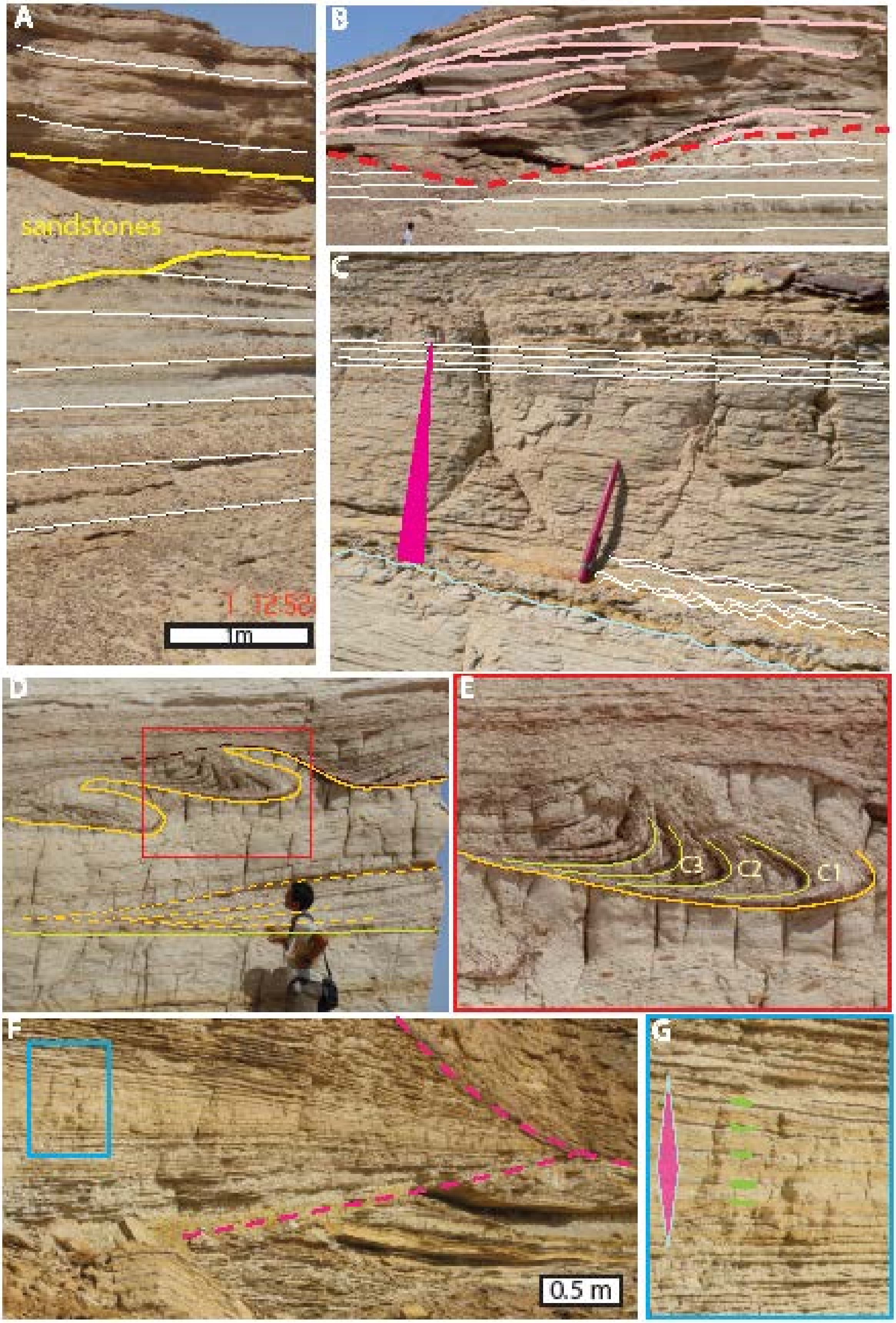


Fig. 5A-G: Laminated mud-siltstone alternation facies. A) General view fine laminated/cross laminated sequence interrupted by fine grained, well sorted and cross bedded sandstone; B) Disconformable contact between Sarir unit represented by laminated facies and the underlying New Idam Unit; C) Fining up expressed by individual beds. Ripple lamination grades up to parallel lamina;

D) Convoluted bed expressing tidal cycles (dashed lines); E) Close view from (d) shows deformed tidal cycles (C1,C2,C3); F) Tidal bedding; G) Close view from F indicating seasonally influenced neap-spring-neap cycles. This facies are in general located in the northern reaches of the cliff (i.e. basin ward).

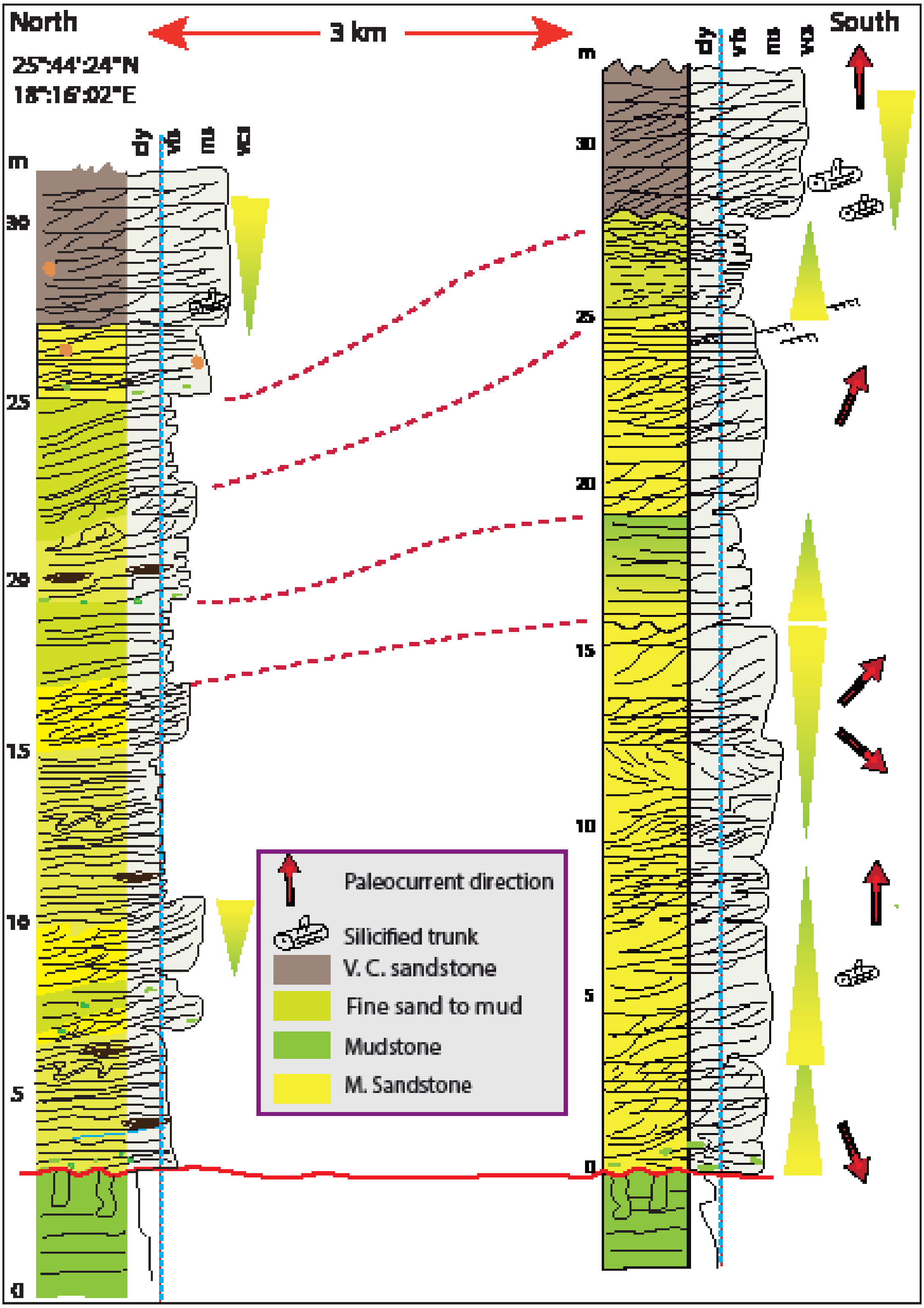


Fig. 5H: The lateral facies changes (south-north) that expresses basin ward bathymetric changes. Most striking is the differences in grain size between the distal and proximal locations.

2.4 Fine grained inclined heterolithic stratifications (IHS) facies

This facies (Fig. 6) consists of inclined (laterally accreted) beds of very fine to medium sandstones intercalated with laminated mudstones and siltstones. The sandstones are well sorted, colored light gray and yellow. The mudstone is laminated and colored light green. Beds of this facies are stacked obliquely one on the other, breadth of one stacked unit is up to few hundred meters with a total thickness of up to 5 m. In some well exposed cases individual beds are pinching out laterally within several meters to several tens of meters in the direction of inclination (to the bottom set). Thickness of individual beds forming this facies varies from few tens of cm decreases laterally into a few cm. Inclination angles of these beds are variable from one outcrop to the other (Fig. 6). Inclination angle are ~ 5-15º, smaller units seems to exhibit lower angle. The sandstone beds internally exhibit a relatively small scale cross bedding grading laterally, in the same bed, into low angle cross-lamination and parallel lamination. Very important for the interpretation of this facies is, in some units, the direction of cross stratification that is perpendicular to that of the master beds (Fig. 6E, F). Tidal sedimentary structures such as mud drapes, poorly developed bundles, and flaser bedding are preserved in this facies. Neap-spring expressions are also recorded by some of the inclined heterolithic units (Fig. 6G, H), longer rhythmicity cycles is likely suggested by some heterolithic units (Fig. 6I). Very scarce bioturbations in form of millimetric size irregular tubes are locally preserved in this facies, some of these resemble rhizoliths.

2.4.1 Interpretation the fine grained IHS facies

Current ripples as well as current megaripples oriented perpendicular to the oblique master bedding combined to the obvious lateral accretion are characteristic features known for point bar deposits (Reineck and Singh, 1980; Thomas et al, 1987; Fenies and Faugéres, 1998; Dalrymple and Choi, 2007, and many others). Laterally accreting beds are also a component of delta lobes (e.g., Collinson, 1970; Thomas et al, 1987). Tidal sedimentary structures though not always striking but are significant to suggest tidal influence on sediments of this facies. Among other structures, good sorting of the sand beds is also attributed to tidal dynamics (e.g. Zhenzhong and Eriksson, 1991). More importantly is, in figure (6G) for instance, semi sigmoidal sandstone beds can be attributed to the spring tide, and the thinner bounding muddy layers to the neap episodes. Apogean-perigean influence cannot be excluded as an alternative explanation in such cases. Sandy beds could be assigned to perigean whereas more muddy beds to apogean times. Most indications such as continuously well-organized beds and sigmoidal structures suggest that this facies is predominantly emplaced under subtidal conditions. Episodic subaerial exposure cannot be totally excluded, suggested by the local occurrence of possible rhizoliths.
The overall fine grain size, the internal small ripples that are oriented perpendicular to their hosting master beds suggest lateral accretion mechanisms, all together known for meandering stream. In prograding delta, the ripples and their master bedding are commonly similarly oriented. Commonly, both are in the direction of progradation. To summarize, this facies carries all the criteria described (e.g. Thomas et al, 1987; Ashley, 1990; Dalrymple, 1992; Choi and Dalrymple, 2004) for the meandering point bars.

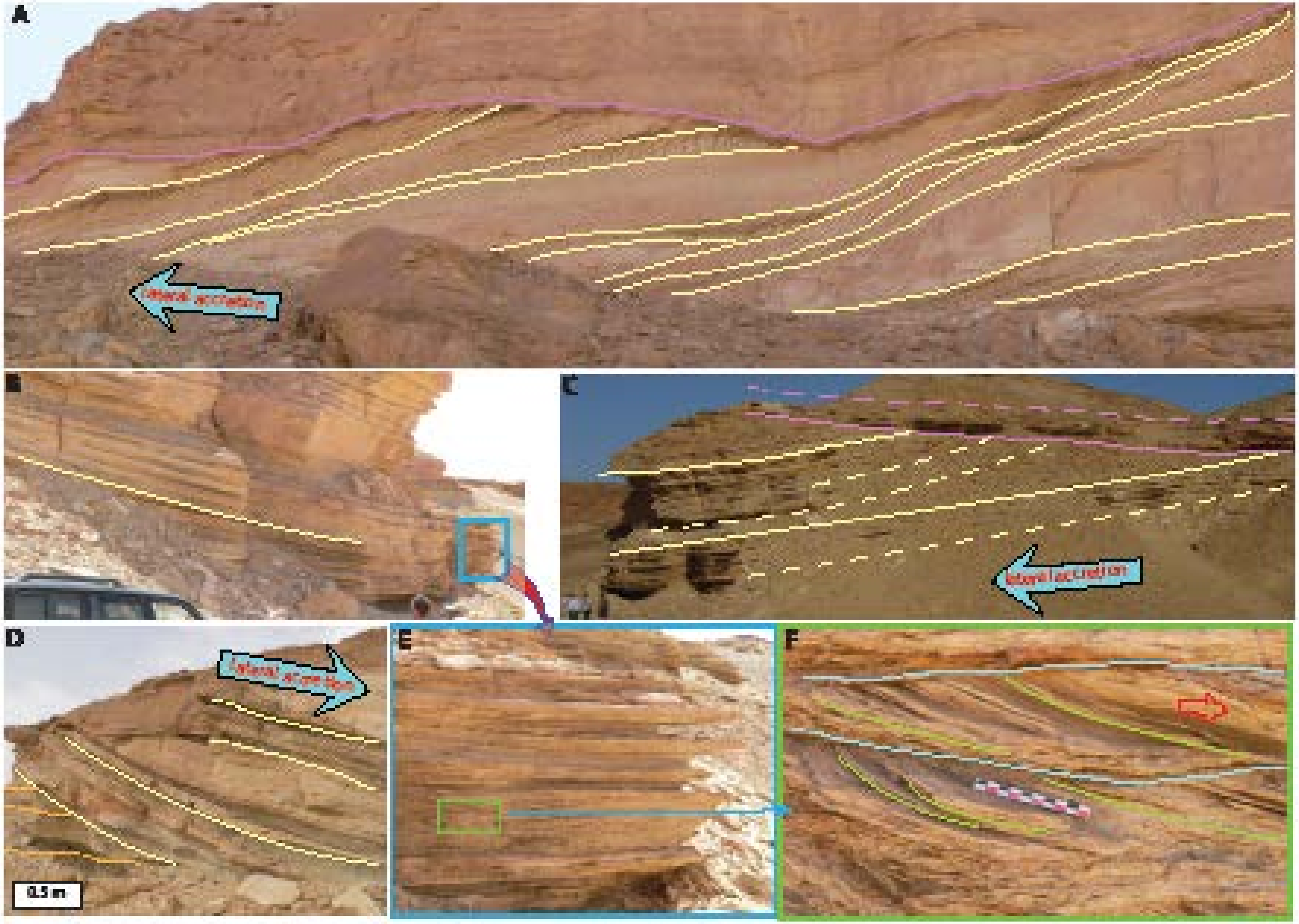


Fig. 6A-F: Inclined heterolithic stratification facies (IHS); A) General view shows the lateral accretion; B) and C) Two side of the same IHS sequence; D) example of small-scale sequence of IHS facies; E) Side view from B (the blue rectangle) shows the interbedding of sandy and muddy reflecting tidal energy changes; F) Detailed view from (E) showing tide modulated cross beds.

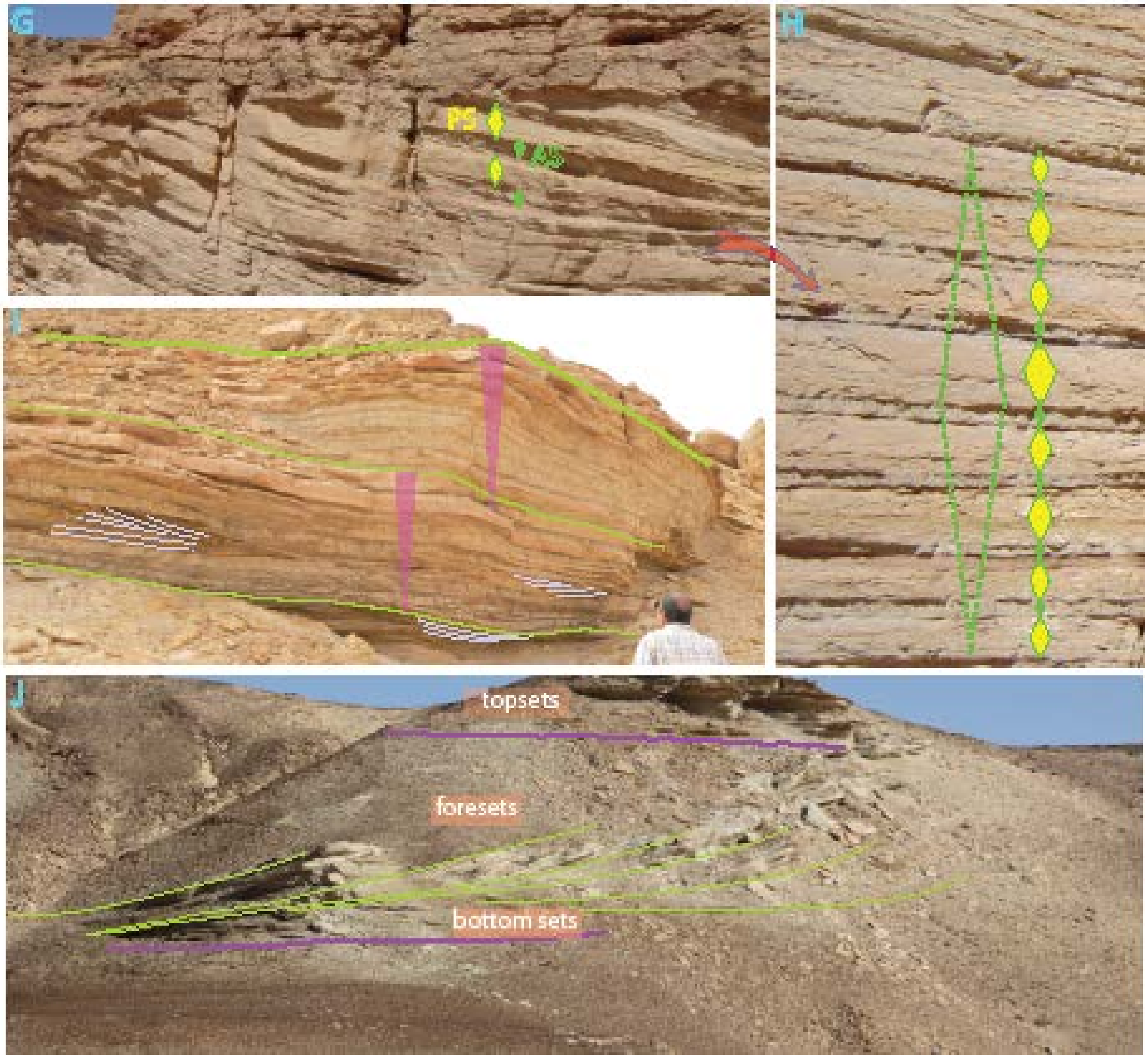


Fig. 6G-J: G) IHS exposing n-s-n cycles; H) Detailed view from the same outcrop showing neap-spring neap cycles incorporated into longer tidal cycles; I) Long duration (annual) tidal cycles expressed by IHS; J) Several tens of meters outcrop of IHS composing-bottomset-foreset-top set architecture.

2.5 Massive sandstone facies

This facies is composed of fine to coarse grained, poorly to moderately sorted mud-free sandstone. It is characterized by poor to no bedding, and by different scales of convolution structures as well as other features of synsedimentary deformations, of centimetric to metric scale. This facies is exposed as irregular beds of variable morphologies (Fig. 7), showing sharp contacts with the adjacent, underlaying as well as commonly the overlaying sediments. Beds of this facies have variable average thickness (max. around 3 m), and variable lateral extension. Maximum observed is few hundred metres (Fig. 7A) and the minimum is few metres (Fig. 7B, C). The large bodies preserve irregular silty/sandy layers inside them. The small scale bodies of this facies appear as a concave up wedges and lenses having a channel-like morphology. These small sand bodies are erosively intersect into the facies 2.1 (Fig. 7B), and facies 2.2 (Fig. 7C),

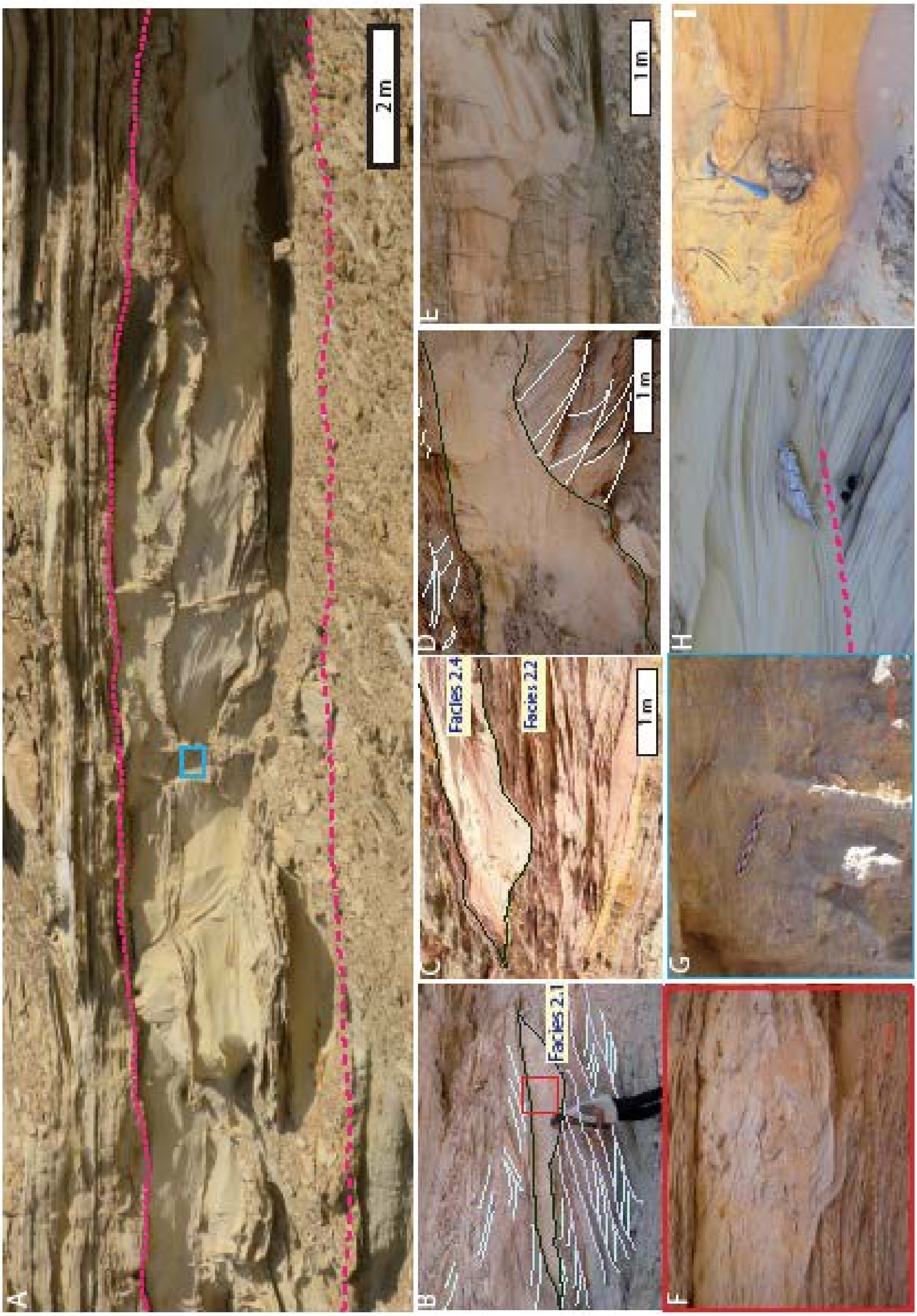


Fig. 7A-I: The massive sandstone facies. A) Structureless sandstone preserving irregular layers of siltstone. lateral extent is few hundreds of metres; B) few metres body of massive sandstone intruding into the cross bedded sandstone.; C) small body of the massive sandstone within the cross bedded sandstone of facies 2.2; E, F) supplementary examples of the massive sandstone indicating its sharp contact with the surrounding cross bedded sandstone; F) convolution preserved in the massive sandstone, close view from (B); G) mud flacks probably represent ruptured tidal mud drapes; H) massive sandstone embedding lager remnant from relatively older sediment, an indication of strong flow; I) massive sandstone facies consists of petrified wood oriented north-south, location close to the top of lower Sarir.

with almost no major change in lithology between them and the hosting facies.
Sedimentary structures are poorly developed in this sandstone, but convolution, disturbed laminations and cross-lamination are preserved occasionally. Poorly developed normal grading within sand grains is locally displayed. Dish like mud flacks and others with irregular shapes are randomly scattered in some beds (Fig. 7G). The color of these sediments are clean light gray to grayish white at lower location of the sequence brownish yellow and laden with silicified wood closer to the top of the cliff (Fig. 7I).

2.5.1 Interpretation of the massive sandstone facies

Notably, this massive sandstone facies is characterized by the lack of classical sedimentary structures compared to the other facies in the Sarir Unit. Bioturbation is also absent. On the other hand, this massive sandstone exhibits synsedimentary deformational structures, mixed grain size and irregularly variable morphology of the sand bodies. These aspects could suggest gravity debris flow (Postma, 1986; Parsons et al, 2007) as deriving process responsible for the formation of this facies. Gravity flow is enhanced by rapid sediment accumulation in frontal (lee) side of large mouth bars (Einsele, 1992), at such point slumping of liquefied sandy sediments occur due to the overloading (Fisher, 1983) where grains transport themselves with the aid of gravity and dewatering mechanisms. In marine environment, this can be induced by sediments accumulation produced by flooding river (Parsons et al., 2007). Smaller units are probably the consequences of the same mechanism, associated with rapid accumulation of sand dunes in tidal influenced channels. Minimal amount of upward-fining and the presence of sharp basal contact with the subjacent and adjacent beds have been ascribed for liquefied gravity flow (Einsele, 1992; Giresse et al., 2009). The hosting, in this sandstone, of silicified wood close to the top rather than at the lower locations might confirm the increasing upwards of fluvial influence. To summarize, this sandy facies which shows deformational sedimentary features represents subaqueous fluidization of water-rich sediments aided by slope and overload-initiated gravity flow.

2.6 Horizontal heterolithic stratifications (HHS) facies

This facies (Fig. 8) is typically composed of alternating beds of very fine sandstone (few to several centimeters thick) with thinner, parallel laminated silt and mudstones. The beds composing this facies are commonly horizontal to subhorizantal, showing slight (few degrees, Fig. 8A) dipping to the north. They can be laterally traced for up to few hundreds of meters before they disappear, truncated or amalgamated with other facies. Sequences built by this facies may reach around 6 m in thickness. The sandstone beds display subtle inverse grading (Fig. 8B, C) occasionally associated with paired laminae of sand (Fig. 8D), and are also characterized by dominance of ripple cross laminations and flaser structures (Fig. 8E, F) as well as lenticular and wavy bedding. The wavy beds exhibit subtle thick-thin aggradational pattern (Fig. 8F) which is attributable to neap/spring energy fluctuations during successive fortnightly tidal cycles. In plain view, flaser structures (which are the most common in this facies) appear as centimetric scale trough (lingoid) cross-stratification (Fig. 8G). It is comparable with 'rib and furrow' structures (Stokes, 1953; Picard, 1966). Moreover, bedding plain of some beds preserve poorly preserved mud cracks. Others (rare) display footprints that could be assigned to small four-legged animals (Fig. 8H). Skolithos trace fossil are locally obvious, preserved in some sandy beds), Diplocraterion also exist but are rare. Both ichnospecies are of small-scale (few to several centimeters long).

Northward palaeocurrent directions are preserved in the (centimetric scale) trough cross-lamination, coinciding with that of low angle master beds. This HHS facies display wide lateral and vertical distribution along the escarpment. They are frequently overlaying the cross-bedded sandstone of facies (A, channel facies). In addition, beds of similar sedimentological and architectural characters (IHS) are frequently exposed as a filling of typical channel morphology. In the latter case (channel filling), this facies exhibit better organized sand-mud interbedding showing overall thickening up by the constituting beds (illustrated in Abouessa et al. 2012, Fig. 10C-E). Inverse grading is also expressed here, especially in the sand beds. Bioturbations are absent in most of these channel fill sequences, and some of sandy beds contain small pieces of north-south oriented fossil wood. In fact, many of the channels themselves have north-perpendicular cross sectional area. The channels that constitute this facies are variable in depth (average 3m, rarely reach 10m) frequently observed throughout the escarpment.

2.6.1 Interpretation of HHS facies

There are two particular aspects shown by this facies. First, their nearly flat bedding, and second the preponderance of lingoid current ripples, lenticular, wavy and flaser structures. In the later, mud drapes deposited during slack water is very remarkable. All these are well known to occur in inter-to-subtidal flats. They are interpreted to occur due to the alternating deposition of bed load and suspended load sediments in tidal environments (e.g., Reineck and Wünderlich, 1968; Terwindt and Breusers, 1971). Despite the presence of the described emersion features (scarce mud cracks and questionable foot prints), the uniform bedding with repeated mud-sand couplets, and the preserved neap-spring neap cyclicity tend to support deposition in subtidal with subordinate intertidal domain (Terwindt, 1971; Visser, 1980; Nio and Yang, 1991).

Furthermore, the 'rib and furrow' structures (also called festoon cross-bedding) with mud drapes incorporated in their structure are the result of migration of current ripples of lingoid morphology (Boersma, 1970; Reineck and Singh, 1980). These are widely produced in modern

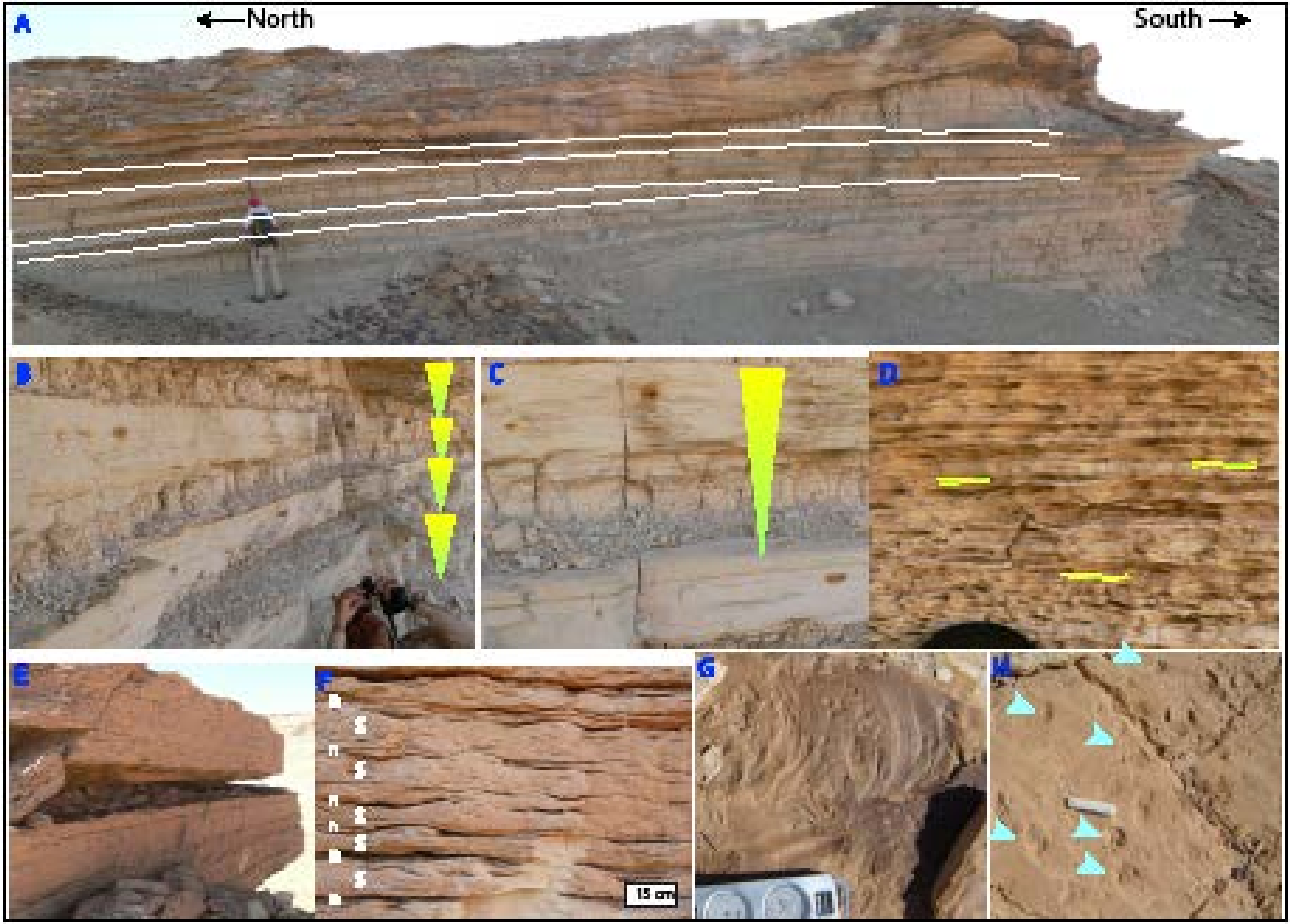


Fig. 8A-H: Shows the horizontal heterolithic stratification (HHS) facies. A) General view show the organization of sand/mud beds in this facies; B, C) The inverse grading, general and close view; D) Detailed view from the sandy beds preserving paired laminae; E) Flaser bedding; F) Tidal bedding preserve neap (n)- spring (s) cycles; G) Surface view of trough cross stratifications; H) Foot prints of terrestrial animal, indicating terrestrial proximity.

tidal flats (Terwindt and Breusers, 1971; Neo and Yang, 1991). Rib and furrow structures are common also in fluvial environments as well as turbidities, but they lack typically recurring mud drapes which sign tidal dynamics. These kinds of structures are, as a matter of fact, attributed to tidal dynamics in the intertidal-subtidal flat (Allen, 1970, 1982; Boersma, 1970; Kreisa and Moiola, 1986). The flat beds intervals formed in maximum flow velocity and the cross-laminated bed developed during decelerating and/or waning flow conditions (Allen, 1982; Kreisa and Moiola, 1986). Inverse grading could be attributed to the same dynamics. Analogous features are observed in the intertidal flat of Mont Saint Michel Bay. Furthermore, interbedding sequences similar to this facies are described from Mississippian tidal flat (Wescotti, 1982), and from the inner sand flats of Bay of Fundy (Dalrymple and Zaitlin, 1985). The presence of Skolithos and Diplocraterion traces support this proposition. The cases where this facies occur as channel fill are (due to better organization and absence of emersion features) probably the distal expression (subtidal) of the intertidal counterparts.

2.7 Cross-bedded mudclasts facies

This facies is present as cross-bedded coarse grained sandstone that is specifically composed of sand-sized mud clasts (Fig. 9). The grain size of the mud clasts composing this facies is uniform and ranges from coarse sand to granule, and is commonly rounded-subrounded with subspherical morphology. This facies has a common but local existence, found mostly in the lower parts of the Sarir sandstone, often close to the erosional contact that separates New Idam Unit from

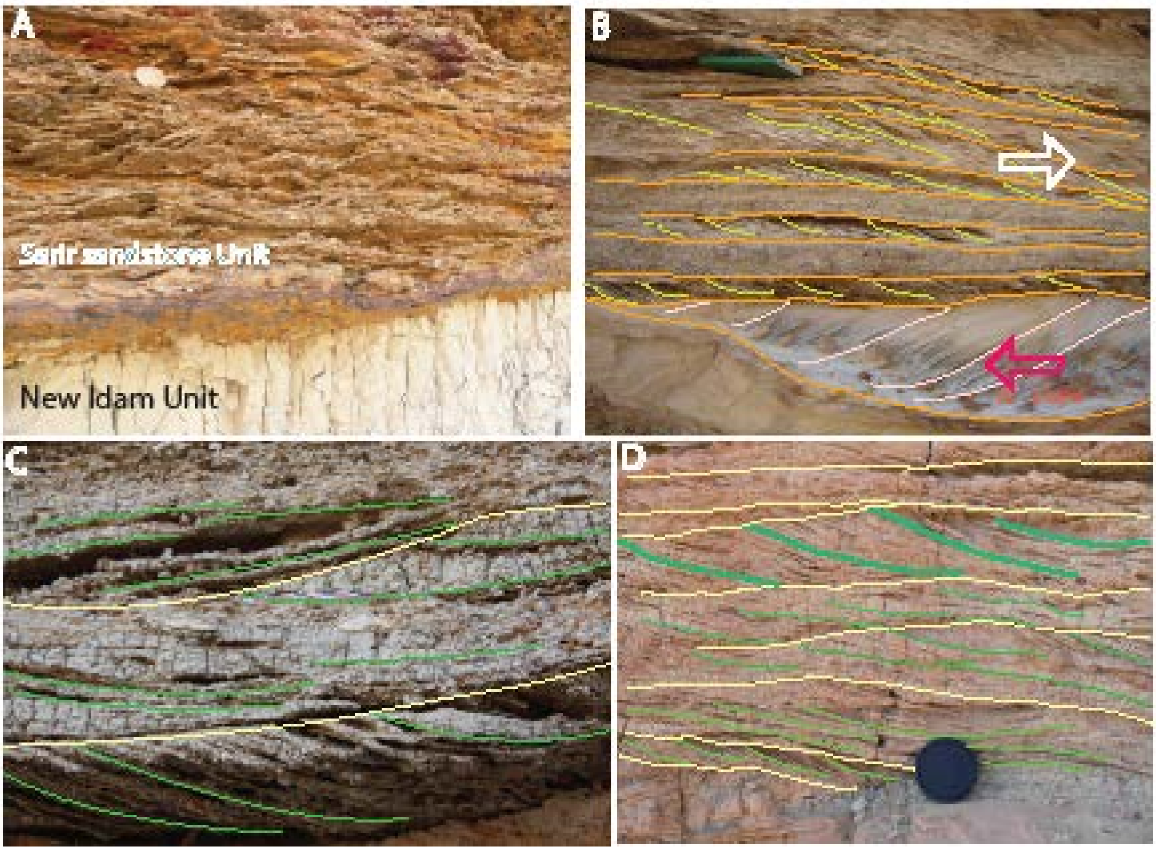


Fig. 9A-H: Cross bedded sand-sized mudclasts from different outcrops of the lower part of the Sarir Unit. A) The cross bedded mudclasts at the base of the Sarir, probably at the base of tidal channel; B) Part of tidal channel, notice the opposite palaeocurrents; C, D) tide modulated cross bedded mud clasts (bundled foresets).

the Sarir Unit. It is closely related to the channel (2.1) and the mouth bar (2.2) facies. Most of their exposures are erosively overly the underneath sediments (Fig. 9A-C). The thickness of this facies is rarely exceeding 2 meters. Unlike the randomly distributed larger and poorly sorted mud clasts at the base of some cross bedding sets (base of the channel facies, 2.1), this time mud clasts exhibit smaller grains and good sorting and specially, it construct very low angle cross-bedding. Some of these cross sets displaying subtle tidal signature (Fig. 9B-D).

2.7.1 Interpretation the cross-bedded mud clasts facies

Mud flocculation occurs during mixing of waters of different salinity (van Leussen, 1988) by coagulation of floating particles, particularly clays. Flocs of a coarse sand size are common, though larger comet-shaped flocs as large as 2.5 cm have been reported (stringers; Berhane et al., 1997). Flocs can be stable at certain physicochemical conditions (Eisma et al, 1983; Leussen, 1988), and, in turn, are bound together along with additional mineral particles to form macroflocs which can reach 3-4 mm in diameter or more (Berhane et al., 1997). When elongated in shape these flocks are called stringers. These are thought to be formed under conditions of low current velocities, and can reach several centimeters in their longest dimension. The conditions in which stringers were observed (current velocities exceeding 100 cm. s-1) suggest that the stringers were not formed in the waters in which they were observed (Berhane et al., 1997), i.e. transported. In this facies the low angle cross-bedding enhances the possibility that these size-sorted mud pellets are originally a flocculated mud formed due to mixing of clay-laden river waters with sea water. Their association with tidal sedimentary structures and their presence as a part of channel facies might support this hypothesis. Flocculated mud scenario remains very questionable, because it is unlikely to resist in such strong dynamic environment. Alternatively, may be less complicated, the cross-bedded mud clasts are just a rip up clasts experienced and can survive short transportation to produce the low angle cross-bedding. This later case has been observed in many places in the intertidal zone of the macrotidal Bay of Mont Saint Michel, especially close to the sites of the tidal channel lateral migration. Both the cases are the product of shallow marine setting.

2.8 Granule (microconglomeratic) sandstone facies

This facies (1-2 m thick) is composed of very coarse grained (occasionally pebbly) sandstones (Fig. 10). Occurring in the upper part of the Sarir unit, it records the first appearance of such coarse grained sandstone in all DAT formation from base to top. Erosional contact intersects into the underlaying medium to fine well sorted (tide dominated) sandstone. This contact is covered with very coarse quartz grains, and locally with angular mud clasts of mixed size, (up to coble) and shape (Fig. 10C, D). Mud clasts are composed of light green clay and silt. Quartz grains and gravel (up to 1 cm in diameter, Fig. 10D) are predominantly rounded to subrounded, and are poorly sorted.
Overall fining in the grains is displayed by these facies. Coarse grained tabular planar bedding is sometimes superposes these microconglomeratic sediments (Fig. 10B, E). The color of this coarse facies is, in over all, reddish brown and brown. Moreover, it is locally laden with large silicified tree trunks (~ 80 cm wide, few meters long), many of these are northern-southerly oriented. In some locations, this facies preserves small (short-lived) roots as well (Fig. 10H). This coarse sandstone facies is laterally discontinuous and disappears within several tens of metres, amalgamated and replaced gradually or erosively with the cross-bedded facies (2.1, 2.2). It is also interfingering with the HHS (horizontal heterolithic stratifications, 2.6). Notably tidal

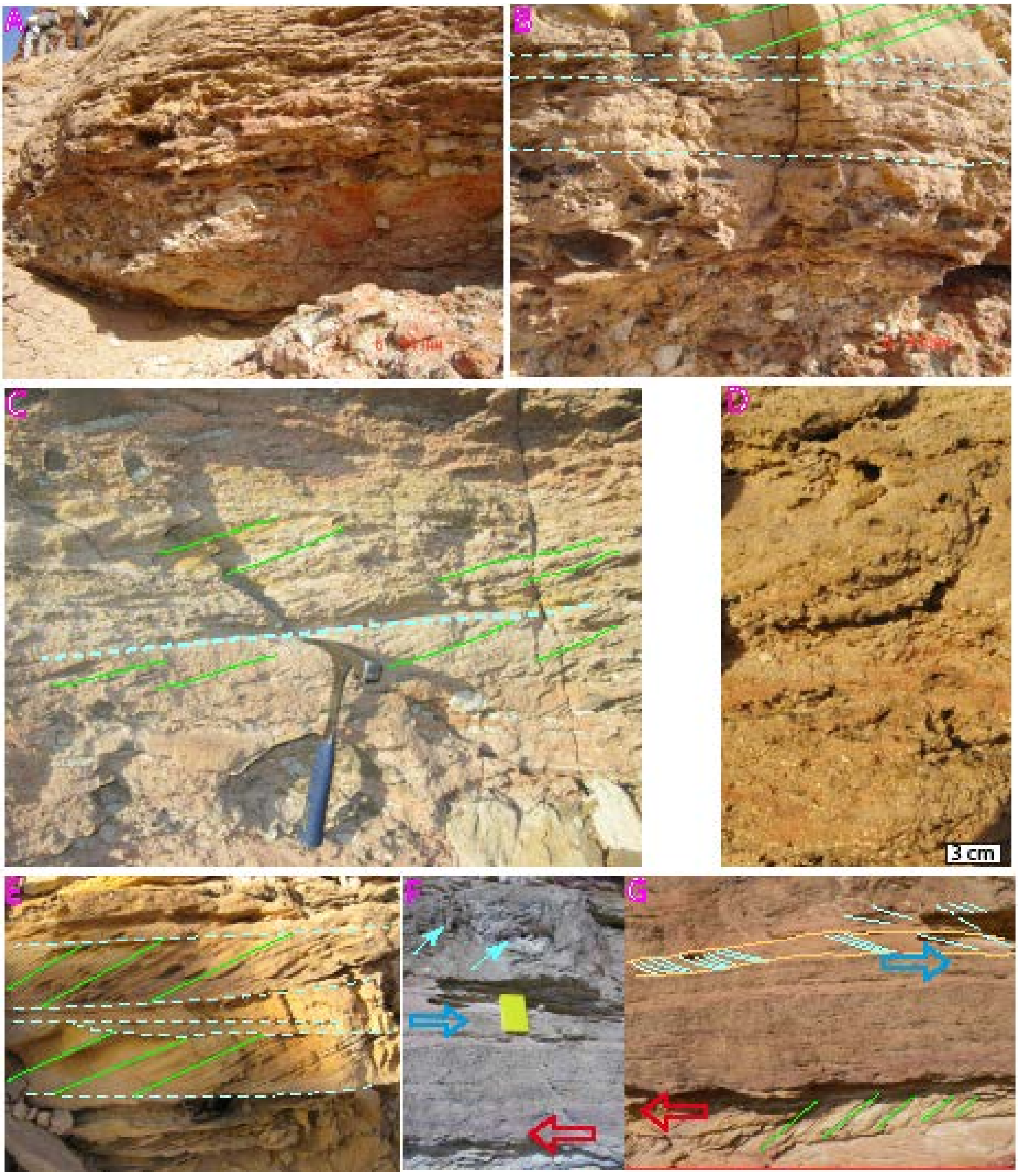


Fig. 10A-G: Granule sandstone facies. A,B) shows the location and grain size respectively; G, D) Close view indicate the strong energy expressed by the blocky mudclasts in (c) and the granule sized quartz grains in (D); E-G) Lateral changes in this facies shows planner cross-bedding in (E) and common presence of wood (small arrows) in (F). In (G) the palaeocurrents below and above the granule sandstone is opposite.

sedimentary structures are absolutely absent in this facies and trace fossils as well. Regardless of the contact of this facies with the surrounding facies, it is (in many outcrops) sandwiched between the finer and better sorted sandstones that preserve evident tidal signature (Fig. 10G, H).

2.8.1 Interpretation of the granule sandstone facies

The very coarse conglomeratic sandstone is in general known to occur (as a channel lag) in low

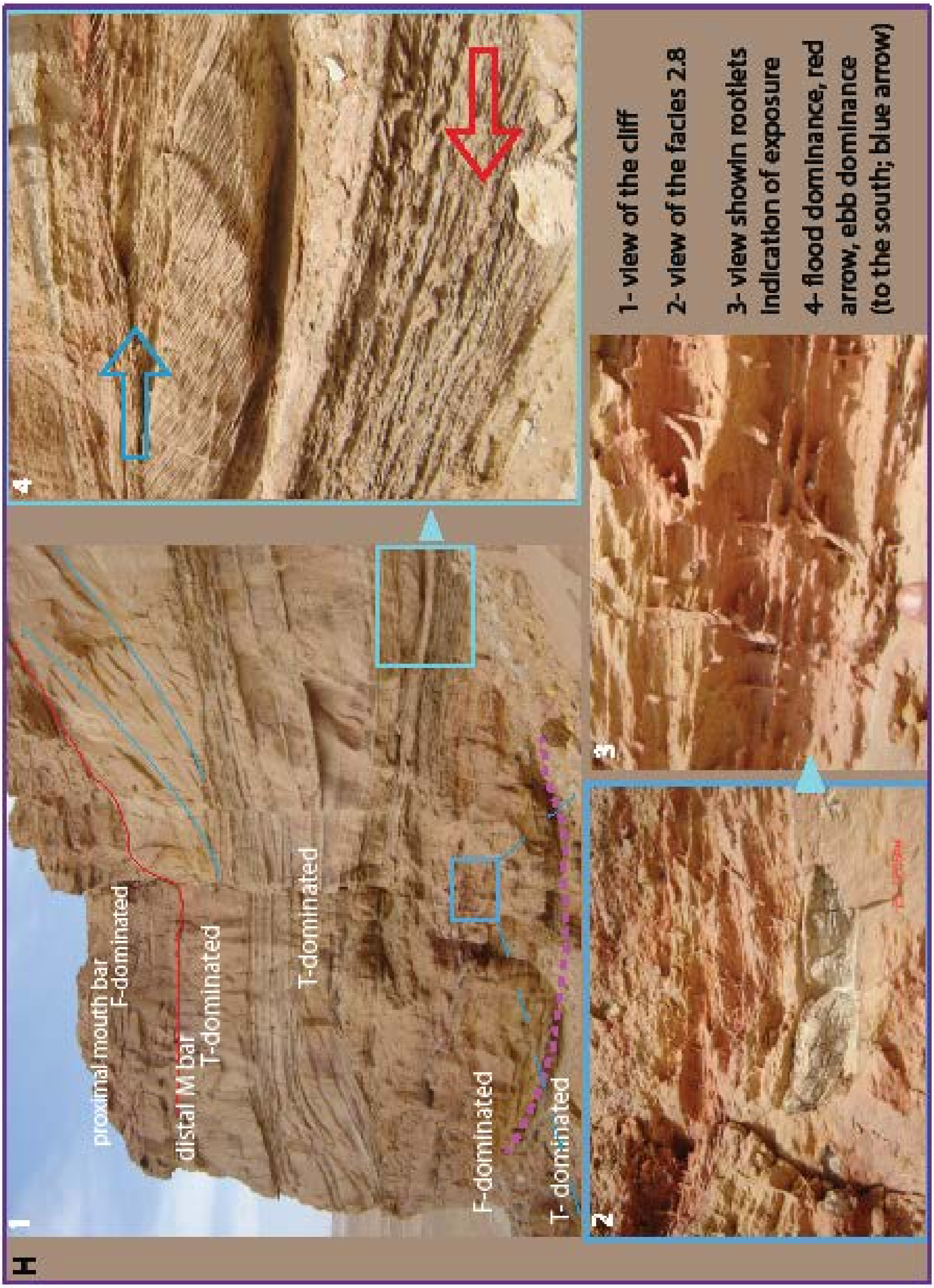


Fig. 10H: Illustrates the interaction between tide dominated and fluvial dominated facies. Such alternation is noticeable along the lower part of the Sarir Unit.

sinuosity channel (e.g. Williams and Rust, 1969; Reineck and Singh, 1980). The strong contrast in sedimentary characteristic between this facies and the finer and better sorted below and above is obvious. In addition to the very coarse sediments of these beds, their content of large silicified tree trunks suggests fluvial stream as a dominating deriving current for the sediments of the granule sandstone facies. Its local occurrences and its location between tidally influenced beds could be attributed to the rapid dislocation between the tidal components and the river-dominated channel. Being amalgamated with facies (2.1, 2.2 and 2.6) suggests that this facies represent fluvial distributary channel acting within a larger complex of tidal channel-mouth bars-tidal flat system. Such obvious spatial and temporal interplay of those facies is exposed and witnessed in many outcrops along the cliff, as illustrated, for instance in figure (10H).

2.9. Cross-bedded, locally rooted, sandstone facies

This facies has a variable thickness (3-7m) is composed of medium to coarse poorly sorted and moderately to poorly cemented sandstone. Pink is the dominant color (Fig. 11), yellow, red and light brown are locally observed. It displays trough and planar low angle cross-bedding, sometimes changing upwards to plan parallel bedding. These sedimentary structures are laterally persistent for the same sandstone, but are not always well developed. Coarsening upward of the grain in this facies is also visible in better exposed outcrops (in this it is similar to facies 2.2, the mouth bar). Several tens of meters laterally, the cross-bedding is mostly obliterated by the existence of intensive roots of centimetric scale (Fig. 11B). Although mud layers are rare in this sandy facies, cross bedding rarely shows a possible mud drapes at the toe of some sets (Fig. 11C, D). Uncommonly, some of the mud draped sets show small poorly developed tidal bundles (Fig. 11E). Internal erosional surfaces mantled with block-sized mud clasts are frequently recurring at some locations of this facies (similar to facies 2.8 the granule sandstone facies). Metric-scale convolutions are laterally observed in some outcrops. This facies is laterally amalgamated with the granule sandstone facies, but the later seems to occur at lower levels. Bioturbations are restricted to ball-shaped termite nests, found sporadically in some exposures. Silicified trees are scantly observed as well. Remarkably, this pinkish colored sandstone has a wide, though not continuous (due to the outcrop conditions) lateral extent throughout the escarpment. It appears as amalgamated sandstone bars.

2.9.1 Interpretation of the locally rooted, sandstone facies

In terms of lithology and sedimentary structures this cross bedded, locally roots dominated sandstone is similar to the facies 2.2 (the mouth bar). Essential differences between the two are that, this facies is locally roots dominated and it exhibit shortage in the diagnostic tidal structures compared with that found in facies (2.2). Based on the similarity in the primary sedimentary structures, this facies is also interpreted as mouth bars accumulation. Being amalgamated with very coarse sandstone (laden with large fossil trees) suggesting that the mouth bar is spatially and temporally intersected by the feeder distributary channels which suggest a landward side of the mouth bar complex (Wright, 1977; Elliot, 1978; Olariu and Bhattacharya, 2006). Both fluvial and less likely tidal signatures are preserved in this facies. Fluvial features (the coarse grains, silicified wood, termites trace, and blocky conglomerates) are predominant, suggesting that the depositional environment is approaching the fluvial proximity (towards the upstream side of tidal fluvial zone). In another word, departure of diagnostic tidal sedimentary

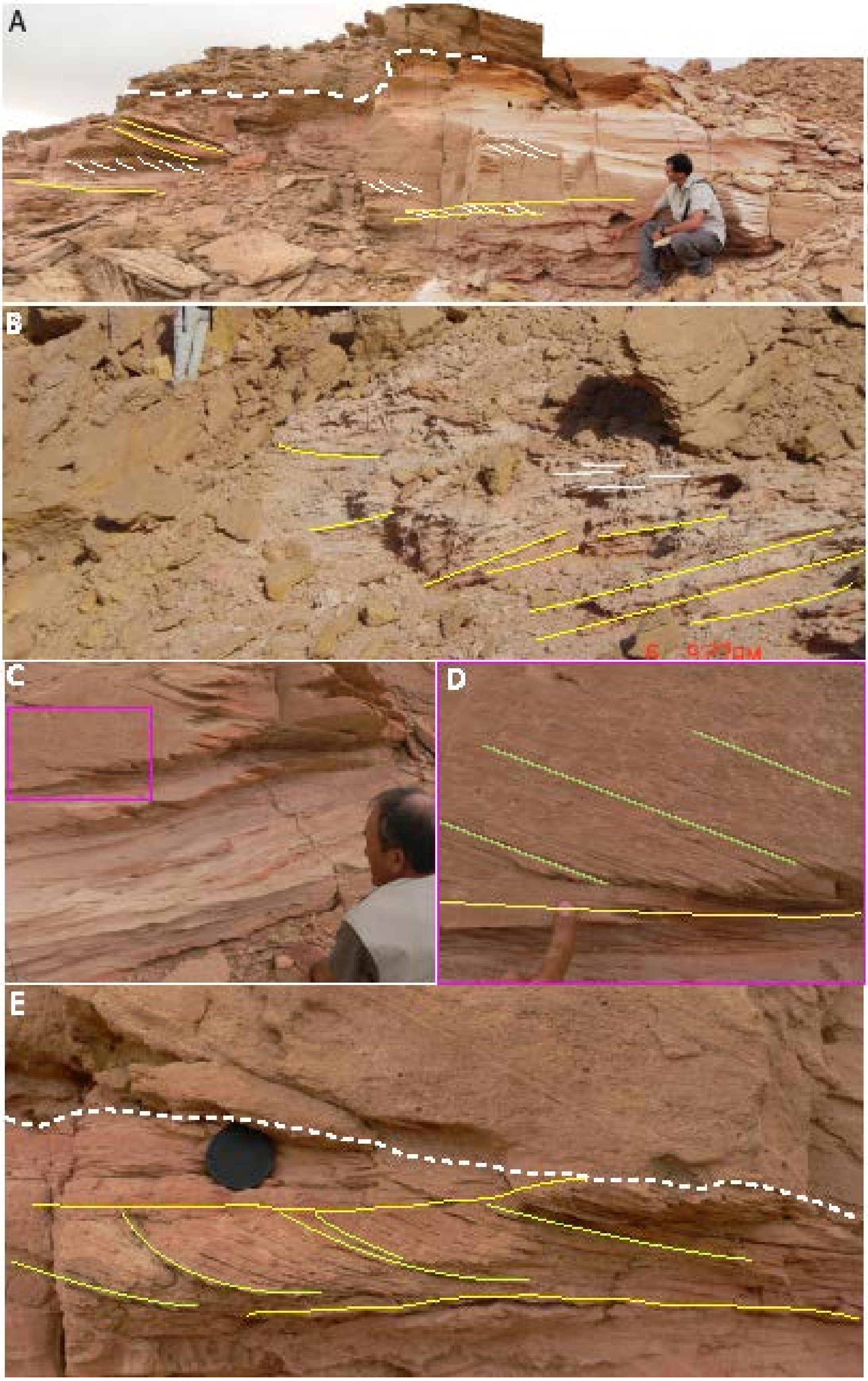


Fig. 11A-E: Illustrates the partially rooted cross bedded sandstone facies. A) shows that the position of this facies is close to the top of the cliff, in this view this facies is overlain by the coarser sediments facies; B) shows that this sandstone (of pink color) is intermittently heavily colonized with rhizoliths of cm scale; C) close view shows the possible tidal modulation; D) close view from (C) exhibiting mud drapes (the green lines); E) tide modulation presented as small bundles with mud-drapes foresets.

structures are obvious in this facies compared with its underneath counterparts. It represents a mouth bars complex landward shift of facies, confirmed by the first appearance of very coarse facies and intermittent dominance of vegetated areas in some of these sand bars.

2.10. Cross-bedded root-dominated sandstone facies

This facies (Fig. 12) is composed of medium to coarse, occasionally very coarse, almost mud-free, and yellow to brownish yellow sandstones. It is exposed closer to the upper edge of the cliff with thickness of (4-5 m) and lateral extent traceable for few hundred meters. Sediments of this facies resemble that of underneath (and adjacent) facies (2.9), but the roots are more abundant and the cross beds are commonly unidirectional. Color mottling is occasional, yellow-pink- light brown colors are locally prevailing. Sedimentary structures are highly disturbed by remarkably intensive rhizolith (fossil roots) network that colonized the whole sand. Nevertheless, cross bedding are sometimes still distinguishable. Troughs of medium sized sets composing few meters thick cosets (Fig. 12C) are recognizable. The intensive fossil roots (rhizoliths) are the most significant feature affecting this sandstone. Sandstones are colonized from base to top by strait and bifurcated millimetric to centimetric-sized cylindrical trace interpreted as roots. The roots are frequently intersected by the foresets and more frequently by sets boundary (Fig. 12C-E).
Bioturbations other than root traces are apparently of low diversity. Most distinguishable is of insect traces, particularly the work of termite (Fig. 12E). Termites burrow here are spherical to oval (few to several cm in diameter). Both termites and roots appear denser towards the top of this sandy facies. This facies also disappears laterally and is in many locations (especially the western side of the cliff) overlain by facies (2.11; pedoturbated facies).

2.10.1 Interpretation of the root dominated sandy facies

Two characteristic sedimentary aspects are distinguished in this root dominated sandstones. First, the coarse size of the grains, and second the shade of cross-bedding that is left after colonization by the roots. Coarse grained (mud-free) unidirectional cross bedding is a classical criterion of fluvial channels and interchannel bars, of probably braided streams (Miall, 1977; Cant and Walker, 1978; Selley, 1992), providing the lack of tidal sedimentary structures. This is likely the case in this root dominated sandstone. In this context, the absence of mud layers could possibly be attributed to the lack in fluvial dynamics, of daily (slack) and fortnightly (neap) energy fluctuations which are responsible for mud settling in tidal dynamic. Supplementary evidence of pure fluvial setting is provided by the dominant of centimetric scale rhizoliths that shows intersecting relationship with the encountered foresets lamina, indicating often syndepositional vegetation. The later occurs during temporary (episodic) switching among channel and interchannel bars. Colonization with rhizoliths and termite trace fossil in this facies are strongly comparable with the fluvial sandstones of the Jebel Qatrani, described by Bown et al. (1982) and Bown and Kraus (1988). Otherwise, termite traces associated with roots suggest, at least, several years of subaerial exposure.
To summarize this facies, it is reasonable to assume that either it is deposited completely under fluvial conditions or it is deposited under mixed (tidal fluvial) conditions, then subjected to prolonged periods of emersion. The first assumption is confirmed by the uninterrupted recurrences of grass vegetation and termite burrows.

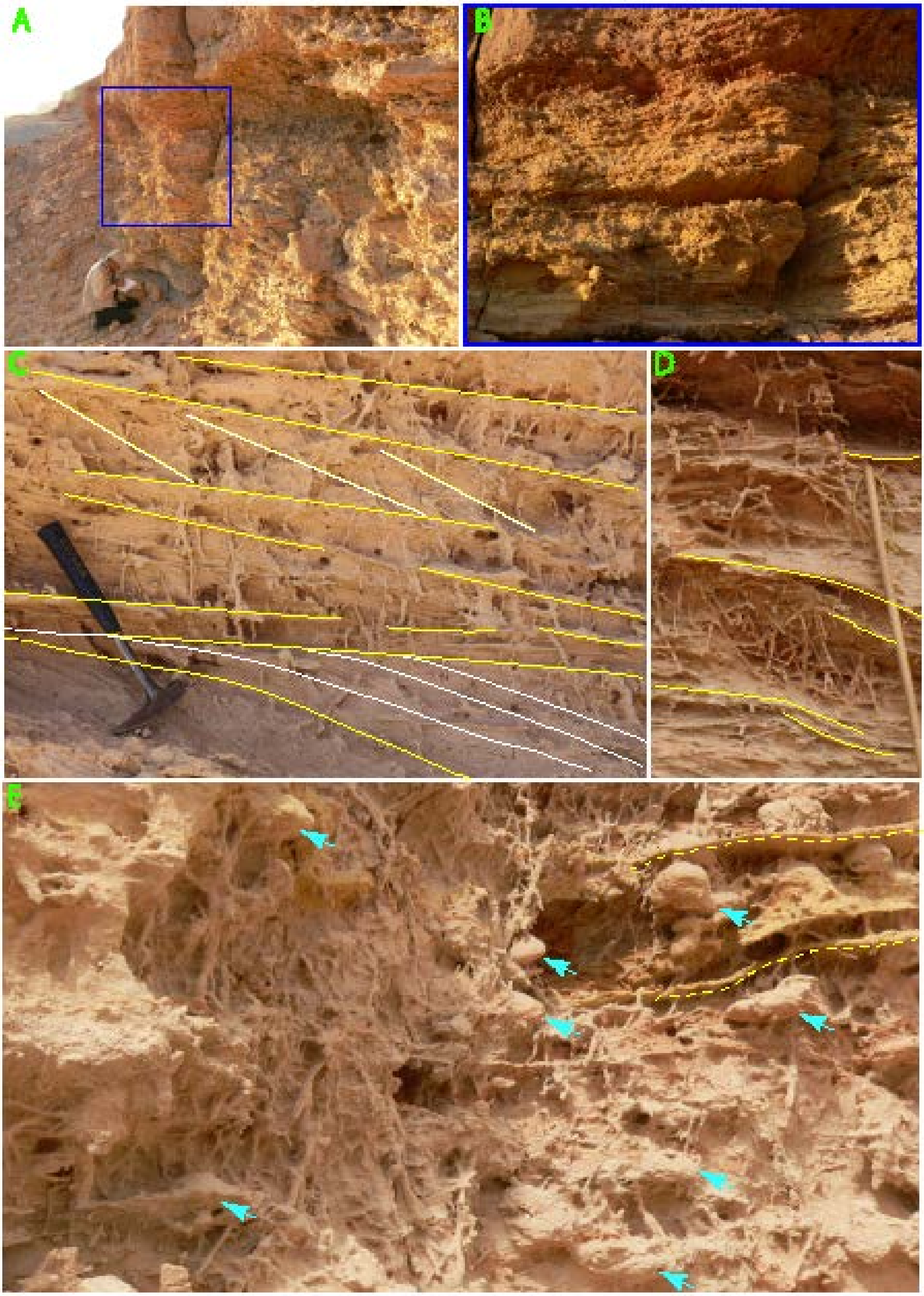


Fig. 12A-E: The cross bedded root-dominated facies. A) general view shows the thickness of this facies and density of the roots; B) closer view from (A) indicating that roots are of small size and colonizing superposed sand bars; C) remaining shades of the cross bedding; D) shows that the roots are truncated by the foresets lamina; E) Roots dominated sandstones associated with plenty of insect (termites nests, blue arrows), some foresets still recognizable (dashed lines).

2.11. Pedoturbated sandstone facies

This facies (Fig. 13) is composed of fine to very coarse grained, poorly sorted, generally orange to pale yellow colored, intensely pedoturbated sandstones. It occurs as very thick massive consistent unit of several (up to 6) meters thick that lacks primary sedimentary structures. This facies is also best observed in the western side of the escarpment. Here, it can be traced for few km, showing gradual decreasing in its thickness, before it disappears laterally. It is lateral interplaying with facies 2.9 and 2.10 (the locally rooted sandstone and the root-dominated sandstone). The grains composing this facies are a mixture of sizes, varying from very fine sand up to granule and occasionally pebbly. Intensive pedoturbation is the most significant feature distinguishing these sediments, to which grain mixing is attributed. Pedogenic alterations are appearing as color mottling of light shade (orange-light green-light gray), common presence of root tracks, undifferentiated small burrow and fungus combs chambers of termites. Concretions of iron and manganese oxides are also frequently developed in this facies. This in general, occurs as irregularly parallel granular horizons, of which, individual concretions are up to several cm in diameter.

2.11.1 Interpretation of the pedoturbated facies

The pedoturbated sandstone facies records the first appearance of a thick typical soil bed in the Sarir Sandstone. Sedimentary structures in this sandstone are almost completely obscured due to the intensive soil forming processes. Both biological (including rhizoliths and bioturbation) and chemical (resulted in the formation of concretions and the color mottling) are prevailing. Despite the absence of sedimentary structure, this paleosoil facies are similar (in terms of overall grain size and the presence of roots) to the adjacent and subjacent facies (facies 2.9, 2.10). Regardless of their abundance rhizoliths and termites are common criteria for these three facies. In this geological context, the sedimentary interpretation of the pedoturbated facies is originally a deposit of fluvial dominated channels and interchannel pebbly sandstone bars. These are later abandoned and subjected to relatively prolonged soil forming processes and leaching until they lost their all primary sedimentary structures.

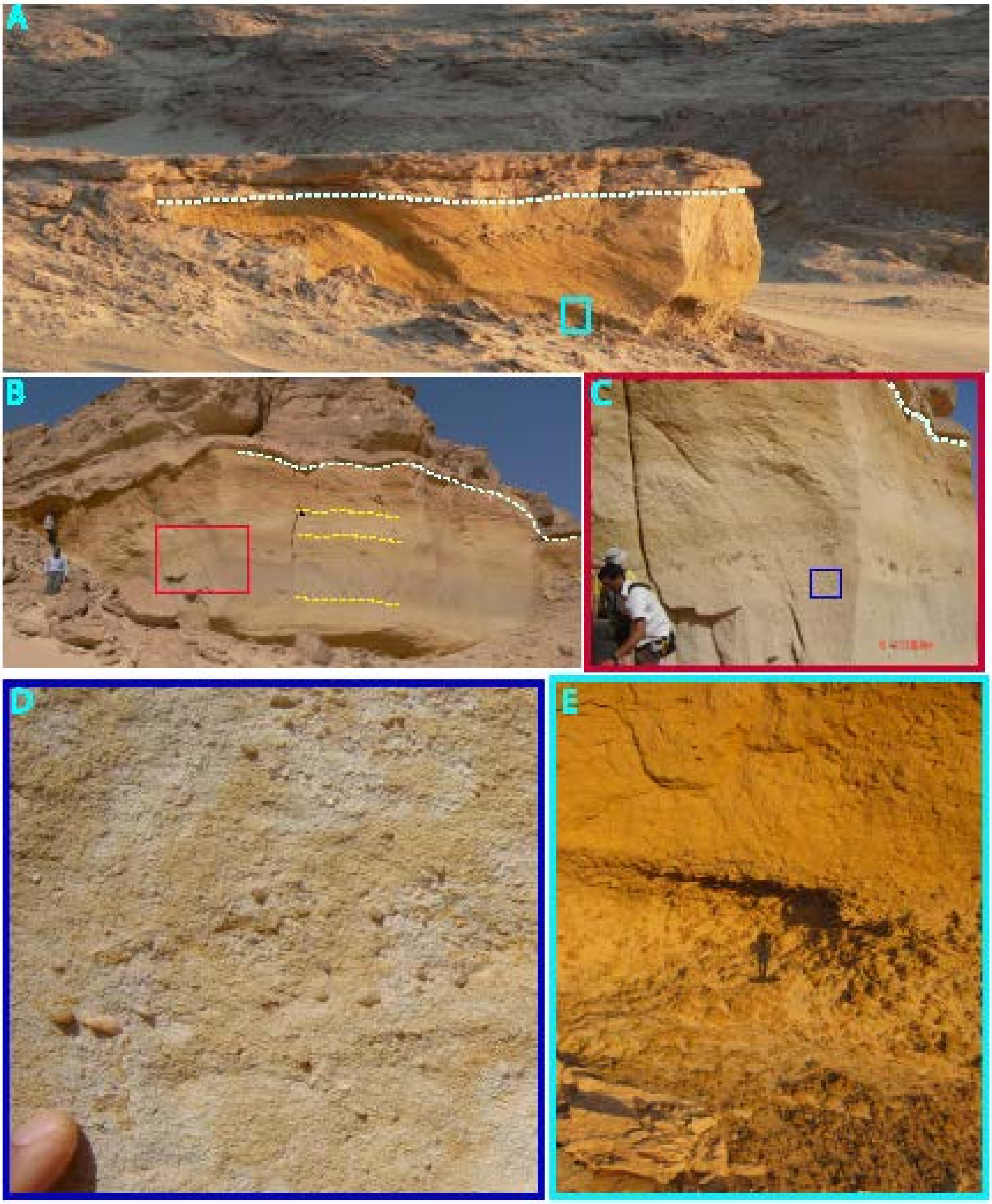


Fig. 13A-E: The pedoturbated facies: A) general view shows the location of these deposits (at the top of the cliff (i.e. the top of lower Sarir). B) is a closer view where the unconformable contact with the microconglomeratic is well exposed, color zonation can also be noticed (between the yellow lines); C) close view from (B) a horizon with concretion at the middle of the photo; D) detailed view shows the poor sorting (mixing of grains); E) a detailed view (the rectangle in A) show intensive concretion, attributed to prolonged soil formation processes.

2.12. Microconglomeratic sandstone facies

The conglomeratic sandstone facies varies in thickness from 2 to 5 m, thicker occurrences are at the lower part of upper Sarir, where it shows up as an extensive mud-free sand sheet. It is distinguished from the different underlaying facies by the comparatively coarser grain size (Fig. 14), poor sorting and better consolidation. Wherever this facies observed, a sharp break with the underlying facies is obvious, presented as a different forms of unconformities. This microconglomeratic sandstone deposition is commenced at the top of the cliff and recurs upward to occupy greatest part of the (available) isolated hill on the plateau (Fig. 14A). Constituting grain sizes of this facies is always coarse sand to microconglomerate. Dominant colors are light pinkish brown, and white to light gray (Fig. 14B-E), most of the time contrasted with the color of the underlaying rocks. The dominating grains composing this facies are quartz, with subordinate amount of feldspar. These are mostly rounded to subrounded with subspherical forms.

Sediments of this facies are distinctively presented as large troughs (Fig. 14B,C) and uncommonly planar cross-bedding. These are distinguishable only at the lower outcrops of this facies where it is extensively exposed. Troughs are of low angle and of several meters to several tens of meters wide, characterized by thick mud-free foresets (Fig. 14B-F). Individual foreset exceeds 10 cm in thickness and are characterized by normal grading in the grain size. Each foreset commences with microconglomeratic grains and gradually ends up with medium to coarse grains. Palaeocurrents shown by these cross beds are generally unidirectional, most measurements show northerly oriented currents (with dispersal angle of up to 40°). Small roots (centimetric scale) and termite traces are generally common (Fig. 14G), but are less frequent in the coarser outcrops. Silicified wood are very rare if ever, observed pieces are small and are detached from the rock

The contact between this facies and the underlaying facies (2.2, 2.9, 2.10, 2.11) is always sharp and erosional (Fig. 14H). The coarse sediments of this facies are presented as a wide (several tens to few hundreds of meters) and shallow (few meters) channels. These channels represent the basic architectural unit forming this facies. Lateral amalgamated channels are responsible for the building of the several km long microconglomeratic sandstone sheets. Within the isolated hills this facies is due to the limited outcrop did not show up as an extensive sheet. In this situation the microconglomeratic sandstone is exposed as repeated sequences with poor fining up trend (Fig. 14A). These sequences are up to 5 m thick, commence with the microconglomeratic sandstone which forms at least 3/4 of the sequence's thickness and end with silty/muddy sandstone of facies (2.13, below) which form the reaming part of the sequence.

2.12.1 Interpretation of the microconglomeratic sandstone facies

The microconglomeratic sandstone forming large cross bedding is an usual essential component of low sinuosity rivers channels (Mail, 1977; Cant and Walker, 1978). The geometrical and the grain characteristics of this facies, as well as overall palaeocurrents, make this facies lying among the range of the criteria of the braided river. The wide lateral spatial extent of this facies coupled with the width of individual channels suggested the presence of several channels acting simultaneously to form the large sand sheet. The absence of large fossil roots probably indicates high energy and continued supply of the coarse sediments, allowing only for small sporadic plants to grow on the bars surface. Based on their morphology and grain size,

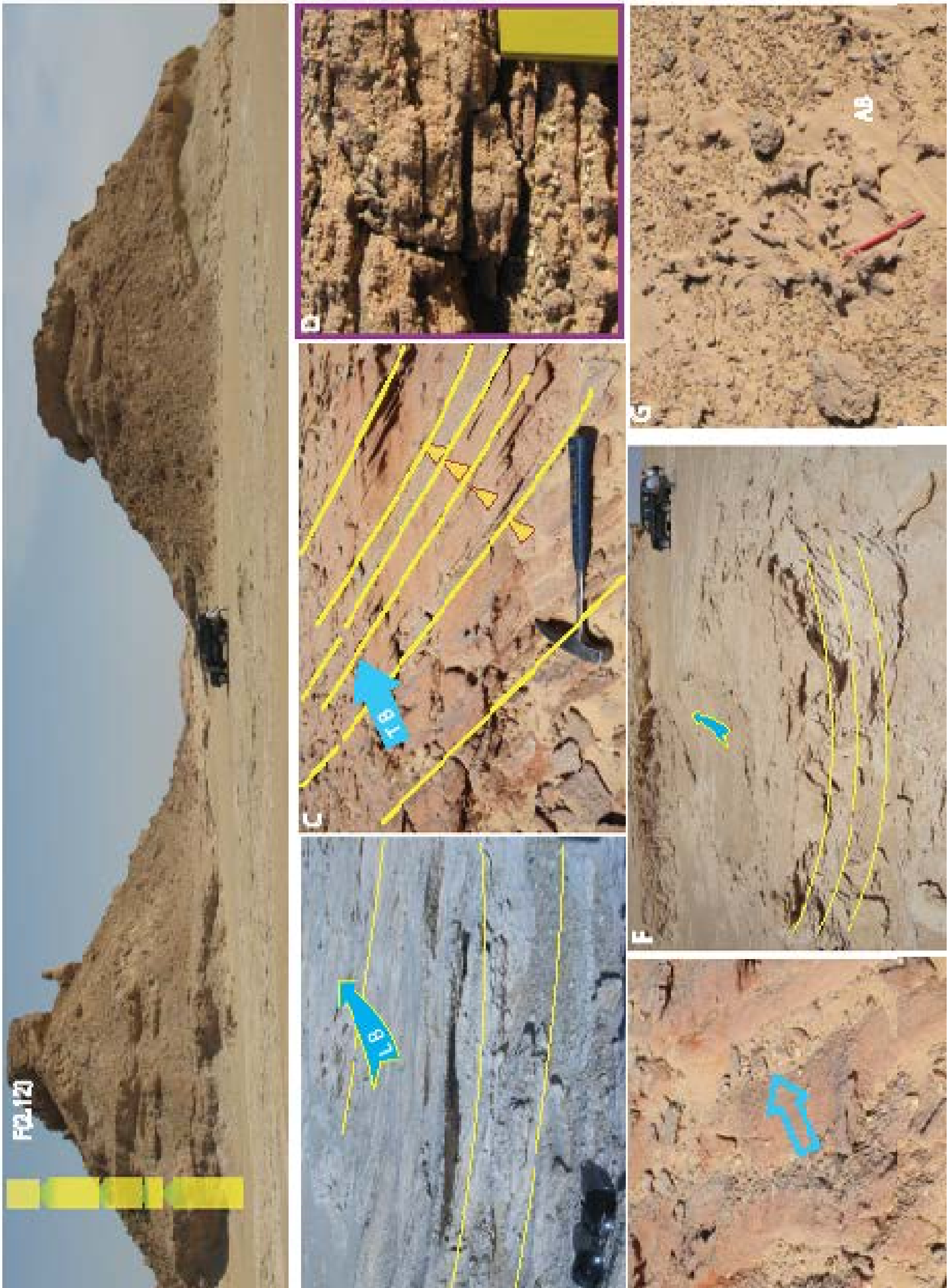


Fig. 14A-G ~~(previous page)~~: A) Outcrop view of the microconglomeratic sandstone facies. The facies is intercalated with muddy sandstone of facies (2.13, the greenish zone above the yellow shape. B) longitudinal fluvial Bar (LB); C) Transversal bar (TB) composed of large troughs with thick foresets showing graded bedding; D) strike view of large microconglomeratic cross sets; E) detailed view shows the set thickness and the normal grading; F) large troughs composing the longitudinal bars; G) rhizoliths, locally dominating some bars. The palaeocurrent shown by this facies is predominantly to the north.

Fig. 14H: Shows the contact relationships between the microconglomeratic sandstone facies (upper Sarir) and the underlaying sandstone of the lower Sarir of the escarpment. From the top: 1- fluvial intersects paleosoil, 2-intersect roots dominated (tide influenced) sandstone, 3-tide dominated sandstone, and photo 4 the fluvial cuts into amalgamated tidal point bars.

sediments of this facies are comparable in modern braided rivers to longitudinal and transversal bars and interchannel bar. Taking into consideration the fining up sequences exhibited by the isolated hills, meandering (probably of low sinuosity) channel deposits cannot be entirely excluded. Despite this, IHS feature known for the meandering river point bar does not show up in this facies where it is extensively exposed. Anyway, very coarse sandstone sequences end with muddy sediments has been reported from the braided south Saskatchewan rivers (Cant and Walker, (1978) and Donjek (Miall, 1977, 1996).

2.13 The Muddy sandstone facies

This facies (Fig. 15) is composed of pale green poorly sorted sandy mudstone and exists as irregular and apparently structureless beds. Grains composing this facies range from clay to very coarse sand and occasionally pebbles. Sediments of this facies are closely associated with the conglomeratic sandstone of the facies (2.12). The two facies together make the small superposed fining up sequences. Beds of this muddy sand exhibit poorly define irregular boundaries with microconglomeratic sandstone, and it reaches a maximum thickness of 1.5 m, but is commonly less than 1 m.
The contact separating this muddy facies with the underlaying, overlaying and adjacent facies (2.12) is predominantly erosional (Fig. 15A, B), and sometimes appears to be gradational. Similar to that of the microconglomeratic sandstones (facies 2.12), the quartz grains in this facies are also subrounded to rounded, varied in size from clay to pebbles, showing extremely poor sorting. The grains are floating in the muddy matrix and are occasionally embedded as few cm microconglomeratic lag. Remarkably, most beds of this facies are pedogenically altered, left almost no primary sedimentary structures. The most characteristic (recognizable) pedogenic alterations are the color mottling (green-gray-brown-yellow), the local presence of concretions and centimetric fossil roots, in addition to the common traces of probably insects. Among the insect traces, the most evident is the trace of termites (Fig. 15E), this is very commonly preserved as rounded balls with a flattened base cemented into the sediments. Possible physical sedimentary structures preserved are limited to large polygonal shaped tracks interpreted as mud cracks (Fig. 15C, D). This facies rarely contains vertebrate bones of large mammal, observed in only one site, but they are not cemented to the rock (Fig. 15F).

2.13.1 Interpretation of the muddy sandstone facies

Certain interpretation of this facies is difficult because of the poor lateral continuity and the lack of sedimentary structures. The muddy sandstone containing a mixture of mud and coarse sand grains are common as deposits of flood events in rivers (Smith, 1970; Mail, 1985), flood plains and abandoned channel fill (Miall, 1977; Bridge, 2003). Flood plains are elevated areas active only during flood, strong floods are known to carry mixed size sediments, and those are rapidly deposited with insufficient hydraulic sorting. Nevertheless, because this facies is incorporated in apparently a fining up sequences this makes it suitable also for meander channel environment. This cannot be entirely excluded. As it has been said before, the scenario of braided flood plain and the meandering channel, both are possible as a depositional for muddy sand facies. The available sedimentary features seem to be more convincing for braided fluvial. It has

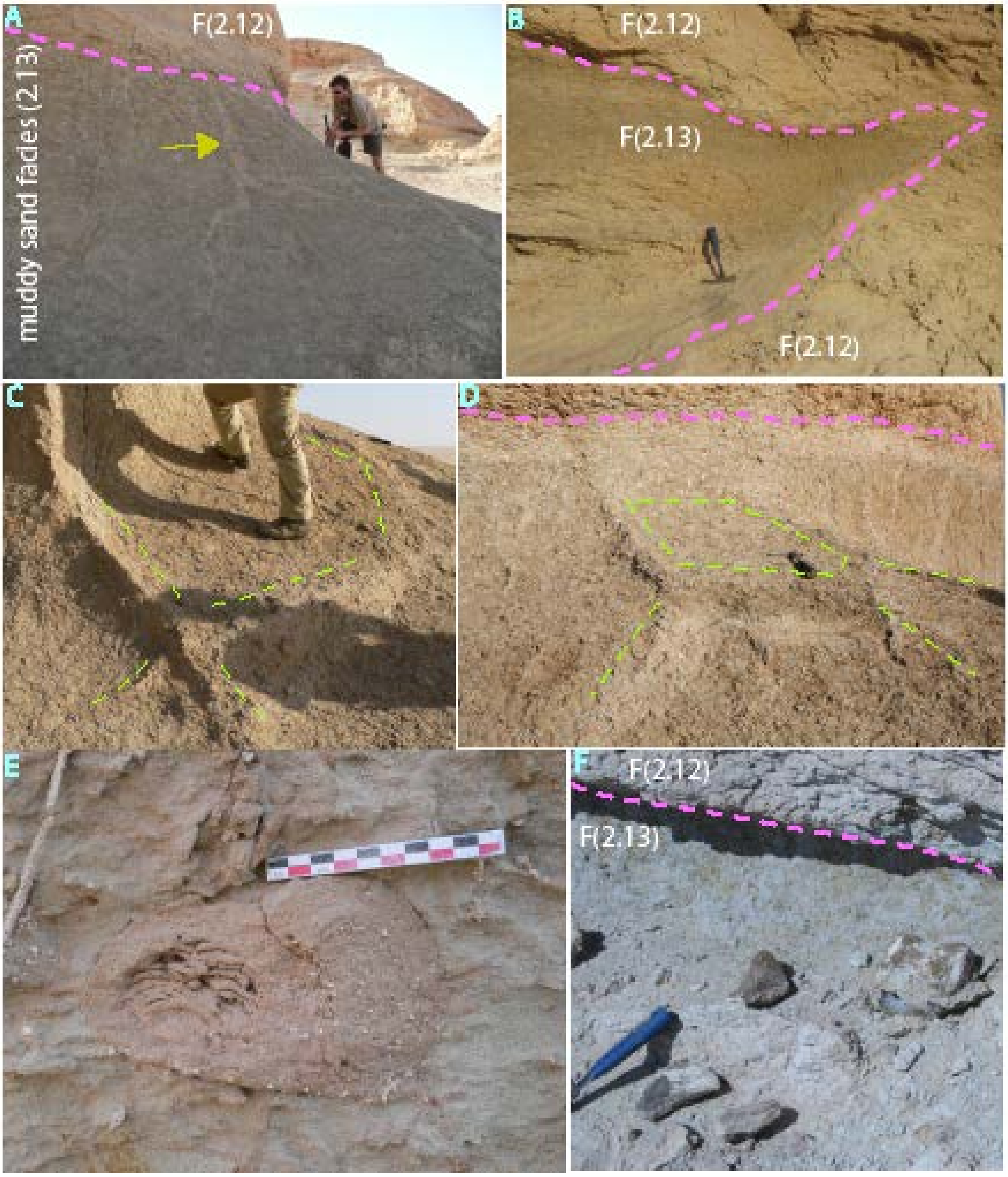


Fig. 15: Illustrates the occurrences of the muddy sand facies. A, B) shows the general appearance of this facies, mottled color and the relation with the microconglomeratic sandstone (F2.12) facies. The arrow in (A) refers to oblique cross sectional view of deep penetrated mud cracks, better view is presented in (C, D, traced by the dashed line); E) termite fungus comb with the internal structure preserved; F) vertebrate bones seen beside the muddy sandstone facies.

been documented (Allen, 1970: Bridge, 1993) that, in fluvial deposits, fining upward sequences could be confused with meandering-river sequences. In fact, in low meandering systems or in the passage from braided to meandering river as it is the case in the Chari river in Chad close to N'Djaména (Moussa, 2010), both facies can be present (very low angle point bars made with fining up cross sets). In our case indications of braided is overwhelming.

2.14 Coarse grained inclined heterolithic stratifications facies

This facies (Fig. 16A-C) is very scarcely exposed, observed in some isolated outcrops in the eastern side of the plateau. In fact they are observed in only few scattered outcrops (several tens of meters wide, few meters thick). It consists of inclined beds (around 5-10°), composed of sandstone intercalated with much thinner beds of mudstone (Fig. 16B). The sandstone beds (40 cm. thick) decreases laterally into several cm. These are white to light gray, consists of medium to coarse grained poorly sorted quartz sand. Fine irregular laminations are the only physical sedimentary structures recognized in these beds. Small roots and termite traces are visible and sometimes common in both the sand and mud beds. The mud layers are 10-15 cm thick and are commonly sandy. Some of the beds display uncertain mud cracks as well as concretions of iron and manganese. Among other differences the essential difference between this facies and facies (2. 4.1) is the poor sorting and the absence of tidal sedimentary structures in this facies.

2.14.1 Interpretation of the coarse HIS facies

Regardless of the scattered and discontinuous exposure of the upper part of Sarir in general and this facies in particular, it is the only facies in the upper part of Sarir that preserves typical architecture of inclined heterolithic beds. The angle of inclination and the frequent sand mud alternation of this facies suggest their deposition as a point bar. Alternative possibility is the deposition as a bank attached side bar of low sinuosity streams. Side bar also usually exhibit low angle and (based on seasonal variations) receive mud and sand deposits alternatively.

3. Conclusive summary of the Sarir Unit

The sedimentological characteristics of the 14 described facies show that each of these facies corresponds to a certain subenvironments that are acted within a larger environment. Many of these subenvironments share similar sedimentary characteristics in common between them. Essential characteristics are related to whether these facies possess tidal signature, fluvial or mixed tidal-fluvial signatures. Accordingly, the encountered facies are assembled into three facies groups (A, B and C; Table. 1). These facies groups are constructed (Fig. 17) to present the framework of the Sarir Unit. Each group is ascribed to specific geological setting. From base to top, these are: tide dominated, mixed (tidal-fluvial) and strictly fluvial environments.

Facies group	Encountered facies	interpretation	Position in Sarir Unit
C	2.12 to 2.14	Entirely fluvial environment	The upper (20-30m) Upper Sarir
B	2.1, 2.2, 2.8 to 2.11	Mixed tidal-fluvial environment	The middle (15-25m)
A	2.1 to 2.7	Tide dominated environment	The lower (15m) Lower lower Sarir

Table. 1. Subdividing the Sarir Unit into 3 facies groups. Group (A and B) compose the lower part the Sarir Unit, and (C) compose the upper part of the unit.

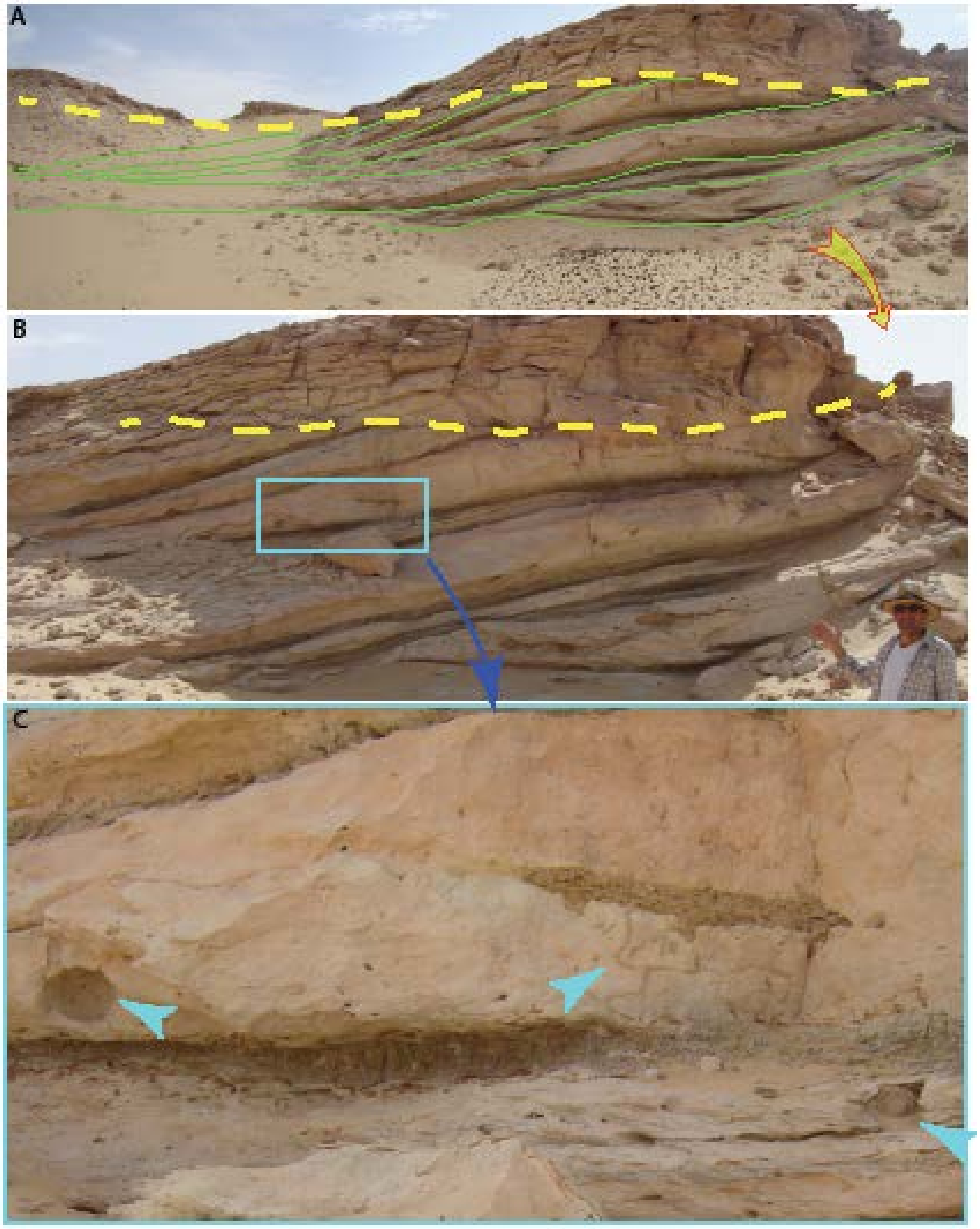


Fig. 16A-C: Shows characteristics of coarse grained IHS facies in upper part of Sarir Unit. A) Low angle of inclinations; B) Close view from (A) showing that muddy beds are much thinner than the sandy beds; C) biogenic traces, manly roots and insect burrows (the arrows).

The tide dominated facies group (A) is dominating in the basal part. Started immediately above the erosional contact with the New Idam Unit and extends up for around 15 m. knowing that the upper part of the New Idam Unit is dominated by fluvial environment (inner estuarine) and the facies group (A) is tide dominated, infers that sea level transgression must be responsible for the deposition of the tide dominated environment (transgressive system tract).

Instead of tide dominated setting suggested by the facies group (A) mixed tidal-fluvial setting is preserved by the superjacent facies group (B), located between 15 to 25 m from the base of Sarir Unit. In fact, there is no actual contact between the two groups of facies (A and B). A blurred narrow interval could be suggested, placed at around 15 m from the lower contact of the Sarir Unit. Around this interval both the tidal and to lesser extent the fluvial signature are preserved. Moving upward from this approximately located interval, both fluvial and tidal indicators mutually adjacently exist.

Approaching the top of facies group (B) fluvial indicators becomes overwhelming. For instance facies 2.8 shows no tidal features and the facies (2.1, 2.2) which show ubiquitous tidal features in their location within group (A), preserve only vey local tidal features in the group (B). Instead these two facies are in many places dominated by in situ roots. The facies (2.11, the paleosoil facies) is devoid of sedimentary structures because, these structures are completely obliterated due to prolonged exposure. These aspects propose mixed tidal-to-fluvial environment to facies group (B). The gradual transition from group (A) to group (B) is proposing a progradational system which is normally associated with normal regression. This situation presumes that maximum flooding surface could be placed between (facies group A and B) the tide dominated and the mixed deposits. Taking this into consideration, the mixed tidal fluvial environment should normally record a high stand depositional system. The dominance of fluvial facies over the tidal facies is attributable to the increasing rate of fluvial influx associated with sea level stand still or lowering.

The deposits of the mixed environment (facies group A) are erosively truncated by the fluvial deposits represented by facies group (C). The contact beneath the fluvial deposits is always marked by abrupt change in lithology (incision), from medium-coarse grained of the group (B) below the contact, to the microconglomeratic sandstone of the facies group (C). A period of nondeposition between the two is presumed by the prolonged paleosoil facies, and by the in situ roots coexists with the silicified trees. This presumes that a hiatus is located between the fluvial environments and the underneath mixed environment (subaerial unconformity). Therefore, lowstand (fluvial) system tract is ascribed for this fluvial deposit.

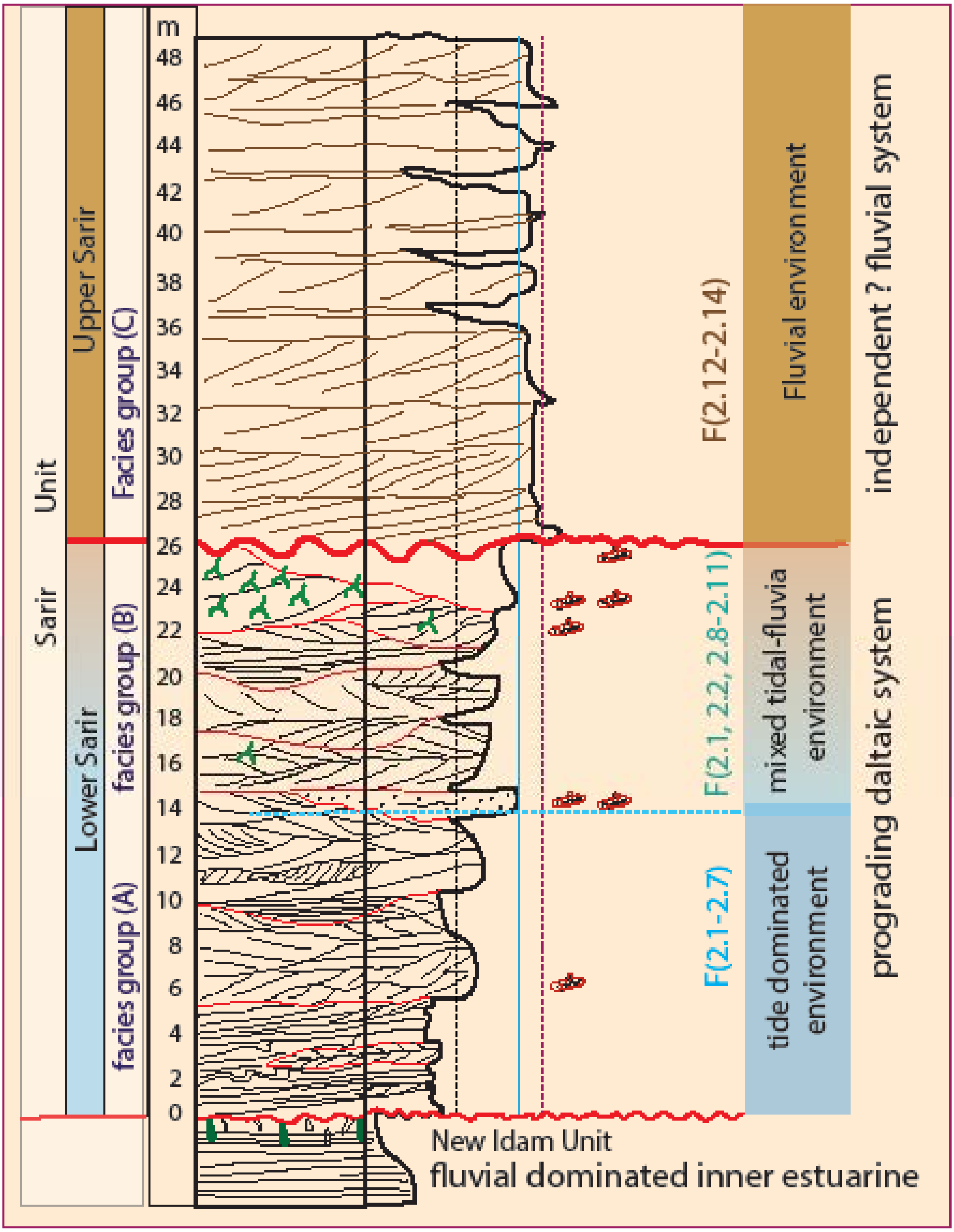


Fig. 17: simplified vertical reconstruction of the Sarir Unit sequences based on the distribution of the constituting facies. The lower Sarir consists of tide dominated deposits changes upward to fluvial dominated deposits the dashed blue line represents the approximit limit between the two parts (subunits). subaerial unconformity separates the lower from the upper Sarir.

CHAPTER FOUR

Sedimentary structures association and their implications in recognizing ancient tidal bedforms. Example from Lower Sarir Unit, Dur At Talah outcrop, Late Eocene, Sirt Basin, Libya.

Abstract

The Dur At Talah escarpment (145 m high and 150 km long) is exposed at the southern part of the Sirt Basin, central Libya. It exposes an Upper Eocene rock succession, composed by highly bioturbated fine sand-claystones alternations at the base (New Idam Unit), and by medium to very coarse sandstones at the top (upper part of the Sarir Unit). The whole succession evolves from tidal dominated shallow marine (New Idam Unit) to fluvial deposits, passing through a marine-fluvial complex transition zone (lower Sarir Unit). Depositional environments range from tidal flat, including tidal bars and channel, to deltaic plain with mixed tidal fluvial features.

The Lower Sarir sandstone (around 25m thick) which is thought to be deposited in a deltaic environment is the focus of this chapter. This sandstone is notably marked by conspicuous subaqueous dune cross-stratifications. Detailed observations revealed multi-scale sedimentary structures evidencing deposition in tidal environment. The diagnostic structures identified here include cross-sets strata with single and paired mud drapes, reversed lamina of the subordinate currents as well as inversed current ripples ascending on the descending cross-bed foresets, draining current ripples perpendicular to the main foresets, well-developed tidal bundles displaying daily, fortnightly, and longer, equinoxial, cycles.

These structures are here documented, discussed and interpreted, for the first time from this outcrop. Their style of association provides an outstanding example of tide-dominated siliciclastic system. In particular, the structures reported here is of great significance in identifying ancient bedforms of tidal origin. They afford evidences of subtidal and intertidal depositional environments. Criteria indicative of semidiurnal regime of the tide are also presented, particularly within the bundled foresets of spring tides. Furthermore, this study concludes that the most reliable sedimentary structures for recognizing the tidal bedforms are the ripple-scale sedimentary structures preserved inside and at the base of large scale cross-beds.

Keywords: Mud drape, tidal bundle, perpendicular and opposite ripples, tidal dunes, subtidal.

1. Introduction

The large-scale cross-bedding are known to occur due to the unidirectional migration of bedforms (megaripples/dunes) of decimetric to metric dimensions. Knowing that the tidal processes are characterized by the dominance of one tidal current (ebb or flood) over the other (e.g. Allen and Narayan, 1964; Klein, 1970; Terwindt, 1971; Dalrymple et al, 1978; Visser, 1980; Hayes, 1980; Dalrymple et al., 1992; Nio and Yang, 1991; Féniès and Faugéres, 1998), the cross-bedding resulting from a fluvial current may resembles those resulting from tidal currents (especially if mud drapes are not registered). Taking this into consideration, identifying diagnostic sedimentary structures exclusive of tidal processes becomes essential for distinguishing the origin of ancient cross-bedded sandstone.

In tidal environments, the combination of spatially varied flow (i.e., different flow paths and directions of ebb and flood) and temporally varied flow (e.g. daily, fortnightly, and longer tidal cycles) generates recognizable signatures in the sedimentary record left by the migrating bedforms. Among those, the most conclusive ones are (1) mud drapes (Allen and Narayan, 1964; Terwindt, 1971; Allen and Friend, 1976; Allen, 1981; De Mowbray and Visser, 1984), (2) mud double drapes (mud couplets; Visser, 1980; Smith, 1988), (3) tidal bundles of one event (ebb or flood; Boersma, 1969), and (4) tidal bundle sequences with or without reactivation surfaces (e.g. Klein 1970; Terwindt, 1971; Visser, 1980; Boersma and Terwindt 1981; Terwindt and Brouwer, 1986; Smith, 1988).
Other structures known to occur due to the periodic change of tidal current direction include herringbone cross-stratification and reversed (180°) climbing ripples as well as perpendicular draining ripples at the foot of large scale cross beds.

All this typical tidal features are uniquely well preserved in the studied sandstone of the Lower Sarir sub-Unit (especially at the basal part) which is part of Upper Eocene Dur At Talah escarpment, located in the southern part of The Sirt Basin (Fig. 1). This sub-Unit is composed dominantly of fine to medium grained sandstone, characterized by wide range of cross-stratifications, and local occurrences of petrified tree trunks, which increase up ward and appears to be in situ at the top of this sandstone.

This article presents this upper Eocene case study, concerned mainly with the associations of sedimentary structures of millimetric to metric scale. An attempt has been made to interpret these structures and highlighting there possible implication in defining depositional environment. In addition to the role of the described structures in distinguishing ancient tidal bedforms, it also presented evidence that the environment of deposition of Lower Sarir sub-Unit was dominantly subtidal, with local intertidal settings. Furthermore, semidiurnal tidal regime acting during the deposition of these sediments has been deduced.

This work is supported by field observations of modern tidal deposits in the Bay of Mont Saint Michel (France), as well as by comparison with numerous published modern and ancient case studies.

2. Geological setting of the Dur At Talah escarpment

The 150 m thick siliciclastic succession exposed in the Dur At Talah escarpment represents part of the southern flanks of Sirt basin. This basin (or embayment; Conant and Goudarzi, 1967; Goudarzi, 1980) is known as one of few giant hydrocarbon reservoirs in Africa and is ranked as one of the world's top 20 hydrocarbon producers (Ahlbrandt, 2002; Abadi et al., 2008).
The basin is considered as part of the Tethyan rift system, with the main extensional phases occurred during Late Cretaceous to Early Tertiary (Goudarzi, 1980; Siha and Mirheel, 1996; Abadi et al., 2008). During Early Paleogene, marine transgression extends to the south, from the basin centre far into the embayment (Gumati and Kanes, 1985). During the Late Eocene, this transgression had reached the southern borders of Libya (e.g., Barr and Weegar, 1972; Benfield and Wright, 1980). The general geological and stratigraphical setting of the Dur At Talah area is documented in Wight (1980), Vasic and Sherif (2007). Abouessa et al. (2012) present a summary of the geological setting of Dur At Talah succession within the framework of the Sirt

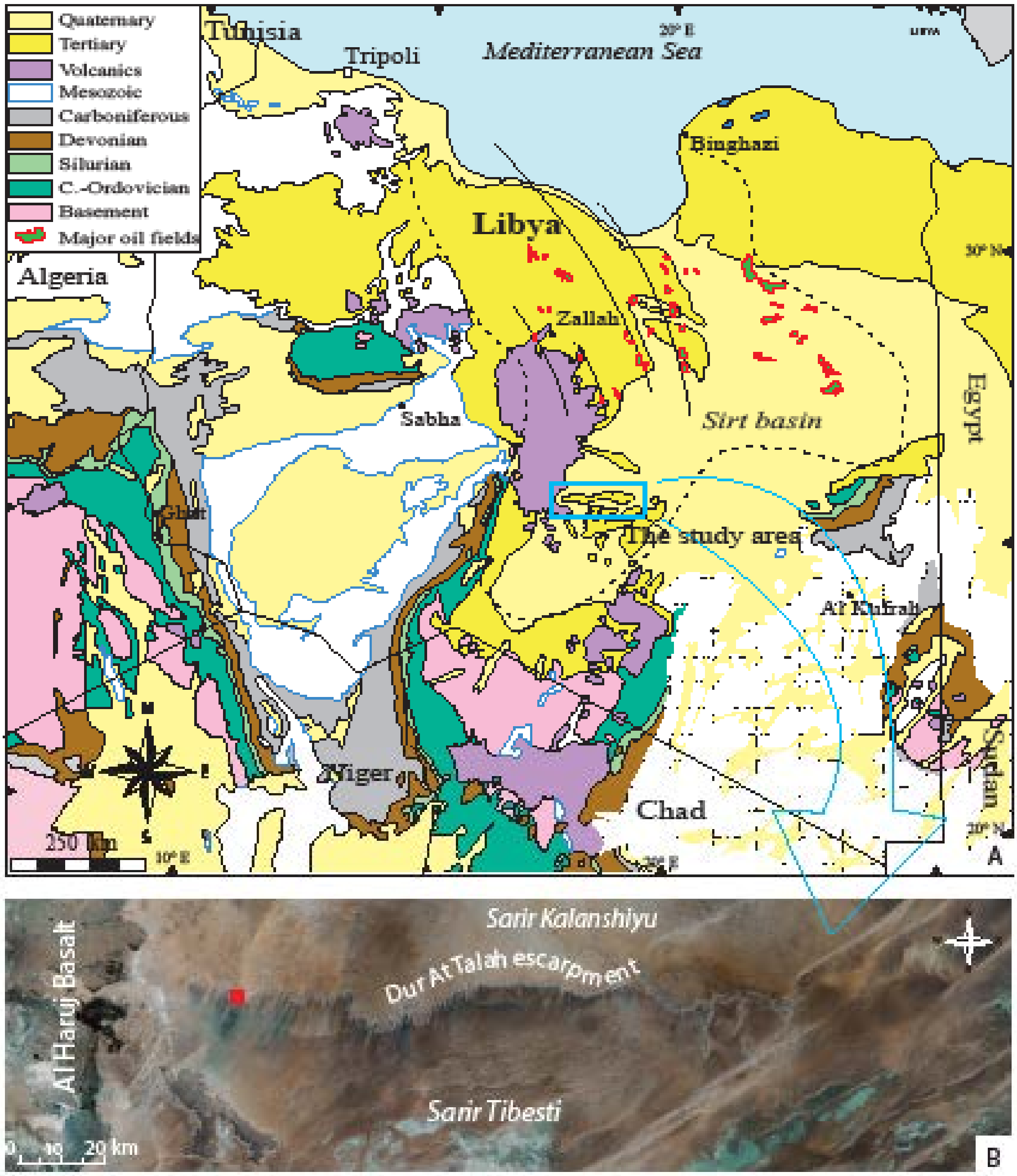


Fig. 1. A) Geological map of Libya with the location of Dur At Talah (blue rectangle); B) Satellite view of the Dur At Talah escarpment

Basin. Influx of sediments composing the studied section was from the south where Precambrian basement as well as sedimentary rocks of Palaeozoic and Mesozoic age is exposed (Barr and Wegeer, 1972; Bellini and Massa, 1980; Rasmussen et al, 2008).The entire succession is composed of two main sedimentary units (Fig. 2), the lower New Idam Unit and the upper Sarir Unit. This latter is in turn subdivided into a lower and upper sub-unit (Abouessa et al., 2012). The New Idam Unit (80–100 m) is composed of intensely bioturbated and stratified sequences of claystones, and very fine-grained sandstones. Bioturbations are characterized by a number of ichnospecies, dominated by a firmground of Thalassinoides and softground of Teichichnus. This unit is characterized by evident occurrences, in many levels, of mixed continental and

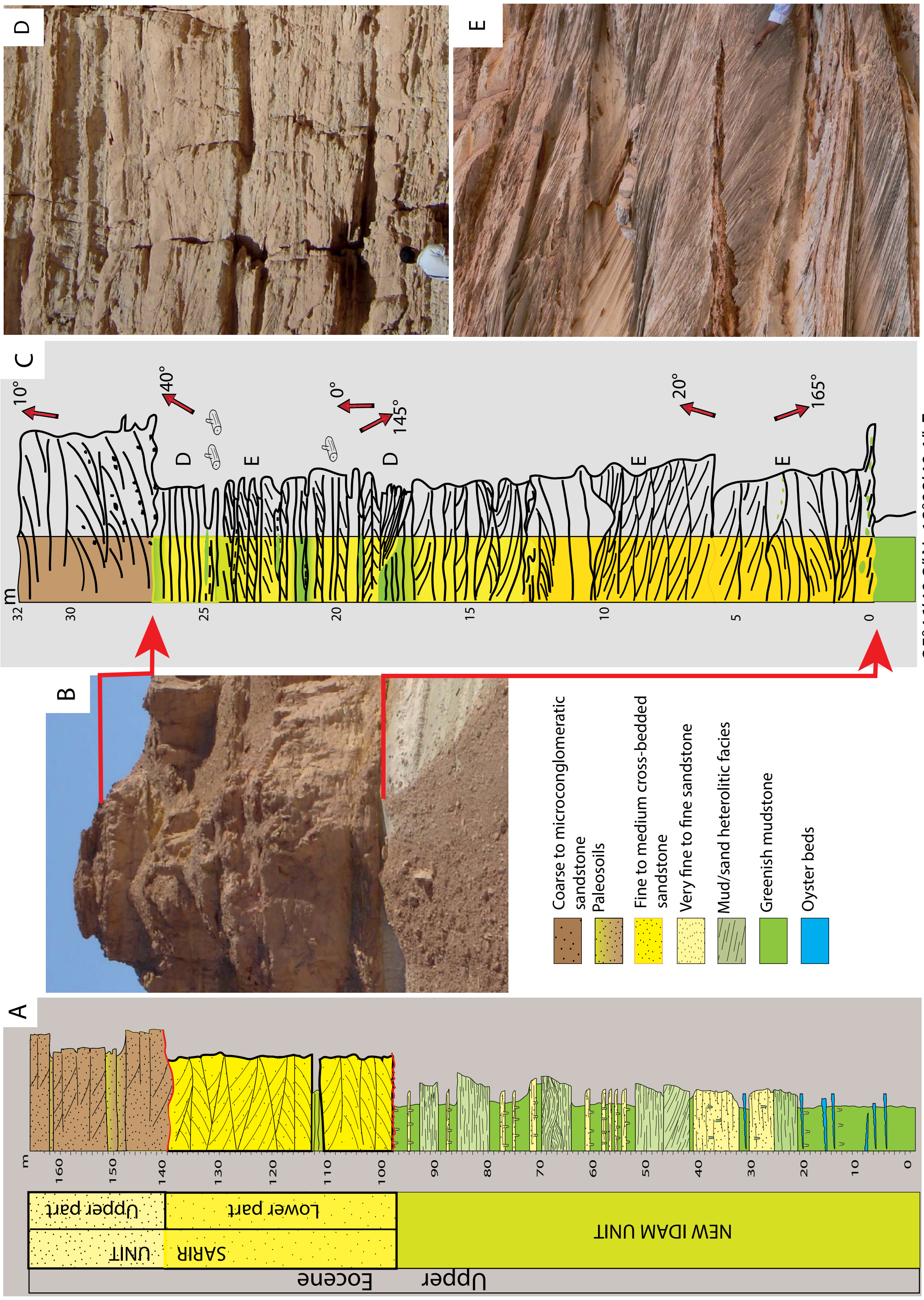


Fig. 2: Dur At Talah sequence. A) Stratigraphic position of Lower Sarir subunit between the fine sediments of the New Idam Unit and the very coarse sediments of the Upper Sarir subunit; B) Morphology of the Lower Sarir sandstone, highlighting its position in the sequence; C) sedimentological log of the studied interval; D) Interbedding of sandstone and mudstone, which occasionally intersects with the cross-bedded sandstone represented in (E). The positions of (D) and (E) differ with the location.

marine vertebrate remains, including early primates (e.g. Rasmussen et al, 2008; Jaeger et al., 2010a and b), which assign the age of this unit to the Late Eocene.

The New Idam Unit is interpreted as being deposited in a shallow marine tide-dominated estuarine environment (Abouessa et al., 2012). The contact between the New Idam Unit with the overlying Sarir Unit (~ 70 m thick) is largely erosional in the western side of the escarpment and apparently more gradational in the eastern part. Unlike the New Idam Unit, the Lower Sarir Unit (studied interval; Figs. 2B and C) is composed dominantly of cross-bedded sandstones which are coarser in grain size and shows far fewer biogenic structures; those that exist are restricted mainly to silicified tree trunks and very sparse small vertical burrows.
Based on the differences in texture and sedimentary structures, the 70-m thick sequence of the Sarir Unit is divided into two different sub-units. The lower sub-unit (25–40 m thick) is principally made up of fine- to medium-grained cross-bedded sandstone. This part is regarded as representing tidal–fluvial transitional facies (Abouessa et al., 2012). Vasic and Sherif (2007) assigned this interval to deltaic environment. The upper (30–35 m thick) part of the Sarir Unit is a sequence of coarse-grained, microconglomeratic sandstone. Several palaeosoil horizons, including roots development as well as termite nests, which occur from the base to the top of this coarse sandstone, are interpreted as being deposited in a fully continental fluvial environment (Abouessa et al., 2012).

3. Tidal processes and products (Review)

Tidal flow is known to exhibit a considerable degree of unsteadiness on a wide range of time scale (e.g. Klein, 1970; Dalrymple et al. 1978; Elliott and Gardiner, 1981; Dalrymple, 1984; De Mowbray and Visser, 1984). Most important aspects of tidal processes unsteadiness according to Nio and Yang (1991) Kvale et al. (2006) and many others are: 1- the depth and velocity fluctuation within ebb and flood events including the interim cease of flow (slack water period), 2- flow reversal associated with successive ebb and flood, 3- neap-spring tidal flow (current velocity) variations, 4- seasonal (semi-annual) variations in tides between equinox and solstice. These tidal aspects are reflected as regular vertical and lateral variations in the sedimentation pattern. The lateral changes or variations are recorded as a variety of particular internal sedimentary structures, preserved within the cross-bed sets of the sandstone megaripples.

In modern environments, subaqueous sandy bedforms have received strong attention from geoscientists (e.g. Houbolt, 1968; Boersma, 1969; Allen and Friend, 1976; Reineck and Singh, 1980; Boersma and Terwindt, 1981; Terwindt and Brouwer, 1986; Harris, 1988; Ashley, 1990; Dalrymple, 1990; Dalrymple et al., 1990; Harris et al., 1992; Dalrymple and Rhodes, 1995). In all subaqueous environments, flow velocity, flow depth, and grain size are the main parameters controlling occurrences of different bedforms (e.g. Allen and Friend, 1976; Boersma and Terwindt, 1981; Dalrymple, 1990; Selley, 1992; Dalrymple and Rhodes, 1995; Harris et al., 2002; Dalrymple and Choi, 2007; Tessier et al., 2010). In modern tidal environments, several metres thick sequences of cross-bedded megaripples lacking indicator of tidal process are reported from southwest Netherland, southern North Sea estuaries of mesotidal range (e.g. Terwindt, 1971; De Mowbray and Visser, 1984) and from macrotidal Bay of Fundy (e.g. Dalrymple, 1984; Dalrymple et al., 1990; Dalrymple and Choi, 2007).
The same aspect of unidirectionality is exposed in many observation pits we have made in some cross-bedded sand sequences, in the macrotidal Bay of Mont Saint Michel, where dominance of one current direction is reported by Lesourd et al. (2001). Explanation for such unidirectionality of cross-bedding is given by the fact that, at any one site, either the flood or the ebb portions of the tidal cycle dominates the bedform formation and migration (e.g. Allen and Narayan, 1964;

Klein, 1970; Terwindt, 1971; Dalrymple et al, 1978; Visser, 1980; Hayes, 1980; Dalrymple et al., 1992; Nio and Yang, 1993; Féniès and Faugéres, 1998), and that the flood current commonly does not follow the same path as the ebb current (e. g., Houbolt, 1968; Dalrymple and Rhodes, 1995; Féniès and Faugéres, 1998). Moreover, according to Ashley (1990) all large scale bed-forms (megaripples) are sufficiently similar in terms of formative processes. Knowing that the tidal processes are characterized by the dominance of one tidal current (ebb or flood) over the other, therefore, concerning apparent sedimentary structure, cross-bedded megaripple resulted from fluvial current would appear similar to those resulted by tidal currents (especially if mud drapes are poorly or not registered). Thus, recognizing special sedimentary structures exclusive of tidal processes is essential to distinguish whether the ancient cross-bedded sandstone was settled down in tidal or in fluviatile environment.

In tidal environment, the combination of spatially varied flow (i.e., different flow path and direction for ebb and flood) and temporally varied flow (e.g. daily, fortnightly, longer tidal cycles) generate recognizable signatures in the sedimentary record left by migrating bedforms. Among those, the most conclusive ones are (1) mud drapes (Allen and Narayan, 1964; Terwindt, 1971; Allen and Friend, 1976; Allen, 1981; De Mowbray and Visser, 1984), (2) mud double drape (mud couplet; Visser, 1980; Smith, 1988), (3) tidal bundle of one event (ebb or flood; Boersma, 1969) and (4) tidal bundle sequence with or without reactivation surfaces (e.g. Klein 1970; Terwindt, 1971; Visser, 1980; Boersma and Terwindt 1981; Terwindt and Boersma, 1986; Smith, 1988). These evident tidal structures and others known for tidal dynamics such as herringbone cross-stratification, reversed (180°) climbing ripples, associated with mud drapes, as well as ripples perpendicular to the megaripples direction of migration, all are uniquely recorded in the studied interval, both individually and in association.

4. Distinctive sedimentary structures in the Lower Sarir sandstone

This sandstone interval (25-30 m thick; Fig. 2B and C) exists generally as a repetition of several metres thick sequences of cross-bedded sandstones. Wight (1980) misinterpreted this interval as being deposited in fluvial environment. The reason behind his misinterpretation is the presence of the large channelized cross-bedding, and their content of silicified tree trunks, some of them seemed to be embedded in situ. Another reason might be attributed to the (apparently) total absence of the tidal features in many parts of this cross-bed succession, compared with that of the underneath unit. In fact, these sandstone interval exhibit discrete features characteristic of both tidal and fluvial environments (Abouessa et al., 2012). Wave generated sedimentary structures is limited, mainly restricted to a local, centimetric scale symmetrical undulations.

In this cross-bedded sandstones (the lower part of the Sarir unit) tidal sedimentary structures have, until now, only been partly mentioned, incompletely described and insufficiently illustrated in Abouessa et al. (2012). Their incredible diversity and good preservation, however, deserve this dedicated study, because it brings new data for the interpretation of the Dur At Talah system and more also, because it brings a textbook like example of the sedimentary record of the tides, leading to better understanding of fossil megaripples of tidal origin. The forthcoming paragraphs are devoted to illustrate and discuss both the large-scale and the associated small-scale sedimentary structures, displayed by the cross-bedded sandstones of the lower Sarir Unit.

4.1. Cross beds with mud drapes (daily tidal record)

In the studied sandstone regular and repetitive mud drapes are one of the most indicative tidal sedimentary structures. They are important in themselves and also useful in distinguishing other tidal manifestations. In the literature, mud drape was defined as the mud lamina deposited during the slack water period, culminating each tidal event (ebb or flood). One tidal event (half tidal cycle : flood-slack or ebb-slack) is assumed to occur twice a day (about every 12 hours) in the diurnal tidal regime, and four times a day (about every 6 hours) in the semi-diurnal regime. One tide event is assumed to consist of discrete subintervals representing acceleration, full vortex stage and deceleration of flow (e.g. Terwindt, 1971; Boersma and Terwindt, 1981; Allen and Homewood, 1984). These subintervals are, in general, assumed to be reflected in the internal structures of the migrating megaripples. The period of total cessation of flow culminating each event is the slack water period (Reineck, 1960). This stagnation period lasts for few tens of minutes (e.g. Smith, 1988; Thomas et al., 1987; Shanley et al., 1992; Lanier et al., 1993; Boersma and Terwindt, 1981; Féniès and Faugères, 1998; Féniès et al., 1999). The duration of this period is short but long enough to deposit a thin lamina of mud (depending on the suspended sediment concentration; e.g. Allen and Duffy, 1998) from suspension, this lamina is known as the mud drape (e.g. Reineck, 1960, 1963; Allen and Narayan, 1964; Terwindt, 1971; Allen and Friend, 1976; Allen, 1981; Terwindt, 1981). In this sandstone the two known occurrences of drapes, single and paired do, to a variable degree, occur. The figures 3 to 6 illustrate various styles of the mud drapes.

4.1.1. Single mud drapes

Mud drapes associated with the studied cross-bedding are composed of green and greyish green silty clay (e.g. Fig. 3A–E). Drapes composed of fine sand also exist, associated with the foresets of very thick, medium to coarse sandstone. Morphologically, most mud drapes are oblique, tangential and are conformable to the preexisting sandy foreset. The thickness of individual mud drapes varies from 1 to 4 mm; exceptionally, the thickness of some drapes appears to be more than 1 cm. Maximal thicknesses of the drapes are observed at the lower part (the toe) of the foresets. In spite of their overall subtle existence, single mud drapes (Fig. 3) are the most common elementary tidal structure deposited intra-set of this cross-strata, located between sandy foresets. The abundance of the mud drapes relative to the adjacent foresets of sand is variable from one cross-set to the other. Densely (millimetric-scale) spaced, and widely (centimetric-scale) spaced, mud drapes exist. The transition from densely spaced to the widely spaced drapes is sometimes preserved in one cross-set. In any cross-set, the spacing between the drapes and the delineated sandy foresets are linked to the grain size and the thickness of the hosting cross-set. Commonly, the smaller the set is the more ubiquitous the mud drapes are (Fig. 3D and E). In medium to coarse sand foresets and their delineating mud drapes are spaced at centimetric scale. Contrarily, in finer sandstone, foresets and mud drapes are spaced at millimetric scale.

Based on Allen's subdivision (1981), short, medium (Fig. 3A–C), and long drapes (relative to the height of the adjacent sandy foreset) are present in the studied cross bedding. Thus, the role here is that the thicker the cross-bed set and the coarser the sand are, the shorter and thinner the mud drapes are. More complete drapes (i.e. the "long drapes" of Allen, 1981) are more conspicuous in small sets (Fig. 3D and E) that are less than 15 cm thick.

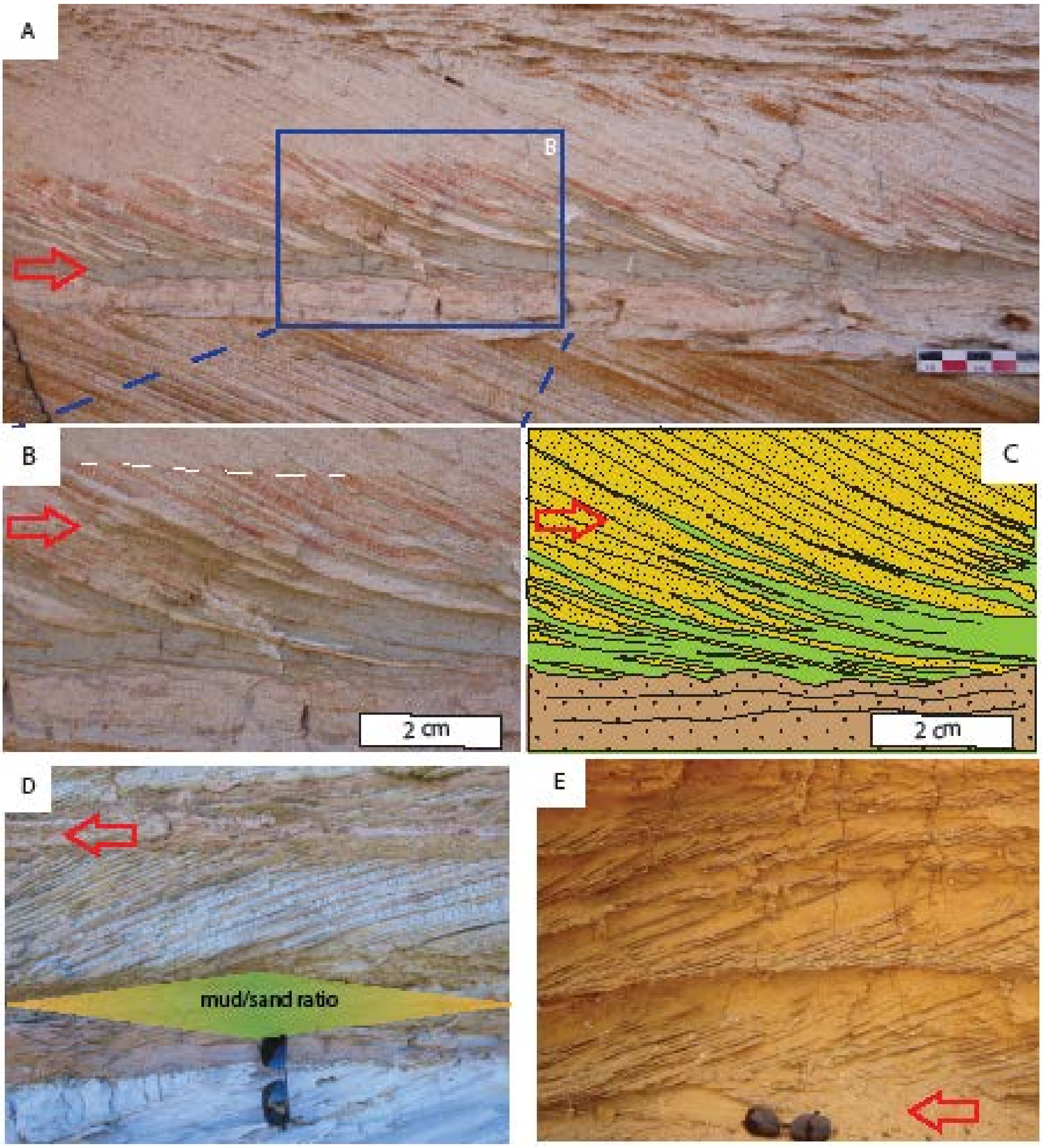


Fig. 3: Occurrence habits of single mud drapes. A) General view showing intense and well-developed mud drapes at the base of dune foresets; B) Close view [detail of (A)] showing closely spaced mud drapes; C) Schematic representation of (B), with mud drapes in green and sandy foresets in yellow; D) Rare example of complete mud drapes extending from the base to the top of the set; E) Example of mud drapes in four successive cross-sets; foresets between drapes are of variable thickness. Red arrows indicate the dominant current direction.

4.1.2. Double mud drapes

Double mud drapes, or mud couplets (Visser, 1980), are represented in the studied sandstones as pairs of two adjoining, commonly parallel to sub-parallel mud laminae alternating with the forward-accreted foresets of sand (Fig. 4A). The double drapes are of the same composition and nature as the single drapes. The thickness of each drape is ranging from less than one up to few millimetres. Double mud drapes sometimes coexist in the same cross-set with the single mud drapes. However, the forward-accreted sand between two simple drapes is commonly much thick (several cm), compared to the sand lamina (few mm) enclosed between coupled drapes. What is of particular interest, as well as making the distinction between the single and double drapes easier, is that some of the coupled drapes are separated by a delicate, thin (1–3 mm) sand lamina, that appears as ascending against the advancing foresets (Fig. 4B and C). The thickness of some sandwiched laminae acts oppositely to that of the descending foresets. The oppositely oriented laminae are thick at the base of the set and they thin out as they ascend toward the top of the set. Furthermore, there are cases for which mud couplets enclose small ascending current ripples rather than the sand laminae.

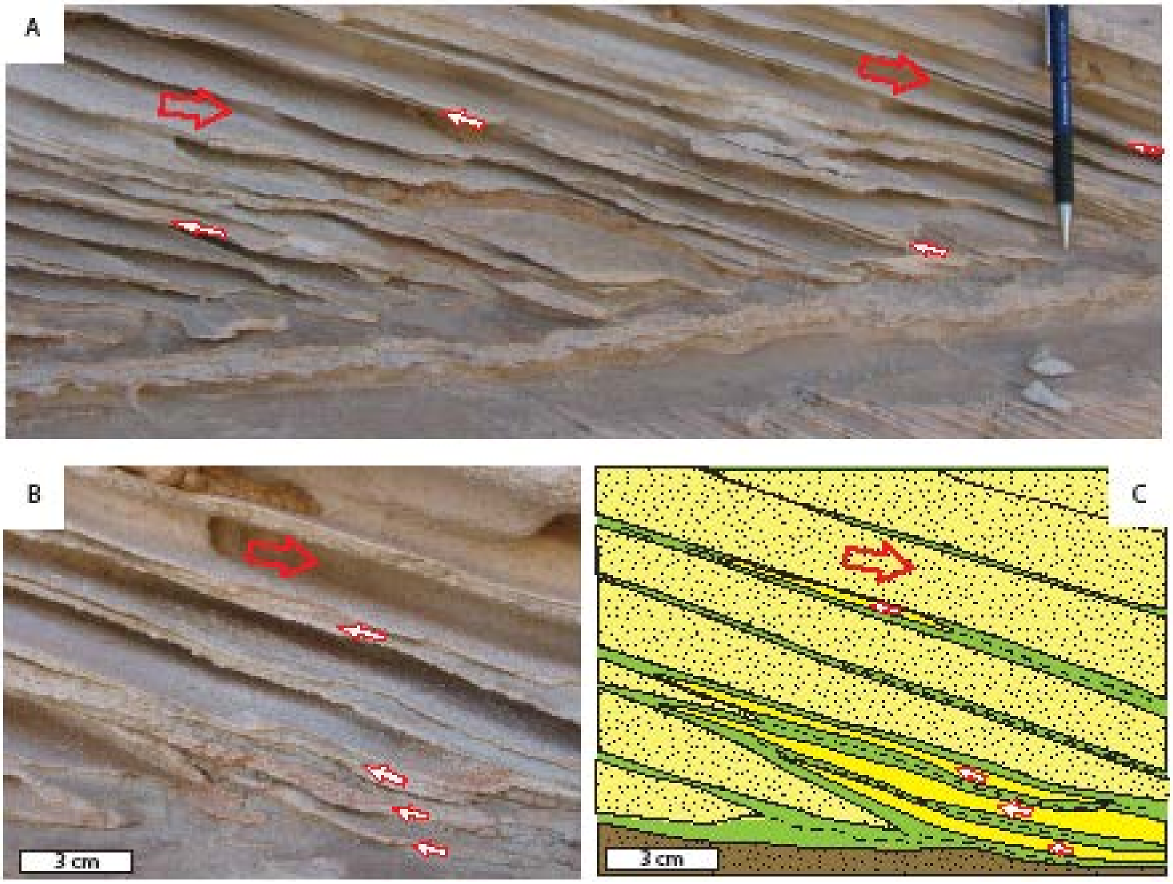


Fig. 4: Thick cross-set with double mud drapes. A) General view of the mud double drapes position (small arrows) relative to the foresets of sand; B) Detailed view from (A); the small arrows refer to the reversed sand laminae between paired drapes; C) Schematic representation of (B) indicating the difference in thickness between the main foresets and the enclosed reversed laminae. The mud couplets and enclosed laminae represent the subordinate current bundle.

4.1.3. Interpretation of single and double mud drapes.

Mud layers in this sandstone predominantly occur as simple drapes, delineating variable thickness sequences of prograding foresets, and to a lesser extent, as double drapes. In tidal environments in general, single mud laminae draping sand layers have long been used to prove deposition from suspension during the slack water tidal phase (e.g. Boersma, 1969; Klein, 1970;

Terwindt, 1971; Allen, 1981, 1982). Meanwhile, forward-accreted sandy foresets between two simple mud drapes, though variable in thickness, are always the product of one dominant tidal current. The dominant current event is equivalent to a half tidal cycle (either ebb or flood). Comparatively, the reversed (ascending) sandy laminae enclosed between coupled drapes (Fig. 4), should then be the product of the following tidal event. This subsequent event normally represents the succeeding subordinate current of the same tidal cycle. This subordinate current is known to be weaker than the dominant counterpart (e.g. Klein, 1970; Visser, 1980; Terwindt and Brouwer, 1986). Therefore it produces relatively very thin (or no) reversed foresets.

In cases where the subordinate current is not strong enough to accumulate sand (or where it accumulates a very thin sand layer), the drape culminating the dominant current and the next drape, after the subordinate current, appear to be coupled. The two mud drapes would be directly superimposed, in cases where there is neither erosion nor deposition during the subordinate current. The later situations explains the exaggerated thickness of some drapes (Fig. 5A and B), observed especially in the lower part of the cross set (Fig. 5C and D). The occurrence within the cross-bedded set of closely or widely spaced drapes or both together in one sequence (Fig. 5E) is a direct response to the changing current strength. In the same way, the preservation of mud drapes (single or double) is entirely linked to the strength of the stream. Even if mud drapes take place during each slack water period, they could be entirely removed during the following flood or ebb, simulating absence of mud and consequently leaving no obvious evidence of tidal record. In fact, it is sometimes very difficult to find obvious tidal structures on some outcrops, so that it is easily comprehensible that Wight (1980) misinterpreted this unit as being fluvial. In comparison with the modern tidal environment, unlike single mud drapes, mud couplets have not been objectively observed in the dunes cross-bedding of the intertidal zone of Mont Saint Michel Bay.

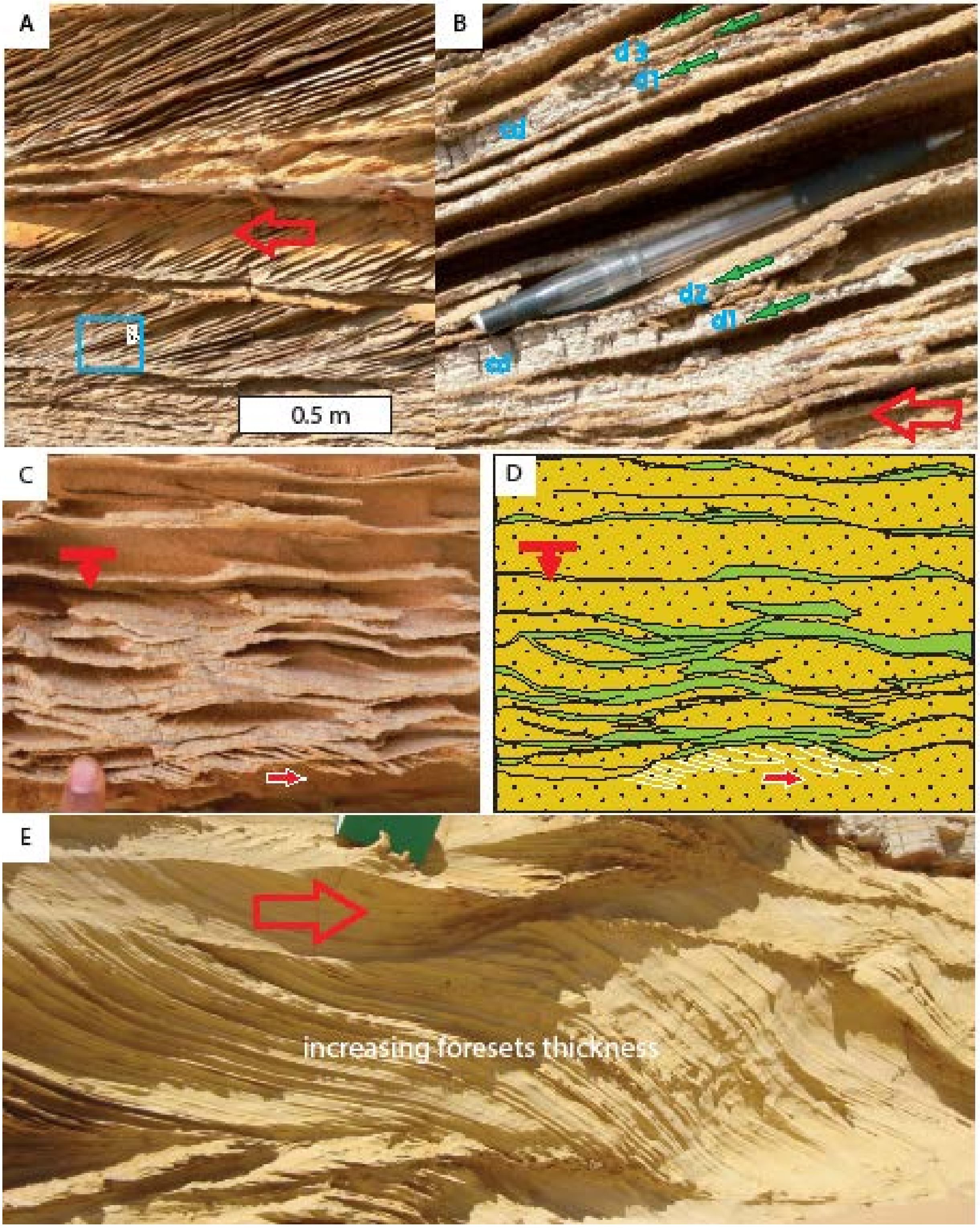


Fig. 5: Characteristics of mud drapes. A) Thickening up sequence of cross-sets with ubiquitous mud drapes of variable thickness; B) Close-up view [from (A), blue rectangle] illustrating that the abnormally thick drapes are a composite (cd) layer made of a number of simple drapes (d1–d3, green arrows); C) Cross-sectional view perpendicular to the dip of the cross-set. It shows that the drape thickness decreases from base to top of the set; D) Schematic drawing of (C); illustrating the associated ripples' cross-laminations (attributed to ebb current, small arrow) at the base of the set; E) Successive increase in the thickness of the bundled foresets (from left to right) coinciding with the increase in the tidal current strength.

4. 2. Bundle, bundle sequence and longer sedimentation cycles

The megaripples cross-bedding foresets can be regarded as the most conspicuous outcrop scale sedimentary features of the sandstones of the Sarir subunit. The sandy megaripple foresets between two mud drapes is called bundle (Boersma, 1969). The variations in the thickness and the habits of occurrence among the bundles allow recognizing tidal processes of different duration. Based on the periodicity and reoccurring manner of sandy foresets and their bounding layers (mud drape), two discernible modes of foresetting commonly exist: 1 - elementary tidal bundle (daily), 2 - tidal bundle sequence (fortnightly cycle). The former forms the basic sedimentation unit of the later. The position of the mud drapes and their nature has a striking role in the recognition and interpretation of these internal structures.

4.2.1. Tidal bundle (the daily cycles)

This section describes the characteristics of cross-sets of lower Sarir sandstone, where the sandy foreset or groups of successive foresets are bound by simple mud drapes (Fig. 6; the bundled foresets, sensu Boersma, 1969). The delineating layers of the sandy foresets are not always a typical mud drapes. Bounding layers here occur also as a ferruginous layer or as a narrow joint-like parting surface which appears to be the equivalent to the classic mud drapes. Such cases are thought to occur when the drape is altered to iron oxide, or respectively when there is little or no mud. Whatever, the unique organization of the sandy foresets and its bounding mud drapes (section 4.1.3) or the equivalent bounding surface, represents the sedimentation unit of the shortest duration, and it coincides to the tidal bundle (e.g. Fig. 6B). The tidal bundle in this sandstone, therefore, exhibits a range of set thicknesses and lengths (the frontal extent), which differ from one outcrop to another as in Figure (6). Taking into consideration that all bundles record the same duration (daily process), and based on their dominance in the outcrop, bundles have been split into densely spaced bundles (few mm long; Fig. 3) and sparsely spaced (few to several cm long; Fig. 6A-E) bundles.
Successive bundled foresets displaying characteristic hierarchical increase-decrease in the thickness (or number) of the enclosed foresets are well preserved in many outcrops. This regular increase (or decrease) is sometimes coinciding with progressive increase in the thickness of the individual sandy foreset (Fig. 6D). Notably, the hierarchical thickness change is exhibited solely by the sandy foresets, not by the bounding mud drapes (Fig. 6D and E). In contrary, the associated bounding mud drapes tend to become thinner.
The criteria of hierarchical thickness change are displayed at different scales (Figs. 3D, 5E, and 6), it is correlatable with the thickness of the hosting cross-set. As an example, in some thick sets (40-50 cm) one bundle counts 3 foreset laminae (~ 2 cm long). In these sets, the number of foreset laminae increases in a sequential manner up to more or less 12 successive sand laminae per bundle (~ 20 cm long; Fig. 6D). In such thick sequence of foresets, the classical mud drapes seem to be represented by joint-like bounding surfaces, with or without mud drape. In modern tidal environments, single dominant tidal event bundle of 15-25 cm thickness, are described (Terwindt, 1981; Nio and Yang, 1991) in modern mesotidal setting, in sets thinner than the one observed in the studied sequence. In this sandstone, bundled foresets within sets as thick as 40 cm is commonly associated with mud free, well sorted medium to coarse sand. Accordingly, it can be ruled out that in this cross-bedding, the larger the sets the thinner are the mud drapes. Moreover, the dip angle of such thick foresets (40-50 cm) is remarkably high (35- 40º; Fig. 6D and E). Comparably, in megaripples of modern macrotidal regime, a dip angle of 26-30° has been reported (Dalrymple et al., 1978; Elliott and Gardiner, 1981). The bounding surfaces or

mud drapes are commonly conformable and concordant with the sandy foreset laminae. Slightly discordant cases are observed.

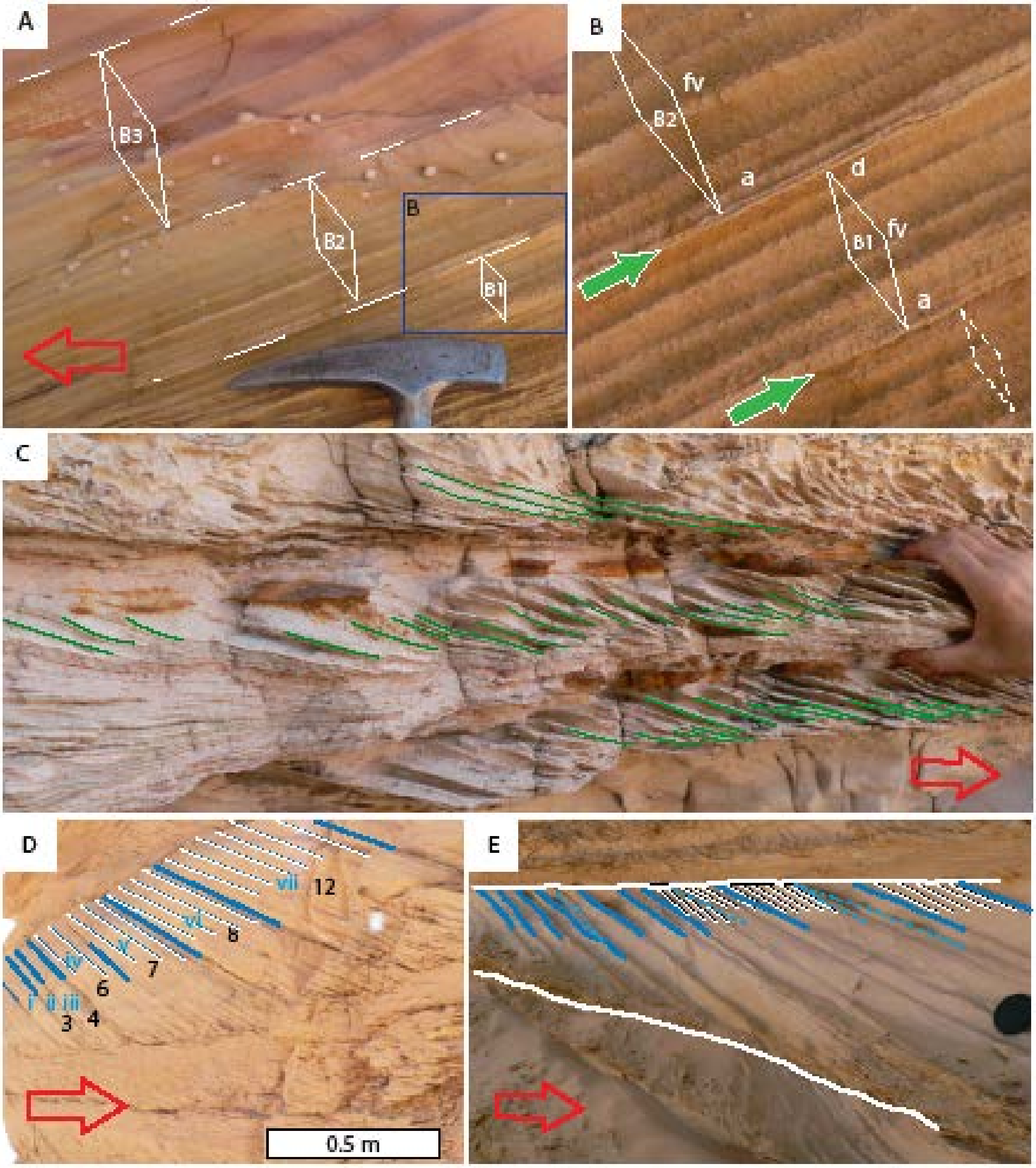


Fig. 6: Tidal bundles of different thicknesses. A) Foresets (B1, B2, B3) bundled between very thin simple mud drapes, usually associated with the medium- to coarse-grained cross-sets; B) Close-up view from (A) showing the record of the different phases of the daily tidal event: acceleration (a), full vortex (fv), and deceleration (d); C) sequence of bundles in fine sand, with drapes thicker than those in (A) above; D and E) Thick cross-sets with bundled foresets (blue lines) of high dip angle. Generally the thickness and number of bundled foresets increase hierarchically (white lines represent sandy foresets). In D) the classical mud drapes appear as a narrow bounding surface with little or no mud. Roman numbers indicate daily bundles and Arabic numbers the approximate number of foresets per bundle. In E) the boundaries of the bundles are sometimes slightly discordant (dashed line) with the foresets. This discordance is comparable to the subordinate current effect presented in Figure 15A.

4.2.2. Interpretation

The described styles of the foresetting (densely spaced or sparsely spaced) are similar, concerning the presence of a single mud drape bounding each case. Therefore, they are similar regarding formative processes, which in this case coincide to sedimentation during single dominant tide event (ebb or flood). The successive regular arrangements of sand-mud laminae are one of the essential criteria known for intertidal and subtidal sedimentary environment. The difference in the thickness and the number of sandy foresets enclosed between the two bounding layers (single or double drapes) is attributed to the sequential change in the tidal current strength (e.g. Homewood and Allen, 1981), which is first increasing and then decreasing during the same half-tidal cycle. This change varies from one location to another in the same estuary (Dalrymple and Choi, 2007). In the case of the bundled foresets bounded by narrow bounding surface (Fig. 6D) the bounding surface is probably equivalent to the diastems surface described by Boersma (1969), indicating erosion or no deposition. It is also comparable to the pause plane described by Allen and Narayan (1964) and Boersma and Terwindt (1981), which separates successive events of dominant tide.
The sequential increase in the number of bundled foresets in the same cross-set, and the associated increase in there thickness should reflect progressive increase in the current transport capacity, which in turn occur throughout a longer tidal cycle. The concordant bounding surface/ mud drape separating successive bundles is equivalent to a non-depositional pause plane of Boersma (1969). But when the bounding surface is slightly discordant it would then represent a gentle erosional surface. It is, in general, the erosion or the low mud content which explains the absence of the mud drape. In tidal environment such weak erosional surface is known to result due to the effect of the reversed weaker subordinate current. It is known as the reactivation surface (e.g. Klein, 1970; Dalrymple et al., 1984; Berné et al., 1988). Reactivation surfaces observed in the present case study is comparable to type B reactivation surface of De Mowbray and Visser (1984), which is also, expresses weak subordinate current.

4. 2. 3. Successions of elementary bundles (the fortnightly cycles)

This style of internal organization of foresetting is less commonly observed. It is represented by the existence of a similarly internally organized, regularly reoccurring sedimentation cycles. Based on the preservation condition, each cycle (cm-m scale; Figs. 7A-C and 8) consists of a succession of several elementary tidal bundles. One well exposed cycle is made up of a series of alternating bundles of sandy foresets-mud drapes (Fig. 7B). Generally, the sedimentation cycles are discernible at its central (expanded) part that is bounded before and after by densely interlaminated, relatively contracted parts. The bounding layer (parts of the cycle) is composed of fine sand-silt laminae separated by mud drapes. In the central part of the cycle, the sandy foreset-mud drapes (tidal bundles) interlamination is more distinguishable. But this is not the case in the frontal and posterior (finer grained and contracted) boundary layers. Nearly a number of nearly 28 or may be more sand-mud couplets can be counted per single sedimentation cycle. The length of apparently complete sedimentation cycle can be as small as 20 cm (Fig. 7). Cycles of 50 cm long are observed, many of which are of sigmoidal shape.
Remarkably, some outcrops provide sedimentation cycles that is organized in sequences. Such sequences of cycles are displaying hierarchical decrease-increase in the length (and generally size) of the successive cycles (Figs. 7A-B and 8A-B). Apart from their changeable size the cycles share common aspects of shape and internal structure. The densely layered muddy zone bounding each cycle is tangential meanwhile the central more sandy foresets are slightly steeper. Concerning overall geometry, sedimentation cycles represented by sigmoidal cross-

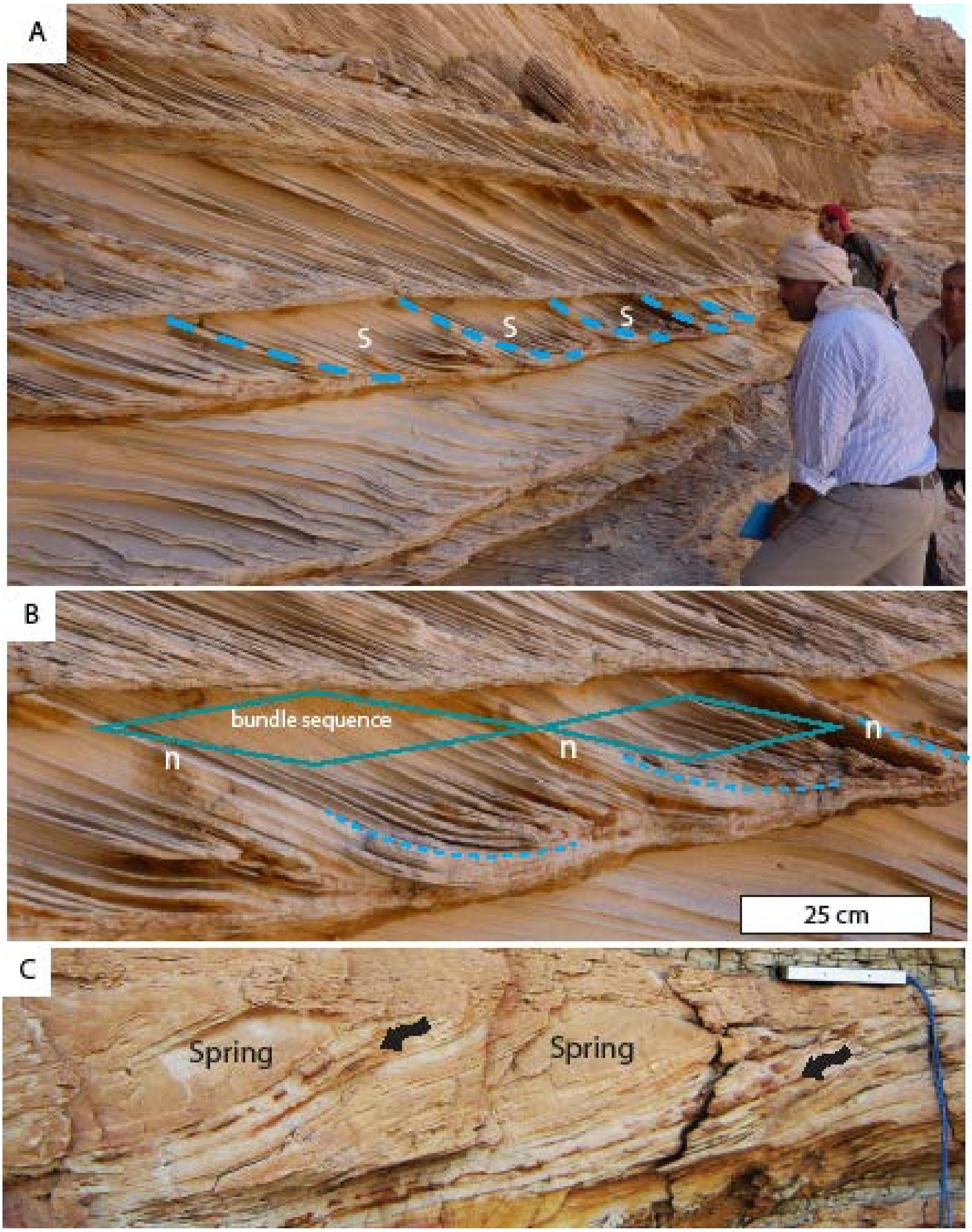


Fig. 7: Tidal cycles of neap–spring–neap (14 days) periods. A) Sequence of cross-sets showing sedimentation (neap–spring–neap) cycles; note the successive decrease in their length [dashed lines show cycle boundaries, (s) denotes spring]; B) close-up of (A) magnifying the neap–spring–neap succession of bundles. Each cycle consists of approximately 28 bundles. Closely spaced bundles of the neap (n) resemble the boundary of the cycle; C) Example of small neap–spring–neap cycles; the neap interval (arrows) is represented by several-millimetres-thick ferruginous layers, it also act like the boundary of the cycle.

bedding, as defined by (Mutti et al., 1985), are observed in many outcrops of Dur At Talah sandstone (Fig. 8). Similarly, these sigmoidal structures also exhibit very obvious contraction-expansion-contraction internal configuration. Generally, in this sigmoidal cross-bedding the successive sandy foresets are grouped to form sigmoids of variable scales (~20 cm, Fig. 7C, up to ~70 cm long and set thickness exceeds 1 m, Fig. 8), these differ from one location to the other. In all cases the sandy sigmoid is bounded (end with) by nearly conformable, laminated layer of very fine sand to mud, this layer is less than 1 to several cm thick. In the case of thicker and coarser sigmoids, medium to coarse sand, 70 cm long, the bounding layers are relatively very thin (few cm, Fig. 8C), and sometimes appear as brown, oxidized silty layer. The internal bundles composing the sigmoids could occasionally be distinguished. A single bundle may extend laterally up to 20 cm.

In many well preserved sedimentation cycles, the thickness differences of the sandy foreset to the adjacent mud (bounding) drape attain its highest at the center of the cycle. This criterion allowed, in some cycles, observation of regular sinusoidal variability among the thickness of the successive bundle. This systematic and periodic thickness alternation is preserved in a variable manner (Fig. 9), as successive thickening followed by thinning of the adjacent bundles of the same set.

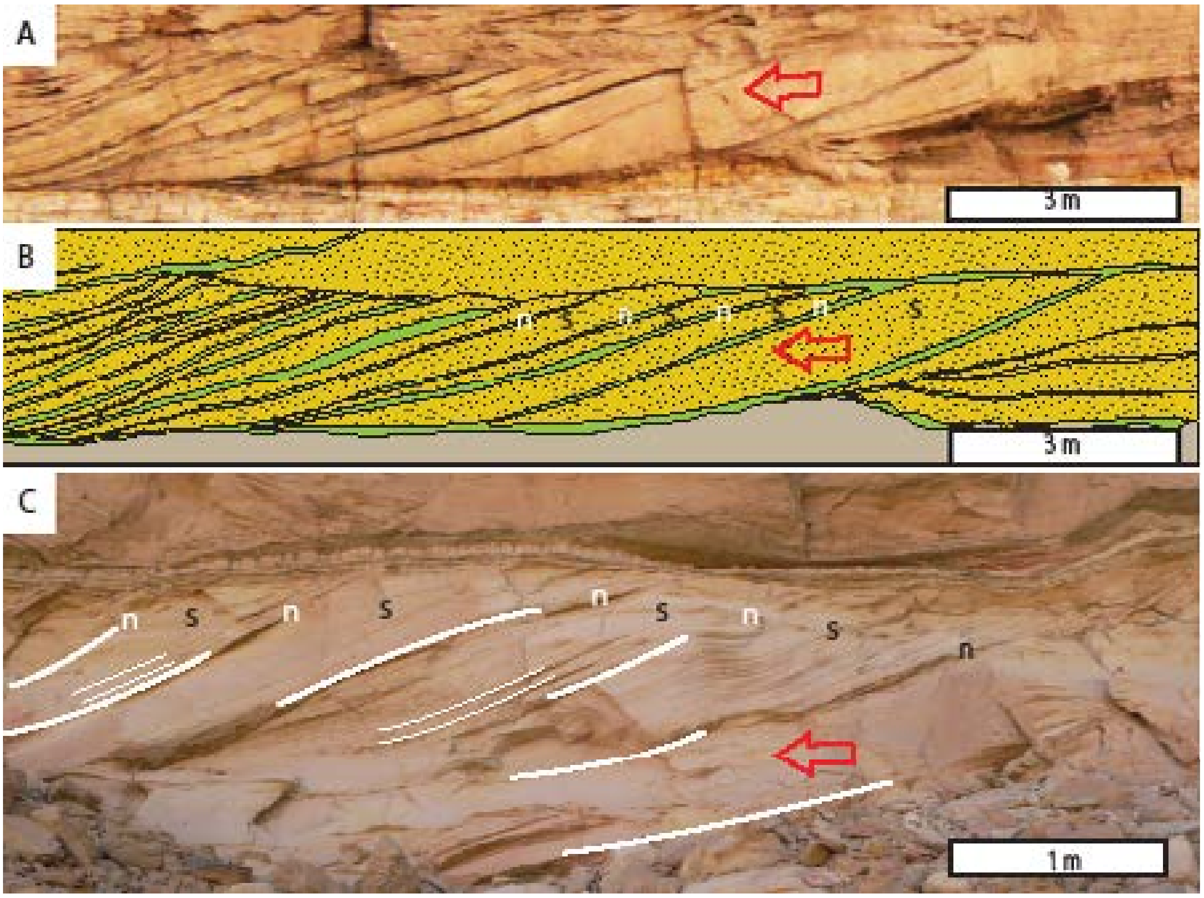


Fig. 8: Large sigmoidal tidal cycles. A) Sequence of sigmoids of sand foresets (spring) bounded by a concordant layer of mud (neap); B) Schematic representation of (A) illustrating spring (s) and neap (n); C) Large sigmoidal tidal cycle (deposits of spring tide; s), bounded with a relatively thin ferruginous silty mud layer, the neap (n). Thin lines mark the internal bundles, thick ones are the cycle’s boundary (n). The arrows indicate the dominant flow direction.

4.2.4 Interpretation

The internal structure of the sedimentation cycles is discernible at the central part of the cycle. One cycle consists of nearly 28 (small) bundles, or probably more (Fig. 9D). In these bundles, each couplet, sand foreset-mud lamina, represents one daily tidal event (particularly the domi-

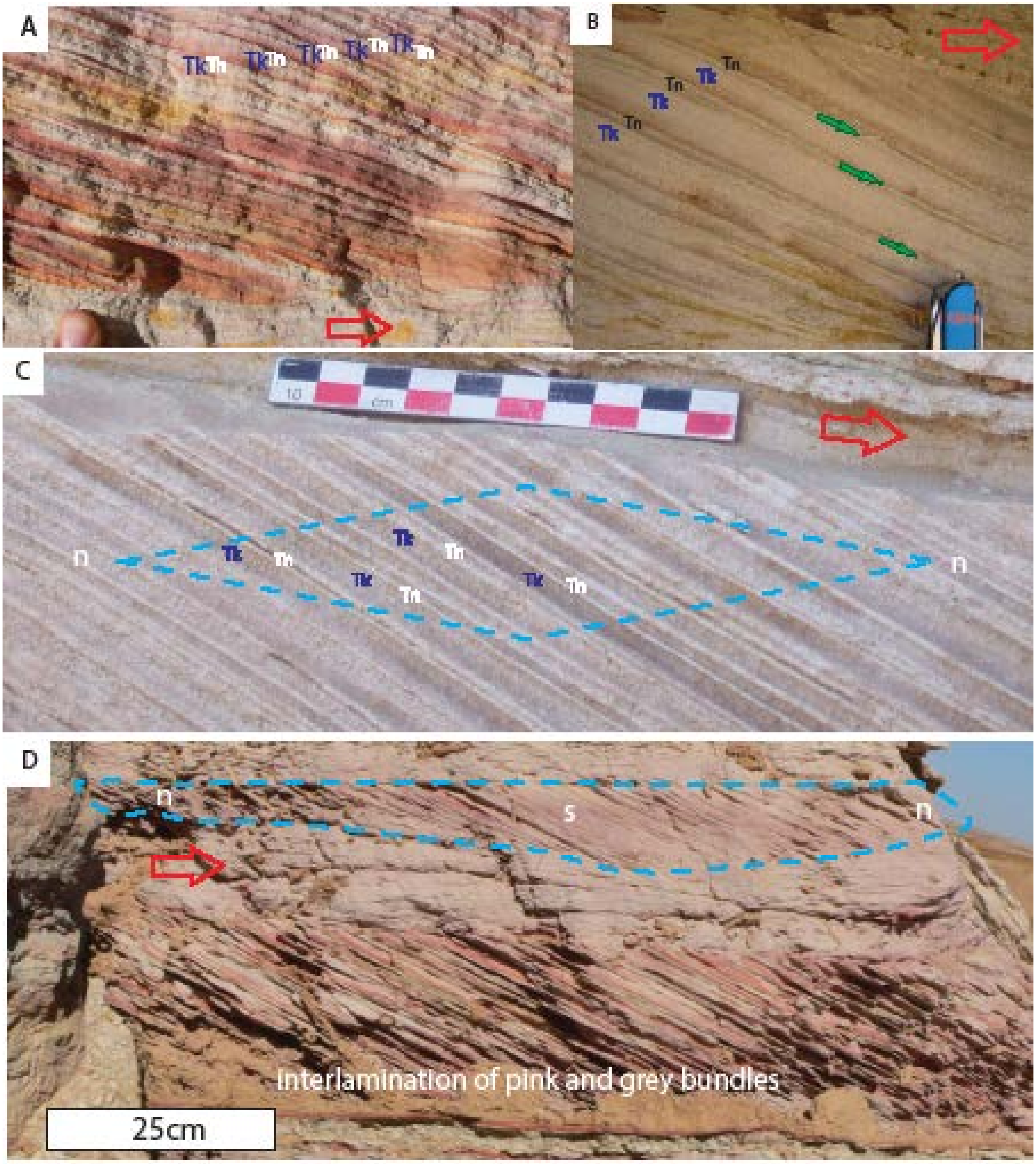


Fig. 9: The internal arrangement of the bundles inside some tidal cycles. A–C) Record of diurnal inequality of the tide in different outcrops, displayed as thickening (Tk) then thinning (Tn) among the successive bundles, D) showing the ubiquity of internal bundles in two cross-sets, probably points to the semidiurnal regime. In the lower set, the interlamination of pink and grey sandy foresets [also exhibited in photo (A)] can probably be attributed to the existence of thin (impervious) mud drapes in between. The neap (n)–spring (s) cycle is marked in C and D. The arrows indicate the dominant flow direction.

nant current). Therefore, in spite of the short frontal extent of some sedimentation cycles (~15 cm; Fig. 7B), one sedimentation cycle must represent a dominant tides of several days. The number of countable bundles (~28) per sedimentation cycle is, in tidal environment, known to deposit during semilunar tidal cycle (14 days; e.g. Allen and Homewood, 1984; De Boer and Visser, 1989; Kvale et al, 2006). The gradual expansion, stretching, and then contraction characterize the uninterrupted sedimentation cycles are in the modern tidal environment coincident with the neap-spring-neap tidal cycle (e.g. Allen and Friend, 1976; De Raaf and Boersma, 1971; Visser, 1980; Boersma and Terwindt, 1981; Dalrymple, 1992; Kvale, 2006).

During neap times, the foreset thickness is known to be minimum (millimetric bundles) because current velocity is at its weakest strength (e.g. Boersma and Terwindt, 1981; Lanier et al., 1993). This also explains the relatively thin (or even absent) bounding layers of some sedimentation cycles (Fig. 8D). Such thin boundary represents the cessation of the bedform migration during neap tides (e.g. Allen and Homewood, 1984; De Boer et al., 1989). The foresets stretching and there thickness increase in the central part of most sedimentation cycle is then certainly attributed to tidal events which occurred across spring period. During this period the bedforms migration is known to attain its maximum (e.g. Van den Berg, 1987; Harris et al., 1992; Dalrymple and Rhodes, 1995). The spring period is also responsible for the greater difference in thickness between the sandy foreset and the bounding drapes at the central part of the sedimentation cycles. At the begging and the end (frontal and posterior parts) of the cycle, the neap time results in much less sand transport and favor the deposition of bounding silt and mud packages.

The lateral arrangement of the sedimentation cycle as thin laminated muddy layers-central sandy foresets-back to thin laminated mud layers obviously coincides to the neap-spring-neap tidal cycle. This suggests that the sequential decrease in the length (and size) of successive sedimentation cycles (Figs. 7A-B) would represent a succession of semilunar (neap-spring-neap) cycles. Such succession then should reflect longer (semi annular/equinoxial) tidal cycle (solstice to equinox; e.g., Kvale, 2006; Tessier, 2010; Longhitano et al., 2012a). The same concept (solstice to equinox) is applicable to the sequential change in the thickness of large sigmoids (Fig. 8). Comparable model to the sequence of sigmoidal sedimentation cycles is described by Mutti et al. (1985) from the Eocene Ager Basin. Those sigmoids are interpreted as being deposited in tide dominated environment. therefore, as illustrated in Figure (8B and C), the sandy sigmoids represent the spring tides, and the thin bounding muddy layers represent neap episodes at which sand transport is much lower, and sometimes approaches to zero (e.g. Allen and Friend, 1976; Boersma and Terwindt, 1981). In the case of large sigmoidal cycles with thin bounding ferruginous layers (Fig. 8C), the bounding layers are thought to occur in situations where water velocity remains always above that required to allow settling of clay (e.g. Siegenthaler, 1982; De Mowbray and Visser, 1984), probably towards the open shelf. Thus only a thin veneer of mud could deposit, and later be oxidized as a result of the permeability differences between the mud and the adjacent sand.

Accordingly, sequence of large sigmoidal cycles (or tidal bundles) with no mud drapes is not impossible in tidal setting, and according to Harris et al. (1992) this is favored by deposition in subtidal channel. Notwithstanding the foregoing concerning fortnightly sigmoidal cycles, it is worth mentioning that the sigmoidal geometry has been described also for one daily tidal event (e.g. Kreisa and Moiola, 1986) from the Curtis Formation (USA). Thus, to avoid misinterpreting of the sedimentation rate, attention should be taken when determining whether the sigmoidal tidal structures are due to elementary tidal event or due to fortnightly cycle.

4. 3. Ripples associated to the megaripples

Asymmetrical and less commonly symmetrical ripple forms and ripple cross-laminations have been observed incorporated within these megaripple cross-bedding foresets. the ripples are concentrated either close to the foot of the megaripple or along its slipface. Based on the position of these ripples and to their orientation relative to the migration direction of the hosting megaripples, three types of ripples have been distinguished: 1- opposite current ripples, upwardly ascending on the megaripple foresets, 2- perpendicular current ripples, oriented normal to the direction of megaripples migration, and 3- oscillation ripples, with crests parallel to the dip of the megaripple lee side.

4. 3. 1. Opposite (current) ripples

These are small-scale current ripples (up to 2 cm high and 12 cm long), whose migration direction is opposite (~180°) to that of the hosting megaripples. They are climbing against the forward accreted sandy foresets (Fig. 10A, B and D). These reversed ripples have more commonly grown close to the toesets. Two or more successive ripples can be observed, but they rapidly die out and disappear after several centimeters of ascension onto the descending foreset laminae of the hosting megaripple. They are composed of sand grains that are slightly finer than those of the megaripples. Close examination revealed that many of these ripples are not placed directly onto the sandy foreset lamina of the megaripple, but are separated from it by millimetric-thick mud drapes (Fig. 10). Moreover, these ripples are also directly covered by a similar mud drapes. Ripples appear thus as enclosed between two mud drapes, separating them from the adjacent, under- and- overlaying, sandy foresets.

4.3.2. Interpretation

the depositional scenario of the opposite ripples, considering their arrangement and position inside the set, becomes easy to reconstruct (Fig. 10C and E), and it can only be generated by changing currents, marked by reversing of direction and intermittent pauses (Boersma and Terwindt, 1981; Allen and Homewood, 1984) which exclusively occur only in the tidal environment. The scenario is as follows: (1) sandy foresets are produced and reflect the migration of a megaripple (strong unidirectional water stream; dominant current), (2) mud settles and drapes the last foreset (still stand; slack water), (3) small ripples migrate in the opposite direction onto the foreset slope (reversed and weaker unidirectional water stream; subordinate current) and (4) mud settles and drapes the ripples (still stand; slack water). As a matter of comparison, oppositely climbing and draped ripples are interpreted by Smith (1988) as being deposited in subtidal environment.

4. 3. 3. Perpendicular ripples

Another style of current ripples has been observed in close association with megaripples foresets. This time the ripples (10-15 cm of wavelength; up to 3 cm in amplitude) are moving horizontally along the bottomsets, perpendicular to the dip of the prograding foresets of the megaripple (Fig. 11A and B). These current ripples exist as single and as train of continuous ripples. Succession of perpendicular ripples displaying hierarchical decrease in the ripple size is preserved occasionally (Fig. 11A). Sometimes only the internal laminations of the ripple are preserved and are associated with well-preserved mud drapes. The latter case is illustrated in Figure (5C and D).

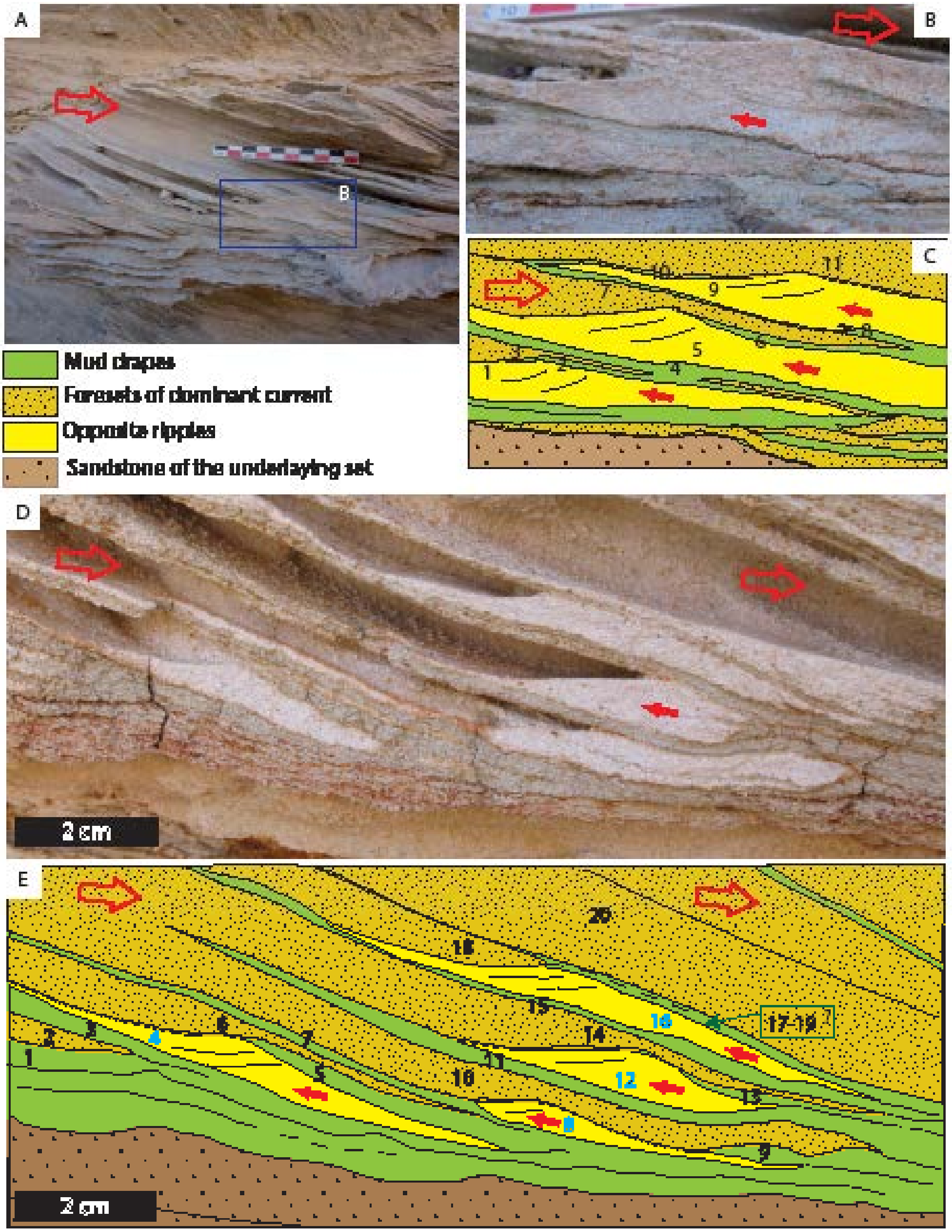


Fig. 10: Examples of opposite ripples produced by the subordinate current against the foresets; A) The location of the opposite ripples at the foot of the set; B) Detailed view of photo (A); C) Hand-drawn interpretation of (B) showing the alternation of sandy foresets (dominant current; large arrows) with opposite ripples (subordinate current, small arrows), separated by mud drapes. The numbers (1–11) indicate the succession of the recurring events (dominant current, slack period, and opposite subordinate currents); D and E) A different example of the opposite ripples and its interpretation. The succession of events [in (E)] is numbered 1 to 20. Mud drapes

(17–19) are superposed; a case occurs in which the sandy foreset (18) is not long enough or is eroded by the subordinate current.

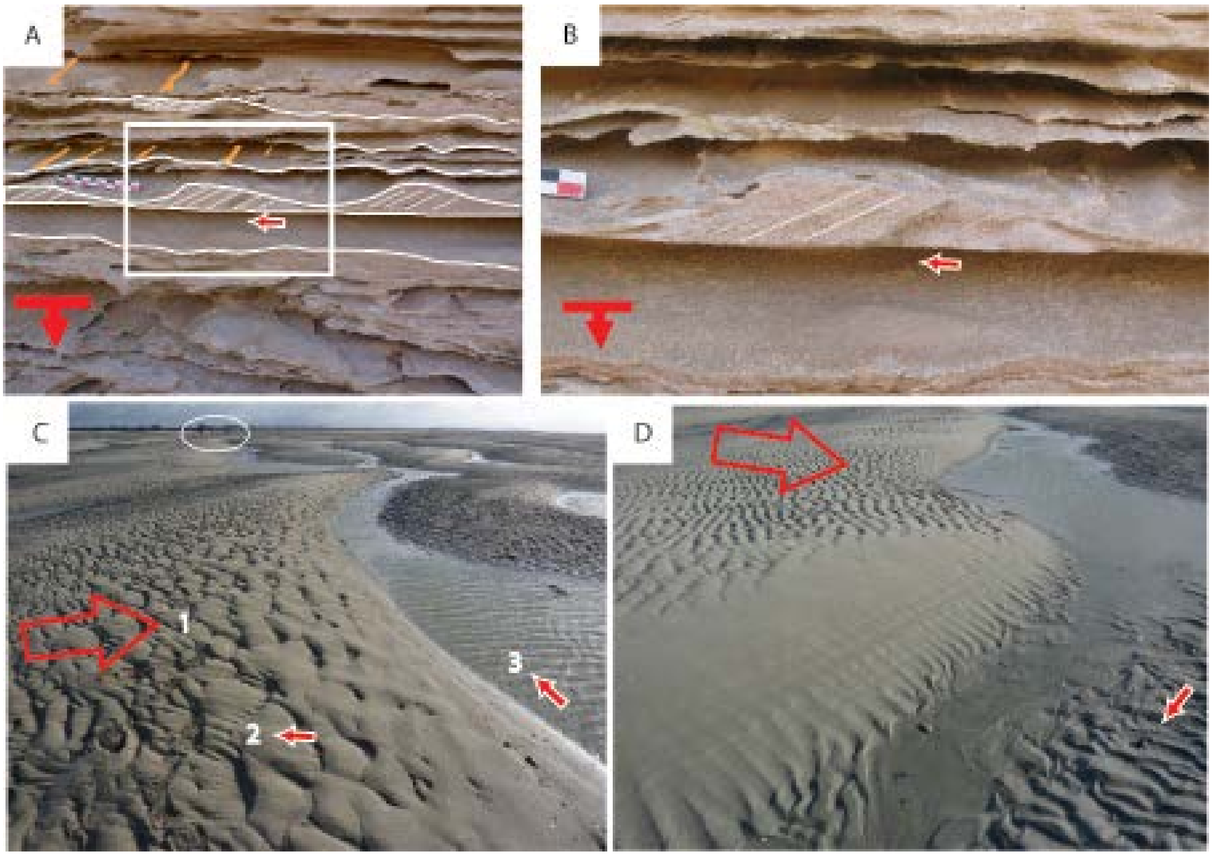


Fig. 11: Perpendicular current ripples. A) Train of ripples developed normal to the direction of foresets; B) Detailed view from (A); the ripples' lamination confirms its direction (small arrow) of migration perpendicular to that of the hosting bedform. The composite arrow in (A) and (B) indicates the strike and dip of the cross-set; C and D) Modern analogue of perpendicular ripples: examples from the Bay of Mont Saint Michel, France). (C) Shows a view of the dunes field with the ebb stream travelling perpendicular to the advancing dune (men inside the circle for the scale). The numbers indicate the sequence of events (1, dominant current; 2, subordinate current; 3, emergence runoff); D) Perpendicular ripples in the trough of the dune, and reshaped wave ripples on the lee side.

4.3.4. Interpretation

The association pattern of the perpendicular ripples and the megaripples hosting them has definitely been generated by two successive currents which differed in their orientations (perpendicular) and in their strengths (one strong, one weak). Successive foresets downlap those ripples, suggest recurrent alternation of these two (time separated) currents. This configuration is typical of water stream that are draining in between large bedforms once the main stream that had generated those bedforms has stopped. This scenario is coinciding with the late stages of ebb current (Klein, 1970, 1977). It has been, for example, well-illustrated by Homewood and Allen (1981) from the Swiss marine molasses. Draining ripples are in modern tidal environment known to occur during the ebb phase as a result of current runoff between the megaripples, which occur during the emergence period prior. The hierarchical decrease described for the size of the perpendicular ripples (Fig. 11A) is probably attributed to the waning of the current strength that generated these trains of ripples.

4. 3. 5- Oscillation ripples

This kind of ripple is preserved onto the surface of foresets (the slipface of the megaripple) as low relief symmetrical undulations (few mm up to 1 cm high, 4-8 cm wave length; Fig. 12). The crests of these typical wave ripples are commonly narrow, straight, and are nearly equally spaced.

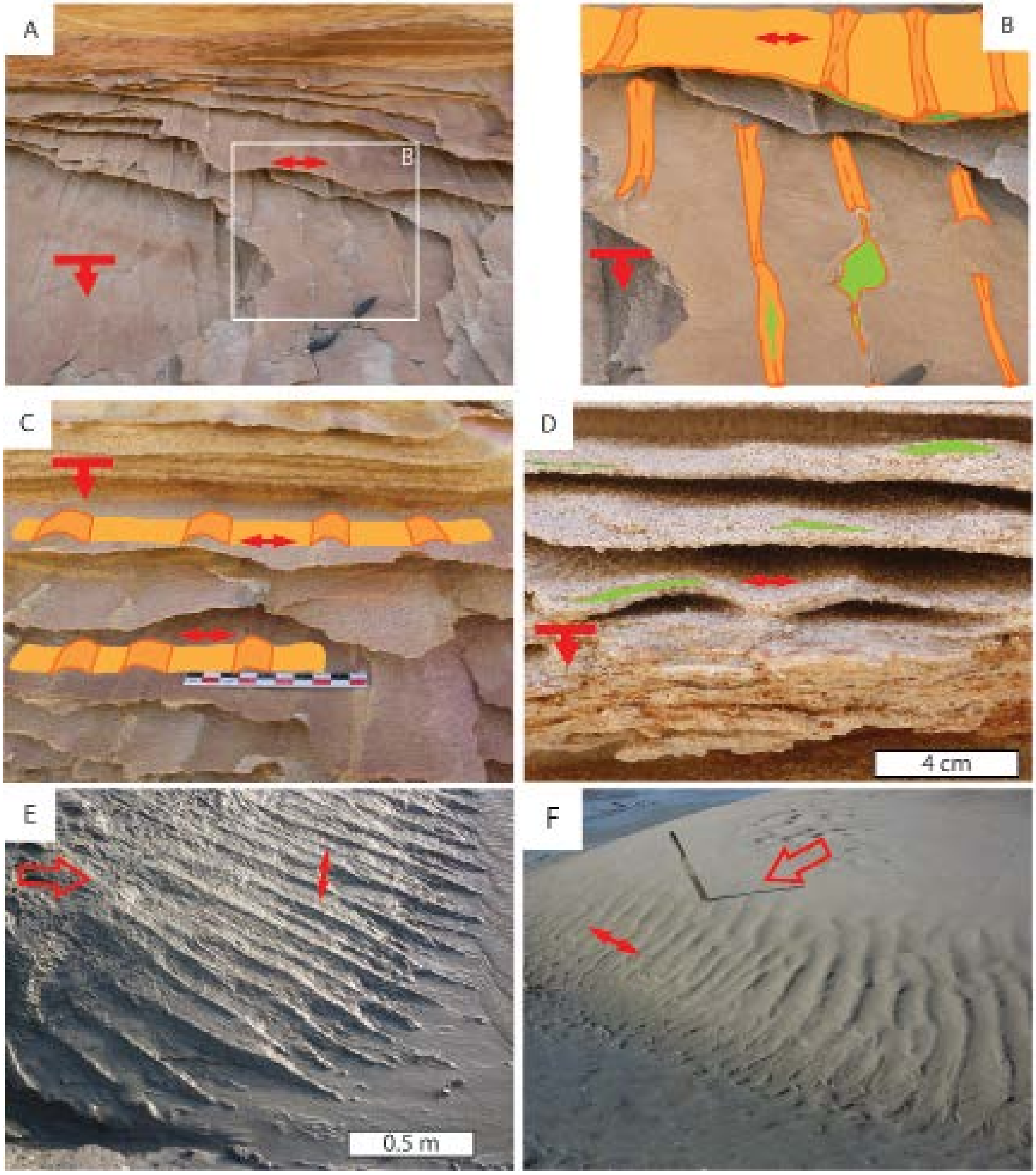


Fig. 12: Wave ripples developed on the dunes' lee side. A) General view of partly removed wave ripples with their crest parallel to the dip (toward the reader; composite arrow) of the megaripple foresets; B) Close view from (A) illustrating wave ripples inside the rectangle (B); note the associated mud drapes (in green; the double arrow indicates the direction of the wave oscillation); C) Details of wave ripples showing their recurrences on each foreset; D) Typical wave ripple morphology associated with mud drapes; E and F) Modern wave ripples (Mont Saint Michel Bay) propagate perpendicular to the direction of dune migration. A close similarity can be noticed between (E) and (A and B).

Sometimes they are partly or completely eroded, so that often only the crest line of the ripple is remaining, giving a succession of parallel fluting relief on the lee side of megaripples. Like the aforementioned types of ripples, these are also embedded inside the cross-sets, superimposed onto the foresets. In fact, they appear as modifications to the lee side, but are sometimes separated by thin film of mud (Fig. 12B and D). Remarkably, the crest lines of these undulations are strictly parallel to the dip of the megaripples lee side, and they particularly extended from the base up to the top of the foresets of the parent megaripple (Fig. 12A-C). This type of ripples, as a matter of fact, is occasionally found in association with the other perpendicular, current ripples.

4.3.6. Interpretation

Perpendicular ripples of both symmetrical and asymmetrical type is reported in subtidal and intertidal as well as other environments (e.g. Klein, 1977; Reineck and Singh, 1980). Different ripples are known to occur due to small fluctuations in current velocity (Jopling and Walker, 1968). Wave ripples are due to oscillations generated by wind at the sediment water interface, above the wave base line. In the studied sandstone, the coexistence of the oscillation (wave) ripples with perpendicular current ripples, and their association with mud drapes and, especially, with tidal bundles and bundle sequence, aptly provide an evidence of their occurrences within tide rather than wave dominated environment. Comparing the oscillation ripples in Sarir Unit with the similar wave generated ripples in modern tidal environments (Fig. 12E and F; the Bay of Mont Saint Michel, France) suggests that these ripples are produced by wind generated waves, probably during the short times of tide stagnation (slack water). As the crestline of these undulations are parallel to the dip of the foresets, it means that the generating wind was normal to the direction of megaripples progradation (i. e. probably normal to the coastline). These ripples are then generated during the pause in the megaripples growth and before the ebb current runoff started. Being some of these ripples are partly (modified) or completely eroded (Fig. 11D), is then attributed to the next ebb current following their formation.

5. Other tidal structure: Directional bimodality and vertical bundles

The cross-bedded sandstone of the studied interval is commonly accumulated as small sequences (3-8 m thick). Generally, at any of these sequences the cross-bedding records unidirectional palaeocurrents dominantly oriented to the North (ebb) with dispersion of about 40° (Abouessa et al., 2012). Southerly oriented cross-sets (flood) are presented in some sequences, observed at the lower part of the studied interval. Moreover, such as directional bimodality (De Raaf and Boersma, 1971) or herringbone cross stratification (Klein 1970; Boersma and Terwindt 1981; Van den Berg, 2007) are also locally well preserved. The oppositely oriented palaeocurrents are preserved both as large cross-bedding and as small cross laminations (Fig. 13A-C). There are outcrops where the oppositely oriented sets are associated with draped and bundled foresets. Oppositely oriented cross-bedding are especially exhibited, locally, at the boundary between two superposed sequences (Fig. 13A). Reversed palaeocurrents in cross lamination are particularly recorded in the better (horizontally) stratified sandstones which appear to represent the distal expression of the cross-bedded sequences. The ripple laminations displaying reversed palaeocurrents are of some cm long and 1-2 cm thick (Fig. 13B), and are observed within aggradational sequences. These sequences are made of beds of fine cross-laminated sandstone intercalated with thinly laminated beds of mud (Fig. 2). Laterally, this sand-mud alternating sequence displays regularly organized reoccurring vertical packages. Occasionally, one package (20-25 cm thick; Fig. 13D and E) counts nearly 28 couplets of sand-mud interlamination

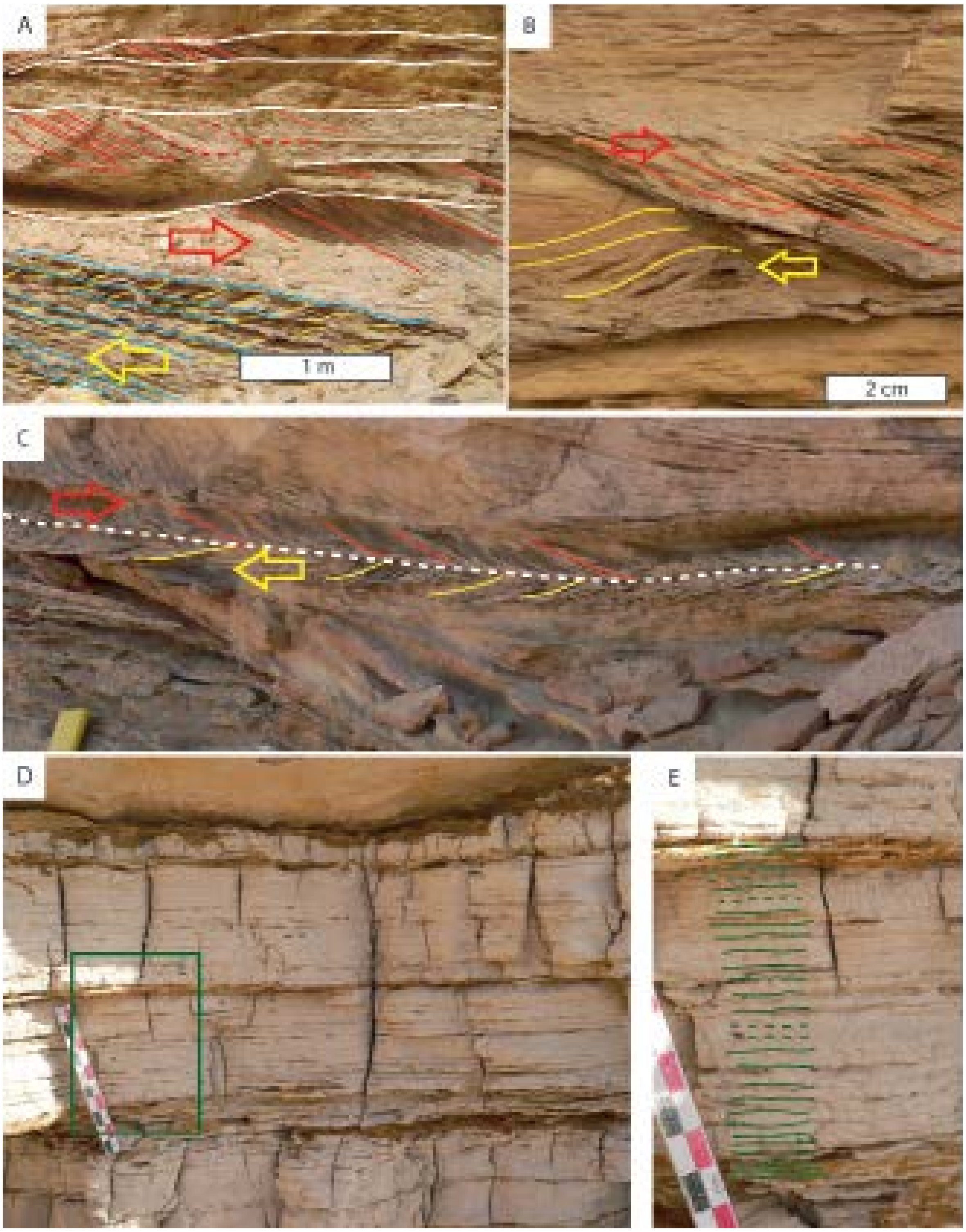


Fig. 13: Directional bimodality and vertical bundles. A) Two superposed packages of cross-bedding sets exhibiting opposite palaeocurrents (arrows); B) Oppositely oriented cross-laminations; C) Herringbone cross-bedding; D) Succession of beds show neap–spring–neap vertical cycles; E) Close-up view of (D) with an estimation of the number of sand–mud couplets (~ 28) in one cycle.

and is bounded by thin (several mm to few cm) layer of brown, ferruginous silt.

5.1. Interpretation

In sedimentary environment regularly opposite oriented foresetting is a reasonable evidence for tidal environment. Ebb and flood superposed foresetting is for example described by Houbolt (1968), Terwindt (1971) and others from southern bights of the North Sea. Dalrymple (1984) described depositional ebb and flood pathways from restricted zones in the macrotidal Bay of Fundy (Canada). From Arcachon Lagoon (France), Féniès and Faugéres (1998) have presented two adjacent channel pathways which simultaneously produce sandy bedforms that record reversed tides. Therefore, as a matter of comparison, herringbone cross-bedding and the chevron-like cross laminations preserved in the studied sandstone (Fig. 13) add a supplementary evidence of tidal dynamics. The associations of the bidirectional cross stratification with mud drapes and sometimes with bundled foresets is an additional unmistakable proof of tidal sedimentation environment of the studied interval. The 28 laterally accreted tidal bundles (section 4.2) reoccurred in the course of megaripples migration should more or less coincide with the nearly 28 vertically accreted, bundled cycles. The group of 28 sand-mud couplet is reflecting deposition around the spring times, meanwhile the thin ferruginous silty layer, reflects the weak currents around the neap period.

6. Discussion

6. 1. Implication of the mud drapes.

Mud drapes in the sandstones of the lower Sarir Unit occur in variable habits, concerning their position within the cross-set. The mode of the mud drapes existence proven to be significant in recognizing tidal dynamics, tidal bathymetry (subtidal-intertidal), and are especially useful in differentiating tidal cyclicity of different duration. In the studied cross-sets, exceptionally, the record of some of the short duration cycle (the daily tidal bundle) is larger than the record of the longer duration (fortnightly) cycle. In such exceptional cases, the mode of occurrences the mud drape played an essential rule in distinguishing different duration tidal cycles. One event tidal cycle, regardless of its thickness (maximum observed is 20 cm) is delineated by simple mud drapes. The longer semilunar (several events, 14 days cycles; minimum thickness observed is 10 cm) is delineated by a composite (condensed) layer of mud and silt rather than individual drapes of mud.

In the case of the bundled foresets delineated by the narrow bounding surface (with or without mud), the bounding surface in such case resembles the diastems surface described by Boersma (1969), which is assigned to represent the flow secession period culminating the ebb or the flood. This surface here imitates the mud drapes but with very little or no mud. The low mud conditions are in general favored more the subtidal than the intertidal setting (Dalrymple, 1990; Dalrymple and Rhodes, 1995; Van den berg and Boersma, 2007). Moreover, the sets where the mud drapes are absent or very thin, relative to the adjacent sandy foresets, are associated with larger cross-bedding. The latter is also known more for the subtidal water depth, and are coinciding with high spring times (Harris et al., 1992).

In modern subtidal environments cross-bedded sets with absent mud drapes is reported from Arcachon Lagoon (France; Féniès and Faugéres, 1998). This situation is probably concomitant with the lack of mud in the system. Accordingly, it can be conclusively confirmed that the absence of classical mud drape does not definitely exclude tidal origin of the cross-bedded sandstone. For example, in most cross-beds from one of the largest megaripples field in the macrotidal Bay of Mont Saint Michel, such structures are weakly developed or totally absent. Compared to the documented modern and ancient tidal deposits, mud drapes can be considered as ubiquitous in many places of this sandstone. The ubiquity of mud drapes would, logically, be used as another witness for deposition in subtidal zone. As it would be a witness also for semidiurnal regime. Theoretically, four drapes per day will be deposited in semidiurnal rather than only two in the diurnal regime. And so similarly, in subtidal setting the chance of mud drapes settling (or its equivalent surface) is commonly assumed to be twice than that of the intertidal counterpart. The mud double drapes in particular should be expected more in subtidal setting, especially of the semidiurnal regime (two tidal cycles per day; e.g. Visser, 1980; Smith, 1988; Ashley, 1990; Shanley et al., 1992). Again, in the studied cross-bedded sandstone tidal sedimentary structures are clear and evident, though subordinate current (reversed) sand lamina are not as common as the dominant current structures. Being the subordinate current laminae are so thin (Figs. 4 and 7), they then provide more opportunity to distinguish mud double drapes. The obvious examples of double drapes (Fig. 5) illustrate that both drapes are parallel, inclined and extend up to the set top, rather than horizontal. Thus, suggesting possible clue that the whole megaripple was submerged during both the flood and the ebb, which might greatly exclude the possibility of the deposition of such double drapes in intertidal setting. Because, in the intertidal setting double drapes occurrences should normally be local, restricted only to small water pools inside the intertidal megaripple field (Féniès et al., 1999). These pools are normally submerged during the flood, and probably retain some water during the ebb. Thus, if both drapes are deposited and preserved (survived the erosion during ebbing current) they would then be more or less horizontal and slightly curved, rather than oblique as in the studied cross-sets.

The subtidal situation inferred from the preservation style of such coupled drapes is supported by the cases where mud drapes are completely draping the sandy foresets from the base to top (e.g. Fig. 4C-D) of the set. In such cases, it can also be deduced that the thick drapes are virtually a double drape, with the subordinate lamina missing. The later conditions made the mud of the subordinate current slack settled directly onto the mud of the dominant current slack. This aspect becomes more persuasive, given the thought that the preservation potential is more suitable in subtidal zone (Nio and Yang, 1991). A supplementary evidence of deposition in subtidal setting comes from the large thickness of some bundled sigmoidal cross-bedding (Fig. 8A-C), which thickness (up to or more than 1 m) gives an indication of the minimal depth of water generating them (Ashley, 1990). Water depth required to produce thick bedforms should be several orders of magnitude more than their thickness (Ashley, 1990; Dalrymple and Rhodes, 1995; Harris, 2002). Furthermore, the mud couplets preserved in this sandstone appear to be associated more with thicker and sandier sets. Such aspect more probably implies deposition in subtidal than intertidal bathymetry (e.g. Klein, 1971; Dalrymple and Rhodes, 1995).

The paired drapes in the studied sandstones are also closely comparable with those described by De Mowbray& Visser (1984), from the subtidal zone of Oosterschelde Estuary (Netherlands). And in ancient deposits, it is comparable to the mud couplet described by Smith (1988) from the Early Cretaceous Mcmurray formation (Canada). The latter is also considered the mud couplets as an indicator of tidal processes in a subtidal setting. Back to the studied sandstone, the coexistence of both single and paired mud drapes (sometimes in the same set), besides the close comparison with both modern and ancient analogues, make it possible to conclude that this sandstone had been deposited in subtidal setting.

6. 2. Implications of the bundle and the bundle sequence

As the shortest duration sedimentation unit in the studied sandstone, the tidal bundle occurs here in a wide range of scales. It constitutes the elementary unit of the longer fortnightly cycles, which also exists in a range of scales. The two situations are in general a product of tidal current untidiness (e.g. Klein, 1970; Kvale et al., 2006) through time and space. Normally the size of the tidal bundle is much smaller than that of the fortnightly cycle. But in these cross-sets exceptions exist. The maximum length of the (half daily) bundle is 20 cm, and the minimum

length of complete fortnightly cycle observed is 15 cm. Both daily bundle and fortnightly cycle are sometimes similar in terms of morphology and possibly general structure. The similarity of both units came from the overall similarity of their formative processes. The aspect of contraction-expansion-contraction shown by the fortnightly sedimentation cycle (Fig. 7B) is comparable in the structure of the elementary tidal bundle to the acceleration-full vortex-deceleration of the one tide (Fig. 6B). Therefore, these two units of different time scale might, in certain depositional circumstances, be very similar. Thus, the distinction between them in the field is not only their shape and size, but mainly the nature of the bounding layer. The occurrence habit of the mud drape remains essential for interpreting the two kinds of structures.
Another important aspects of the tidal current unsteadiness recorded in this sandstone is the diurnal inequality displayed by successive tidal bundles. It is known only for semidiurnal regime (e. g., Visser, 1980; De Boer and Visser, 1984; Tessier, 1998; Kvale et al., 2006). This aspect implies existence of two complete tidal cycles each 24 hours, and that one of the two dominant tides is stronger than the other. This seldom aspect is aptly recorded in the studied sandstone. The case is displayed as the regularly reoccurring sinusoidal pattern, which is represented as an alternation of thickening-thinning bundles (Fig. 9), within the record of fortnightly cycle. The thicking-thining successive pattern is in recent tidal sediments, comparable to the variations in the thickness of the successive bundles, reported by Visser (1980) and by Nio and Yang (1991) in the sandy subtidal bedforms. Such systematic alternation of thickness represents the increase in tidal range from the first to the next tidal cycles. Such small increase in the tidal range is coinciding to significant increase in the transport capacity (De Boer et al., 1989; Kvale and Archer, 1991), and thus of the foreset thickness.
In ancient (Early Cretaceous) environment, sedimentation cycles-cross-sets involving mud couplets and lateral sinusoidal changes in the thickness of associated foresets are reported in (Smith, 1988), assigned to subtidal semidiurnal regime. The presence in the studied sandstone, of large bedforms with tidally organized bundles is an additional indicator that indirectly points to semidiurnal regime. Possible explanation is that in the diurnal regime, the current velocity is rarely strong enough to produce large-scale megaripples with bundled cycles (De Boer et al., 1989). Semidiurnal regime deduced from the internal structures of the studied megaripples is confirmed by the number of bundles per the neap-spring-neap (14 days) cycle. In the studied sandstone up to 28 accreted bundles have been counted between two successive neaps (14 days), such number is exclusively known for semidiurnal regime (e. g., De Boer et al., 1989; Tessier, 1998; Staub et al, 2000; Tape et al., 2003). This aspect has been confirmed by the number of the sand-mud couplets per vertical cycle (Fig. 13 D and E).

6. 3. Implications of the opposite and the perpendicular ripples

The current ripples oppositely ascending on the toe of the descending sandy foresets is in also known for unidirectional (fluvial) flow, it occurs just in front of the lee side of the advancing megaripples (Allen and Narayan, 1964; Boersma et al.1968). In fluvial setting (or any other type of unidirectional and permanent flow) oppositely oriented small ripples form downstream of the megaripple slipface due to the existence of a current backflow. Then the ripples are progressively downlaped by the foresets of the migrating megaripple. Figure (14) illustrates examples of fluvial back flow ripples from modern and ancient river environments. Ripples in these cases are downlaped and interwoven with the river current foresets, they never climb ascending on the megaripple foresets. Differently, in the studied sandstone, opposite ripples associated with cross-bedding sets show clear standardized configuration with foreset lamina as, sandy foreset-mud drape-opposite ripple-mud drape, and so on (Fig. 10C and E) and they climb ascending on the megaripple foresets. The contact of the megaripple foresets with

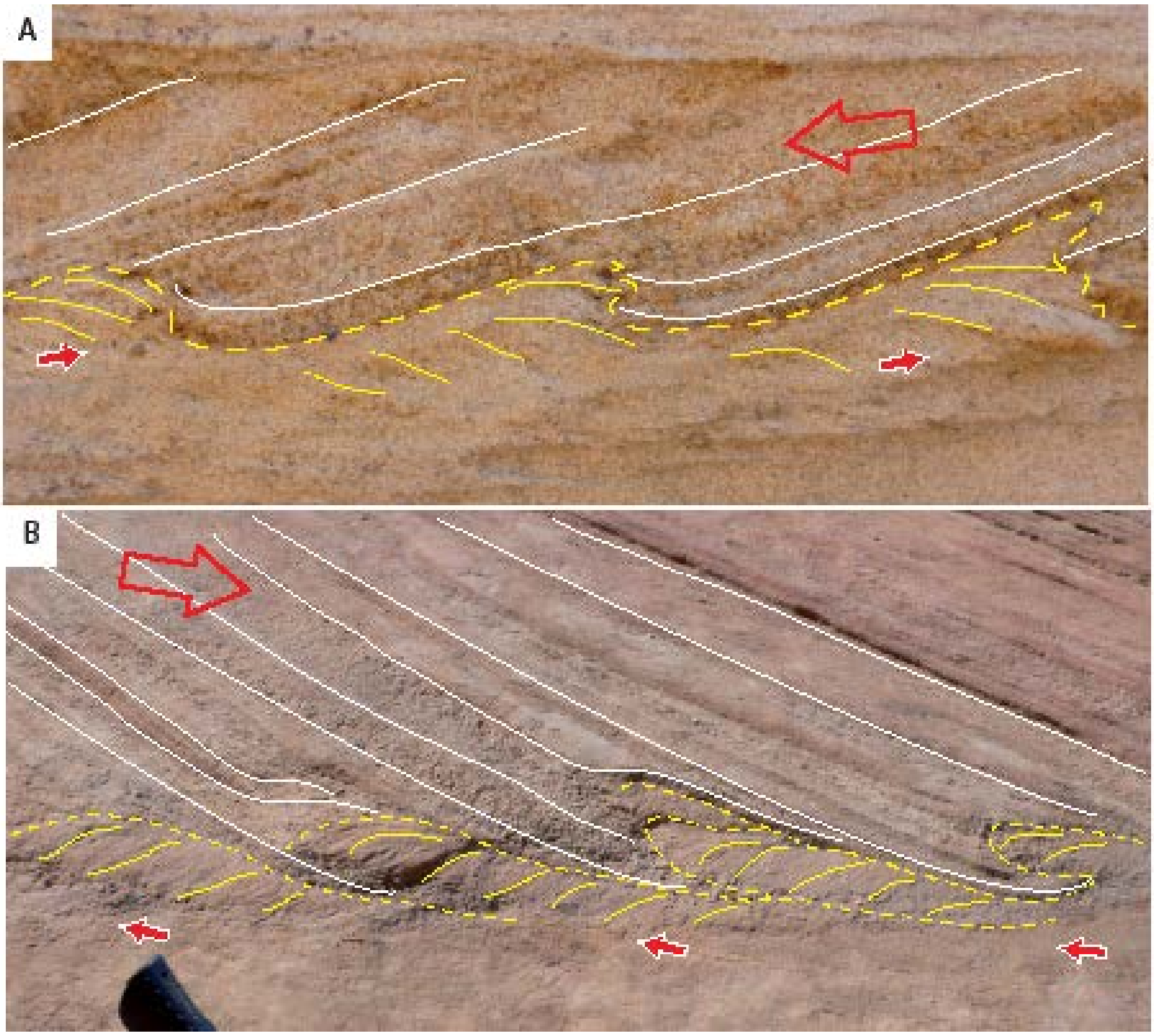


Fig. 14: Backflow ripples in fluvial sand dunes. A) Recent cross-set from Chari river (Chad); the ripples are entangled with the descending foresets; B) Ancient example (Palaeozoic, Jordan); backflow ripples are downlapped by the foresets, (courtesy of J.-F. Ghienne). Note the absence of mud drapes in both cases. The large arrow indicates the main flow and the small arrows for the backflow.

the reversed ripples is thus quite different from the contact in fluvial back flow ripple. Unlike this mud drape-enclosed subordinate current ripple found in this sandstone, the backflow ripple should, by virtue, be directly dewlapped and occasionally interwoven with the descending foresets. Because, in the case of fluvial current back flow, both the foresets and the attached ripples are produced nearly simultaneously, one growing opposite against the other, with no depositional pause, and therefore no mud drapes. In modern tidal environment, reversed (180°) ripples are witnessed in the outer zone of sandy intertidal flat of macrotidal Bay of Mont Saint Michel. They develop during the subordinate current on the lee and also up to the stoss sides of the oppositely migrating megaripples (Fig. 15) of the dominant current.

The perpendicular ripples hosted by this sandstone cross-set are of two forms, symmetrical and asymmetrical. The two forms, in many cases exist together and share some common characteristics, suggesting that they might be subjected to similar process, at certain stage of their development. The perpendicular (current) ripples propagate in one direction along the strike of the advancing megaripple. These ripples are, in modern environment, imitate (Fig. 11C and D) the one generated commonly at the sea side of the intertidal zone, of the Mont Saint Michel Macrotidal Bay. In the Bay these ripples are observed occurring as a result of the current runoff during the current ebbing phases, and are mostly normal to the megaripple direction of migration. Generally, the suitable moment for them to start developing is when the crest of megaripples begins to emerge. At this moment, the water seeks their path in front of megaripple (Fig. 11D). Back to the studied sandstone, where trains of successive perpendicular ripples show hierarchical decrease in the size of these ripples (Fig. 11A). The decrease in this case might reflect the waning of the ebbing current strength that should coincide with the late stage of the ebb event, which normally occurs in the sea side of intertidal zone. This inference leads to conclude that ebb was the subordinate current at least in this configuration.

The preservation of the perpendicular current ripples close to the foot of the megaripple does not exclude their generation under submergence (subtidal) condition. These current ripples reshape the parent megaripple leeside. This proves that the migration of the hosting megaripple has stopped, what would occur in both inter-and-subtidal zones. In the other hand, these current ripples would probably not be able to stand the next avalanching foresets if they grow perpendicular on the oblique slipface, and would more probably be removed (rather than dewlapped). This explains their preferential preservation in the foot of the megaripple. The later situation is also not dependent on whether these ripples occur in inter-or-subtidal zones. To summarize, perpendicular current ripples associated with cross-bed set in a circumstances similar to one occurred in lower Sarir Unit sandstone of Dur At Talah, is a very useful indicator of the presence of two regularly reoccurring currents (separated with short pause) of different directions and magnitude and thus it provide a strong evidence of tidal dynamics. These ripples have more chance to be preserved in the sea side of the intertidal zone, and in the shallow subtidal zone. They could be useful also to determine the ebb direction in ancient sediments.

The symmetrical ripples (Fig. 12A-D) have occurred due to wave oscillation, probably during stagnation times, while the parent megaripples under submerged. These ripples extended from base to the top of the foresets, meaning that they were formed under water deeper than that produced these megaripples. In line with this, Redering (1987) demonstrated the occurrences of wave ripples in shallow subtidal estuarine setting, resulted due to the response of sediments

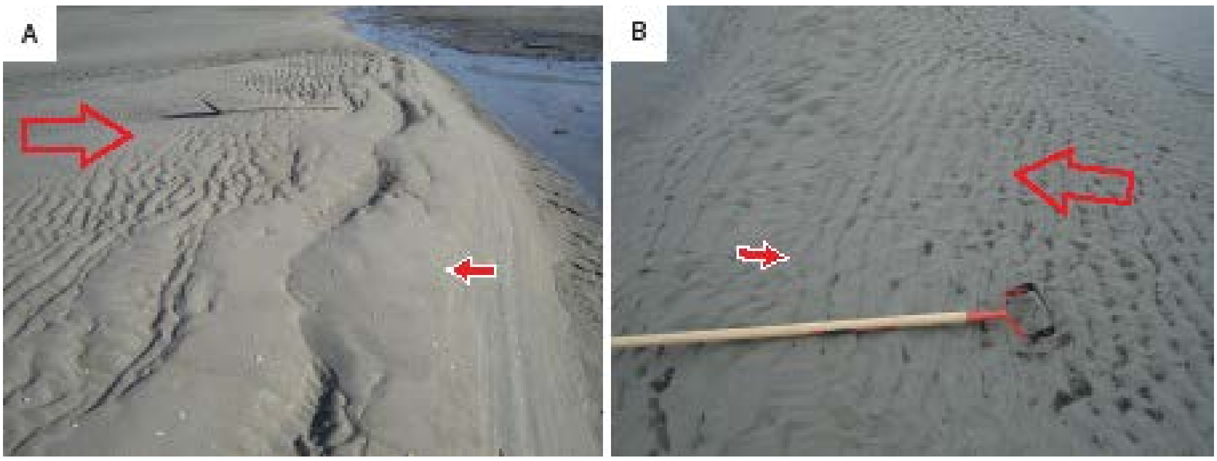


Fig. 15: The effect of the subordinate tidal current, on recent dunes generated by the dominant current (large arrow), (Mont Saint Michel Bay, France). A) Flattened (reversed) crest of the dune, response to the subordinate current (small arrow), comparable with Figure (6E); B) Oppositely oriented ripples formed on both the lee and stoss sides of the dune, as a result of the subordinate current.

to wave oscillation above the wave base line. Being sometimes partly eroded or completely removed, might be the result of the subsequent currents. Similar scenario is witnessed in the Bay Mont Saint Michel intertidal zone (Figs. 11D and 12F) where wave ripples are sometimes remolded or completely destroyed by the succeeding ebb current. Thus based on their mode of existence, the described wave ripples in the studied sandstone are suitable for subtidal as well as intertidal bathymetry.

Notably, the incorporated wave structures in the studied sandstone are very small compared to the magnitude of the tide generated structures. The situation of over dominance of tide generated structures probably points to a high range of the responsible tide (e.g. Klein, 1977; Longhitano, 2012b). The arrangements of this sandstone in uninterrupted sequences of up 8 m thick, combined with the presence of channel-fill morphology of up to 12 m thick, as well as repeated units of tide rhythmites of up to 9 m in the underlaying unit (Abouessa et al., 2012) would be linked to the paleotidal range of this sandstone, compare Klein (1971) and Choi and Dalrymple (2004). The highest tidal range recorded today approaches 18 m in Bay of Fundy, Canada. In the studied cross-sets, the size and geometry of the semilunar tidal cycles and their internal (elementary) bundles show wide range of scales. Such variability reflects variations in the bathymetry and current velocity. Smith (1988) reported that in the micro and mesotidal regimes the thickness of the tidal bundle and the subordinate flow lamina are about the same. This is not the case in the studied sandstones, where the subordinate current laminae or ripples (if exist) is very thin compared to the dominant counterpart. The subordinate current features in the studied sandstone in general are of small magnitude relative to the dominant counterpart. Such aspect is attributed to macrotidal range of the tide (Elliott and Gardiner, 1981). Thus several arguments suggest a macrotidal range during the deposition of the lower Sarir sandstone. Tidal bundles or cycles of bundles described from mesotidal regime of many modern and ancient environment is not as large as the largest ones described in Dur At Talah sandstone.

7. Conclusion

The studied Lower Sarir Unit sandstones of Upper Eocene age, displays wide spectrum of cross-bedding, is embedded between evident supratidal-intertidal deposits below (New Idam Unit), and terrestrial fluvial sandstones above (Upper Sarir Unit). The cross-sets of the studied interval (around 25 m) possess no supratidal features, display some possible intertidal structures, and certainly exhibit indications of subtidal bathymetry.

Physical sedimentary structures preserved here, formed by tidal processes are of variable scale and diversity. The combination of these structures provides key features for recognizing fossil megaripples of tidal origin. In many cases a variety of such indicators are preserved together within one cross-set.

Remarkably most indicative tidal structures in this sandstone are of small (millimetric and centimetric) scale, which reoccur in association with the cyclic organizational pattern of larger scale cross-sets. Most suitable place can be recommended to find these diagnostic small scale structures is the lower part of the cross-set, especially the toesets.

Time-velocity unsteadiness of tidal currents is best reflects in the internal pattern of the foresets and the intervening mud drapes. Accordingly, tidal processes of different time scale are recorded during the course of megaripple migration:

1- Several minutes or tens of minute's structures registered as single mud drapes, which are tidal indicators in themselves. In addition, mud drapes provide an essential tool in delineating and distinguishing tidal cycles of different durations. Mud drapes, as a record of slack water,

are not always occurring as a classical layer of mud, they may occur as an equivalent joint-like bounding surface with or without mud, or as a thin ferruginous layer. All these styles of slack water record should be considered in distinguishing, first tidal bundles, and longer duration of tidal cycles.
2- The shortest duration tidal cycles preserved in these sandstones are the elementary tidal bundle of about 6 hours. These are preserved as dominant current bundles. Individual bundle extends from few mm to few tens of cm. Meanwhile the subordinate countercurrent may or may not generate very thin, few mm, reversed bundle. The latter are typically marked by coupled mud drapes, or result in abnormally thick composite drape.

3- The fortnightly (14 days) cycle which is the product of neap-spring-neap tidal energy fluctuation, is well preserved in variable scale. The tidal bundle is the elementary unit of this cycle. In some cycles successive bundles record a harmonic thick-thin rhythmicity that reflects diurnal inequality within successive tides. This provide evidence that semidiurnal tidal regime was operating in Dur At Talah area during the late Eocene time. Semidiurnal regime of these deposits is also suggested by the 28 counted bundles, recorded inside the 14 days cycle.

The geometry of daily tidal bundle and that of the semilunar cycle are in many cases similar and can be confused. The minimum recorded thickness of the 14 days cycle is around 15 cm, which is less than the maximum, 20 cm, of the half day bundle within greatest megaripples. In such situation the mode of occurrences of the mud drapes (or its equivalent boundary) would play an essential role to differentiate cycles of different durations. Being aware of such situation would help in avoiding misinterpretation of the migration rate of the megaripples. Furthermore, the ubiquity of mud drapes in the cross-set could be regarded as an indirect possible indicator of subtidal bathymetry, especially, when the drapes are coupled and extend from base to top of the sandy foresets.
The ripples associated with the studied megaripples are of centimetric scale. They also have proven to be a key feature for recognizing tidal dynamics. The mode of occurrence of perpendicular current ripples is certainly referred to subtidal-intertidal bathymetry. In the other hand, perpendicular wave ripples are here point to subtidal environments, though their occurrence in intertidal setting could not be excluded (frequent in modern tidal environments). In overall the two types (current and wave) ripples, and the way they are preserved here provide unmistakable criteria of inter-to subtidal setting. Oppositely climbing current ripples support this conclusion. Macrotidal range is preliminary suggested by the degree of differences between recorded features of dominant and those of subordinate current, and by the presence of stacked uninterrupted sequences of up to 8 m as well as channels of up to 12 m.

CHAPTER FIVE

A synthesis and the sequence stratigraphic interpretation of the Dur At Talah sequence

I) Introduction

The Dur At Talah Escarpment is 150 km long and 150 m thick siliciclastic sequence. It is built up by three morphological different sedimentary intervals. This is especially clear for the Western (100 km) part of the escarpment. A complete log of the entire succession can only be obtained around the western most side. At this side of the escarpment, the three units are presented. Considering the concept of genetically related facies (e.g. Frazier, 1974; Mitchum, 1977; Galloway, 1989; Catuneanu, 2006) the entire succession of the Dur At Talah (presented in chapters 2 and 3) is summarized into table (1). A simplified synthetic log (Fig. 1) is constructed based on the well understanding of the sedimentary characteristics of the facies, and their spatial and temporal distribution. From base to top, the main units are the New Idam Unit and the Sarir Unit. The later constitutes the Lower and Upper (subunits) parts. Bearing in mind that Sarir Unit has been considered as one thick unit with two parts (the lower and upper), therefore, in this summary lower Sarir or lower Sarir subunit is referring to the same interval. In the same way, the upper Sarir or the upper Sarir subunit is talking about the same interval.
Anyway, each of the two units (New Idam and Sarir) enclose group of facies that belong to the same depositional regime (table. 1). These facies assemblages are preserved as a range of sedimentary elements that is corresponding to specific processes and environments.
The lower facies assemblages are the thickest, composing the New Idam Unit, the thickness of which varies from 100 m at the western side to 60 m, at the eastern side. The middle facies assemblages (20-30 m) represented by the Lower part of Sarir Unit. The top most facies one (up to 30 m) represented by the Upper part of the Sarir Unit. The Sarir Unit (Abouessa et al., 2012) is better to be considered as Lower Sarir subunit and Upper Sarir subunit because the two parts are genetically different. The lower is mixed tidal-fluvial environment and, the upper is exclusively fluvial. Moreover, the lower Sarir subunit itself presents two opposite sequential trends (LLS and ULS in table. 1). The sequential relationships between these three intervals (New Idam, Lower and Upper Sarir) will be presented hereunder.

Sedimentary unit			Thicknes s m	Facies association	Geometry	Contact with the underlying strata	Depositional environment
Sarir Unit	Upper Sarir		(20-30)	Group (C) F1.12 to F1.14	sand sheet longitudinal bars, transversal bars -abandoned channels	Erosional Unconf.	Fluvial plain
Sarir Unit	Lower Sarir	ULS	(20-20)	Group (B) F2.1, 2.2, 2.8 to 2.11	Mouth bar, Channel bars, Tidal flat. Tidal sand ridge		Delta plain
Sarir Unit	Lower Sarir	LLS		Group (A) F2.1 to F2.7	compound dune, tidal point bar, subtidal channel-fill	Erosional Unconf.	
New Idam Unit	Upper New Idam		(45-55)	F4.1 and F4.2	Fluvial-tidal channels, bars, abandoned channels flood plains	Gradational	Inner estuarine
New Idam Unit	Middle New Idam		(5-15 m)	F3.4	Intertidal-supratidal flat and swamps		Middle estuary
New Idam Unit	Middle New Idam				point bars	Gradational	
New Idam Unit	Lower New Idam		(35 m)	F3.1 to F3.3	Tidal channels, Tidal bars, mollusk bars, aeolian bars	Gradational with Wadi Thamat carbonates	Outer Estuary (coastline)

Table 1: summarizes the different sedimentary intervals composing the Dur At Talah sequence based on the differences on the sedimentary facies dominating these intervals.

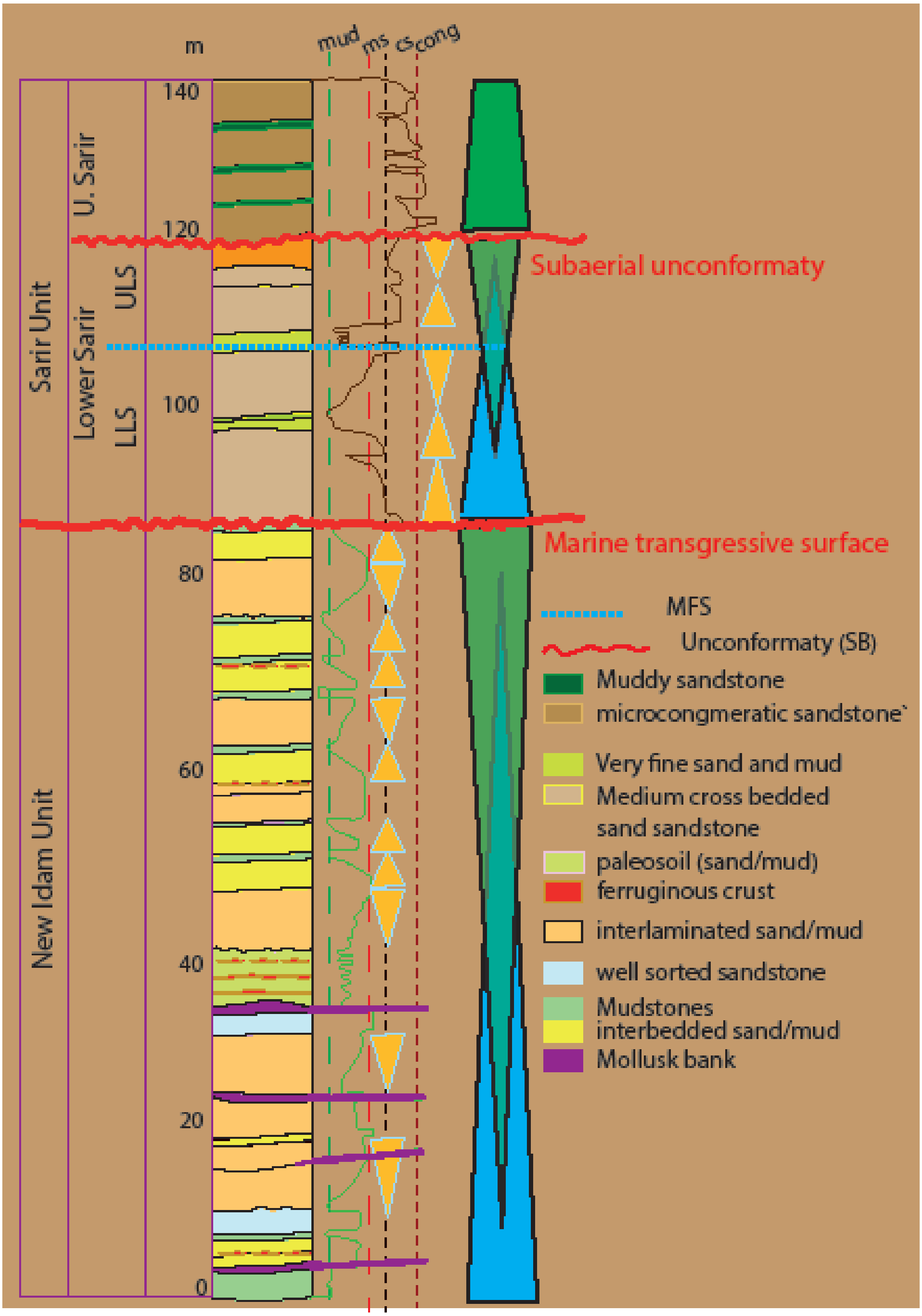


Fig. 1: A synthetic sedimentary log illustrates the 3 main sedimentary intervals of the Dur At Talah sequence. The log is constructed based on the well understanding of the sedimentary characteristics and the spatial and temporal distribution of these three intervals. The lower Sarir (subunit) is split into two parts. Lower lower Sarir (LLS) and Upper lower Sarir (ULS).

II) The New Idam Unit: Evidences of transgressive-regressive cycle.

This unit is essentially composed of very fine grained sandstone and mudstones. The consistency and similarity in lithological composition of this unit, and the shortage, in its upper part of the diagnostic sedimentary structures, made the understanding of its sequential (sea level changes during its deposition) pattern difficult. The recognition of the subtle and unusual key sedimentary features is of great significance in deciphering this pattern (Fig. 2A). These key features are represented by the available direct and deduced sedimentary and biogenic structures and aspects:

1- A trend of decreasing upward in the tidal signature is clear in the New Idam Unit. This is presented by the recurrence of thick sequence (~ 9 m) preserving continuous record of daily and fortnightly tidal cycles, with mud drapes, double drapes, and opposite cross lamination including large variety of flaser/wavy/lenticular bedding. In contrast, in the lithological similar sequences in the upper part of the Unit, these structures become only local and are poorly developed. In the upper part, many of these structures are applicable for other seasonally influenced environments (lacustrine, for instance) rather than tidal. In another word, tide dominated channels, tidal sand and mud flats are widely extensive at the lower 35-45 m of this unit. Unmistakable tidal sedimentary structures are preserved in this interval, in contrast the remaining part (45-55m) of the unit deprive the diagnostic structures.

2- Marine fossils presented as commonly in situ mollusk bars that are widely spread along and across the lower (lower 35m) part of the succession. These totally disappear in the upper part of the unit. These two trends (1 and 2) provide indications of upward decreasing in the marine influence. The repetition (vertical stacking) of the thick (up to 9 m) tidal sequences coupled with the recurrence of mollusk banks could be attributed to the high frequency sea level fluctuation.

3- The association of tidal sediments in the lower parts with trace fossils ascribed for the shallow marine environments. Most obvious of these are Teichichnus, Diplocraterion and Skolithos (e.g. Taylor and Goldring, 1993; Gingras et al., 2007; Seilacher, 2007). Teichichnus in particular presents clear response to the daily tidal sedimentation (vertical adjustment to rapid sedimentation). These trace fossils disappear gradually upward, and are completely absent in the facies composing the upper part of the unit. This fact provides a supplementary evidence of decreasing marine signatures. Of special interest is the terrestrial trace fossils (represented by the burrows of freshwater decapods) are remarkably increasing toward the top of the unit.

4- Emersion surfaces showing upward increasing in frequencies. These are represented by subtle features of subaerial exposure. Mud cracks and recurring rooted levels give a direct evidence of emersion. Local existence of nests and galleries of termite provide a supporting clue for indisputable long time emersions. Other features of emersion are deduced from large-sized cylindrical burrows which are interpreted to have been built by freshwater crayfish.

5- Terrestrial fossil content is increasing upward represented as various species of primates, rodents and proboscideans. This clue is affirmed by the fact that some of these fossils are filling large-sized mud cracks and terrestrial burrows and are associated with erosional surfaces.
6- Another important indicator of the upward domination of terrestrial influence is the increasing intensity and diversity of fossil plants. These are represented by different types of leaves,

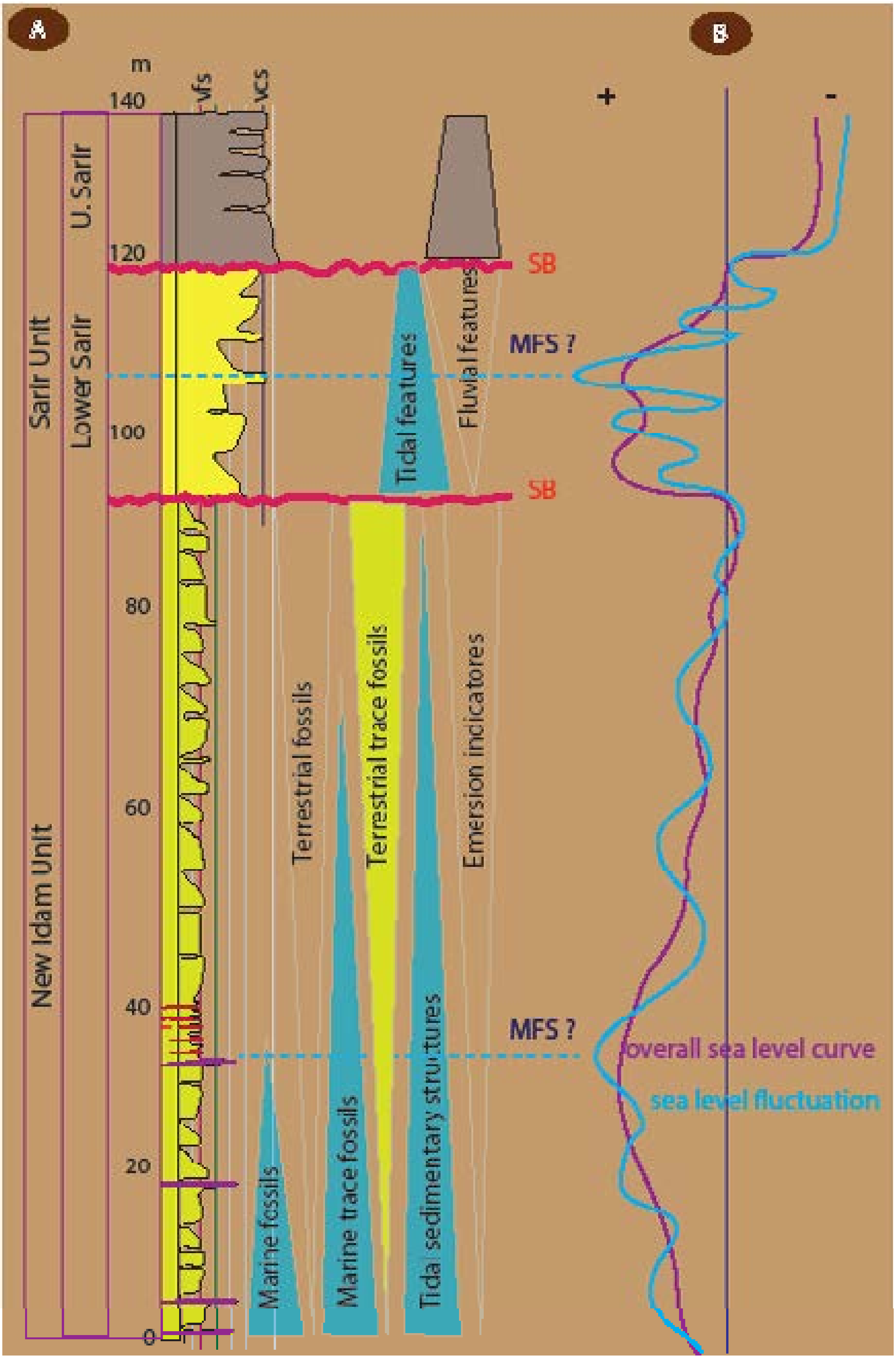


Fig. 2: Schematic drawing of the studied sequence showing (A) the overall shallowing and deepening based on the collective sedimentary indicators; B) proposed relative sea level changes based on these sedimentary indicators.

small branches as well as tree trunks and fossil fruits.

Assembling all these aspects and features allows reconstruction of the overall vertical trends registered by New Idam Unit in response to the environmental changes. Based on these aspects depositional model can be suggested (Fig. 3). Coastal outer estuarine is proposed for the Lower Part of the New Idam Unit (Fig. 3A), and far in land inner estuarine for the upper part of the unit (Fig. 3B)

Two possible circumstances can accommodate all the listed environmental aspects: the lowering sea level, and the decreasing rate of sea level rising. Estuarine depositional environments are dominating the New Idam unit (Pelletier, 2012; Abouessa et al., 2012) and rising sea level is a prerequisite for the establishment of this environment (e.g. Terwindt, 1981; Dalrymple, 1984, 1992; Boyd et al, 1992; Dalrymple and Choi, 2007). Therefore, the situation in this unit fits with the scenario of decreasing rate of sea level rising. The suggestion in Abouessa et al (2012) and Pelletier (2012) that the parasequences (sensu Van Wagoner et al, 1988) composing the New Idam Unit is a Transgressive/Regressive parasequences, is laying within an overall transgressive system tract (TST).

The lower part of the New Idam Unit represented by the recurring oyster banks (associated with beds that preserving diagnostic tidal structures) is the only interval that provides typical shallow marine setting. Considering the evident overall shallowing up in the New Idam Unit, it can be suggested that the latest oyster bank is more or less equivalent to the maximum flooding surface at the time of the deposition of this unit. Approximately, at this point, basinward shoreline migration commenced. This would imply (considering more terrestrial signature towards the top of this unit) that the available top of the New Idam Unit represents the end of regressive phase of shoreline. Based on these inferences sea level scenario during the deposition of New Idam Unit is proposed (Fig. 2B). An overall sea level lowering (or at least shoreline backstepping) is applicable during the deposition of this unit.

III) Sarir Unit: evidences of transgression–regression and incision

Based on facies analysis this unit is split into two genetically related sedimentation intervals (two subunits), the lower Sarir and the upper Sarir.

A) The Lower Sarir (subunit)

The regional erosional contact separating New Idam Unit and the overlaying Sarir Unit is marked also by strong change in lithology, sedimentary structures, ichnology and paleontology. There is a clear jump from the New Idam Unit's laminated fine grained sandstones and mudstones below to the medium to coarse cross bedded sandstones of the Sarir Unit above the contact. This jump in lithology is enhanced by the fossils and trace fossils content of the two units. These are sharply decreasing and markedly changed above the contact. These contact markers do not only mark the contact but give indications about the change in the sedimentation rate and depositional environments. The rate of bioturbation is faster than the rate of the sedimentation below the contact, and the case is reversed above the contact. The shortage of the trace fossils in the Sarir Unit is concomitant with the reappearance of strong tidal signature at the base of Sarir Unit.

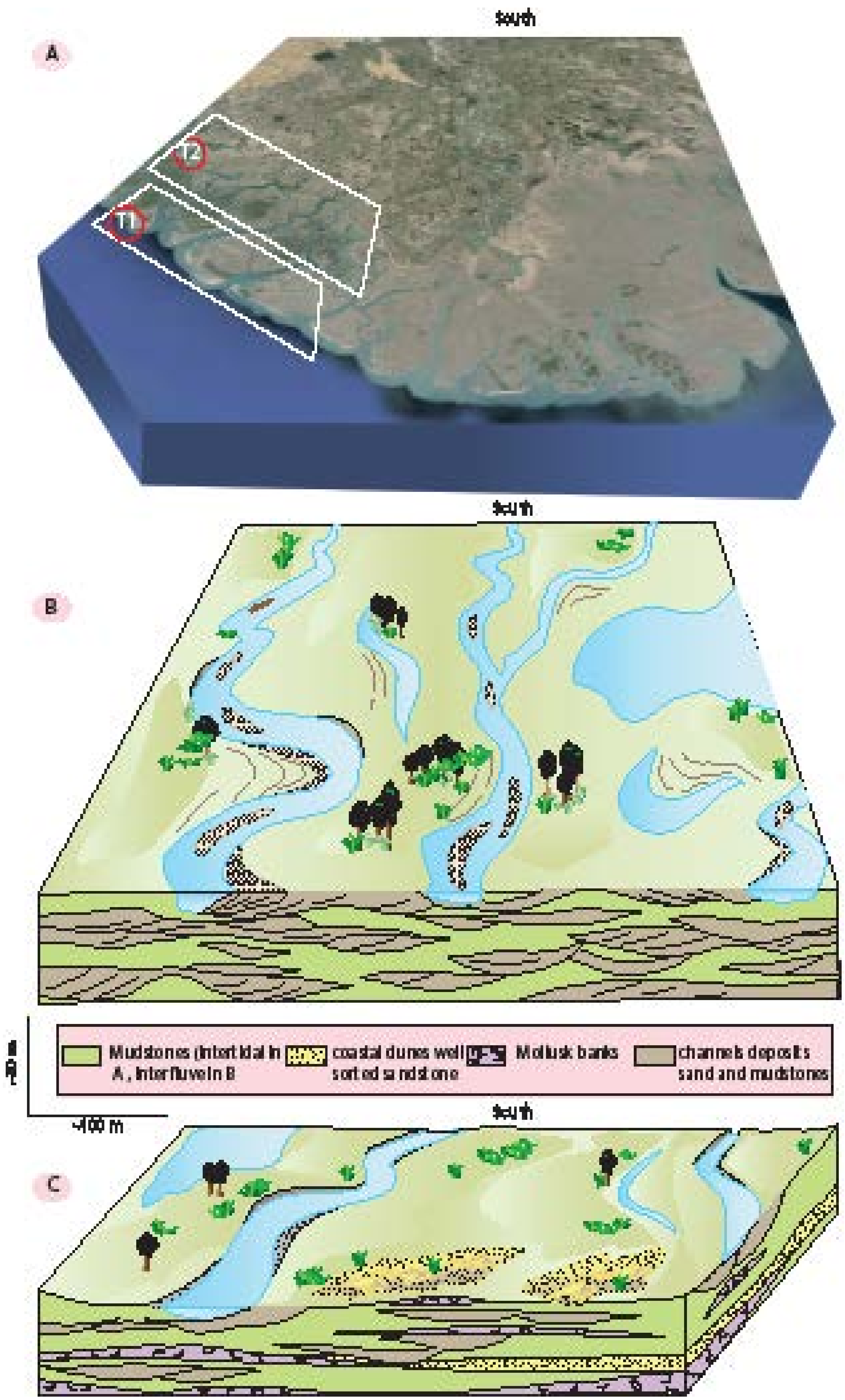


Fig. 3: The proposed depositional model of the New Idam Unit: A) shows the proposed depositional locations relative to the coastline (T1 is older than T2); B) depositional model of the inner estuarine environment acted during T2; C) depositional model of the outer estuarine environment acted during T1.

The ubiquitous terrestrial and emersion indicators preserved in the latest times of New Idam Unit is erosively (unconformably) overlain by the diagnostic shallow marine tidal sedimentary structures of Sarir Unit. Such depositional pattern leads to propse a transgressive surface of erosion (TSE) in the shallow marine tidal environment (Frazier, 1977; Bhattacharya 1993; Tape et al., 2003; Catuneanu, 2006; Runkel et al., 2007; Van den Berg and Boersma, 2007). Transgressive system tract can then be suggested for the subtidal to intertidal deposits dominating the lower part (LLS) of Sarir unit. Despite the marine transgressive surface presented by the tidal interval above the unconformable contact, the entire Lower Sarir (~20-30 m) provides indications of sea shallowing upward trend. These indicators are given in chapter three and summarized hereunder:

1- The diagnostic tidal sedimentary structures at the base of the Lower Sarir (Facies Group A, Table. 1) become faint and only locally preserved in the similar sandstone bodies towards the top of the interval (facies Group B; the ULS). Inversely, coarse grained beds lacking tidal features and roots dominated sandstone bars appear more frequently toward the top of the Lower Sarir.

2- The silicified woods present as scattered trunks embedded in the sediments shows clear upward increase in their density, and finally they exist as patchy accumulations, many of them are in living position (vertical tree stump).
3- Indications of sub-aerial exposure are preserved as mudcracks and possible foot prints of four legged animals, preserved at the top of the Lower Sarir (ULS).

Conclusively, the Lower Sarir Unit (subunit; 20-30 m) commences with tide dominated interval (facies Group A) and gradually ends up with a fluvial dominated interval (facies group B). Profound erosional contact with facies group (C) terminates the lower Sarir (Unit). Under these circumstances maximum flooding surface can be placed in the middle of the Lower Sarir subunit (Figs. 2).

Highly dynamic depositional condition is proposed by synsedimentary deformation structures, general scarcity of the bioturbation and by the rapid vertical and lateral changes in the facies (Fig. 4). These conditions are imposed in the lower Sarir Unit by the interaction between the tidal and the fluvial processes. Ignoring the local flood dominated (southerly oriented cross bedding) bars and channels, most produced sedimentary bodies exhibiting North ward progradational pattern. Sediment supply in excess of available accommodation results in progradation (Galloway, 1989; Van Wagoner et al., 1990; Catuneanu et al., 2011). The coexistence of tide dominated, mixed tidal-fluvial and the fluvial dominated features (in superposition) and their basinward progradational pattern proposing a delta front to delta plain topset as depositional model for the lower part of the Sarir Unit (Fig 5). This short system is commenced by TST represented by the LLS gradually succeeded to HST represented by ULS. The system records basin wards migration of the shoreline.

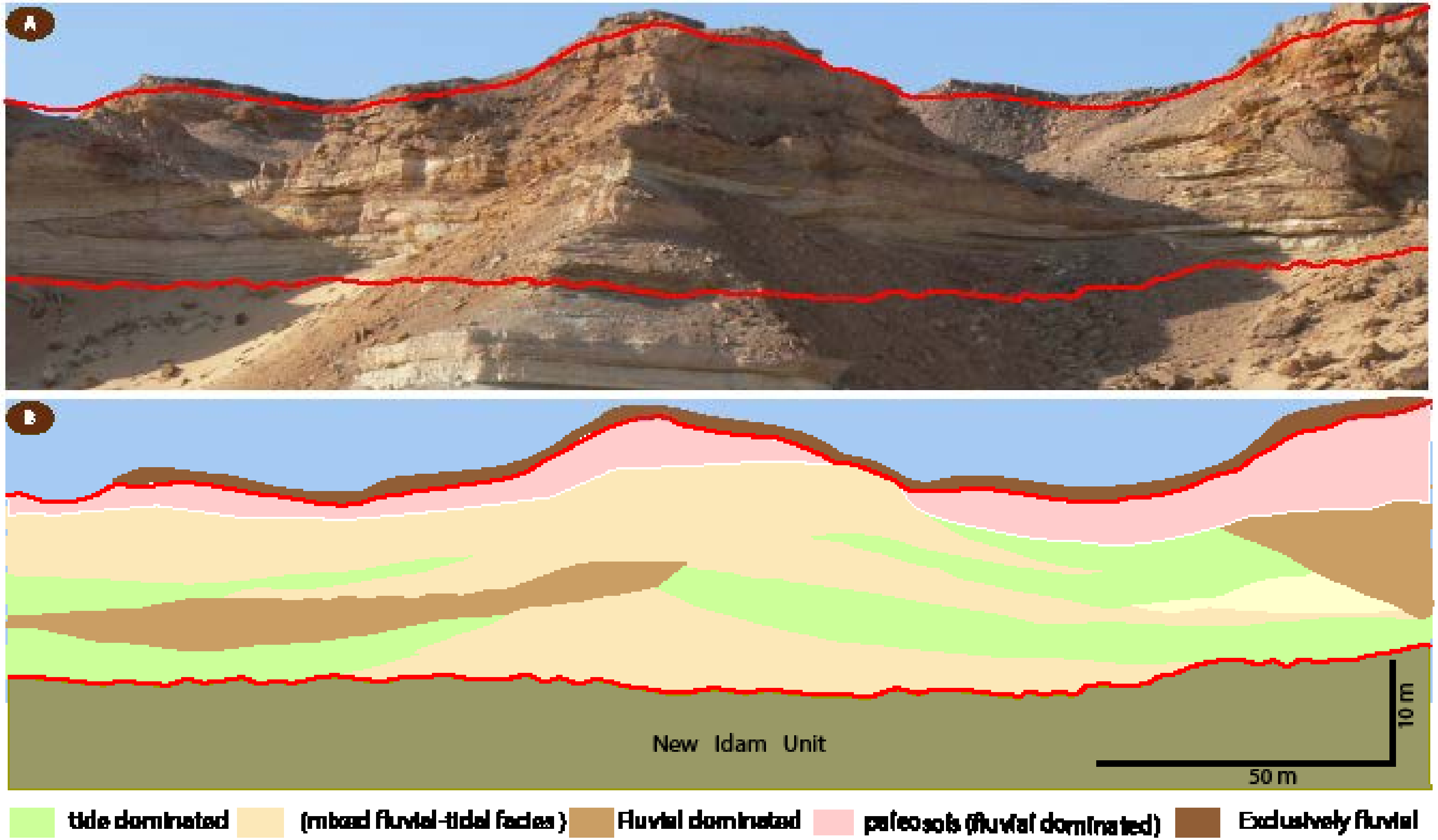


Fig. 4A, B: Outcrop view of the Lower Sarir subunit (A) bounded between two unconformities (the red lines). It shows the amalgamation in the Lower Sarir of the tide dominated and fluvial dominated sedimentary bodies. These are the components of the progradational depositional system. B) Schematic explanation of (A). The red lines locate the transgressive unconformity with the underneath New Idam Units and the subaerial unconformity with the overlying fluvial deposit of the Upper Sarir

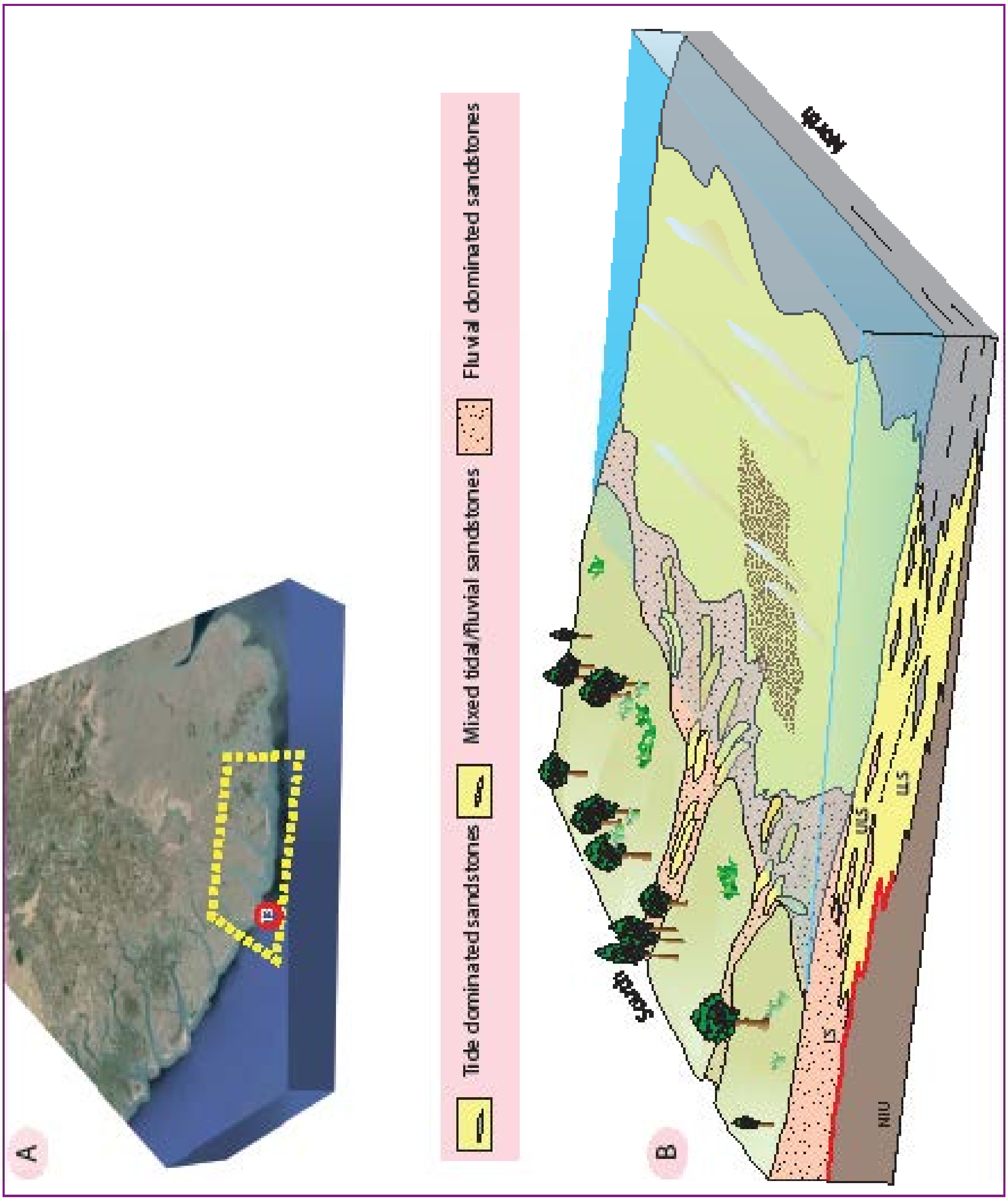


Fig. 5: proposed depositional model of the lower Sarir subunit: A) shows the proposed depositional locations relative to the coastline (T3; T1 and T2 is proposed for the older New Idam Unit, presented in figure 3); B) block diagram suggests a shallow marine deltaic environment for the lower Sarir. It represents an overall progradational system.

B) Upper Sarir (subunit)

The upper Sarir fluvial microconglomeratic sandstone, represented by facies group (C; Table. 1), occupies the upper most exposed rocks in the Dur At Talah escarpment. These very coarse rocks are erosively cutting into the Lower part of the Sarir. The contact here is not as continuous and obvious as the lower contact with the New Idam Unit. This time, due to the outcrop condition, the contact is intermittently traceable. As presented in chapter (2), the contact between the lower and upper Sarir (Fig. 6) is best observed in the western part of the escarpment where it can be traced for few km. Anyway wherever identified this contact is marked by profound change in lithology and sedimentary structures.

The contact suggests that significant but unknown amount of sediments from the Lower Sarir had been eroded preceding the deposition of the fluvial deposits. Regardless of the amount of removed deposits, the discontinuity between the older and the younger sediments is well expressed in the western side of the escarpment, between the microconglomeratic sandstones and the thick paleosoils and the intensely rootled sandstone bars. Towards the eastern sides of the escarpment, the contact is underlain by the lower Sarir sandstones embedding large tree trunks. At intermediate locations between the East and the West of the escarpment, the rocks below the contact are marked by well sorted tidal sandstones.

These variably different features of the contact might give an indication about the overall degree of fluvial incision into the underlaying rocks. In this context, there is one indication that might give an idea that the fluvial incision is shallow. This indication is given by the remaining part of the lower Sarir. If considering that the maximum thickness of lower Sarir is 30 m, the remaining part at any point is at least 15 m. Apart from this assumption, the presence of this obvious erosional contact between the rocks of Lower and Upper Sarir supported by the clear change in facies indicate that the Upper Sarir is deposited within an independent fluvial system. Especially if one takes into consideration the prolonged period of soil formation below the erosional surface.

Based on the fact that the Upper Sarir Unit's depositional environment is exclusively fluvial, a depositional model independent of the shoreline is proposed (Fig. 7). Unlike the lower Sarir which is controlled by marine accommodation, the upper Sarir is fluvial system without any evidence of shoreline proximity. Taking this into consideration, "Cut-and-cover" fluvial accumulation (Holbrook and Bhattacharya, 2012) could be proposed.

Whether this fluvial system involves sediment by pass or not is a matter of how much time is lost before the deposition of the fluvial deposits. Alternatively the fluvial deposit is representing a part of classical low stand system tract (Posamentier et al. 1988; Posamentier and Allen 1999), which is usually attached to low stand wedge. Both alternatives occur under relative sea level fall, i.e. forced regression (Nummedal 1992; Posamentier et al. 1992; Posamentier and Morris 2000).

The Sirt basin is in general a South–North progradational basin (e.g. Selley, 1967; Barr and Wager, 1972; Bellini and Massa, 1980; Singh and Mirheel, 1996) the shoreline proximity during the deposition of the fluvial deposits of the Upper Sarir should be dependent of the time gap of the unconformity separating the fluvial of upper Sarir from the high stand deposits of the Lower Sarir. The prediction of the occurrences and the location of the low stand wedge (equivalent to the fluvial deposits) becomes difficult. It requires a subsurface data northward of the Dur At Talah location, or it requires confirmed age of the fluvial deposits (the Upper Sarir). The chance of the occurrences of the low sand wedge contemporaneous to the fluvial deposits is greater if the age (38-39My; Jaeger el al., 2010) is applicable for the fluvial deposits (of course, it also depends on the depth of the fluvial incision). Otherwise, if the sediments of the fluvial deposits are much younger (Oligocene; Vasic and Sherif, 2007), the fluvial system should be

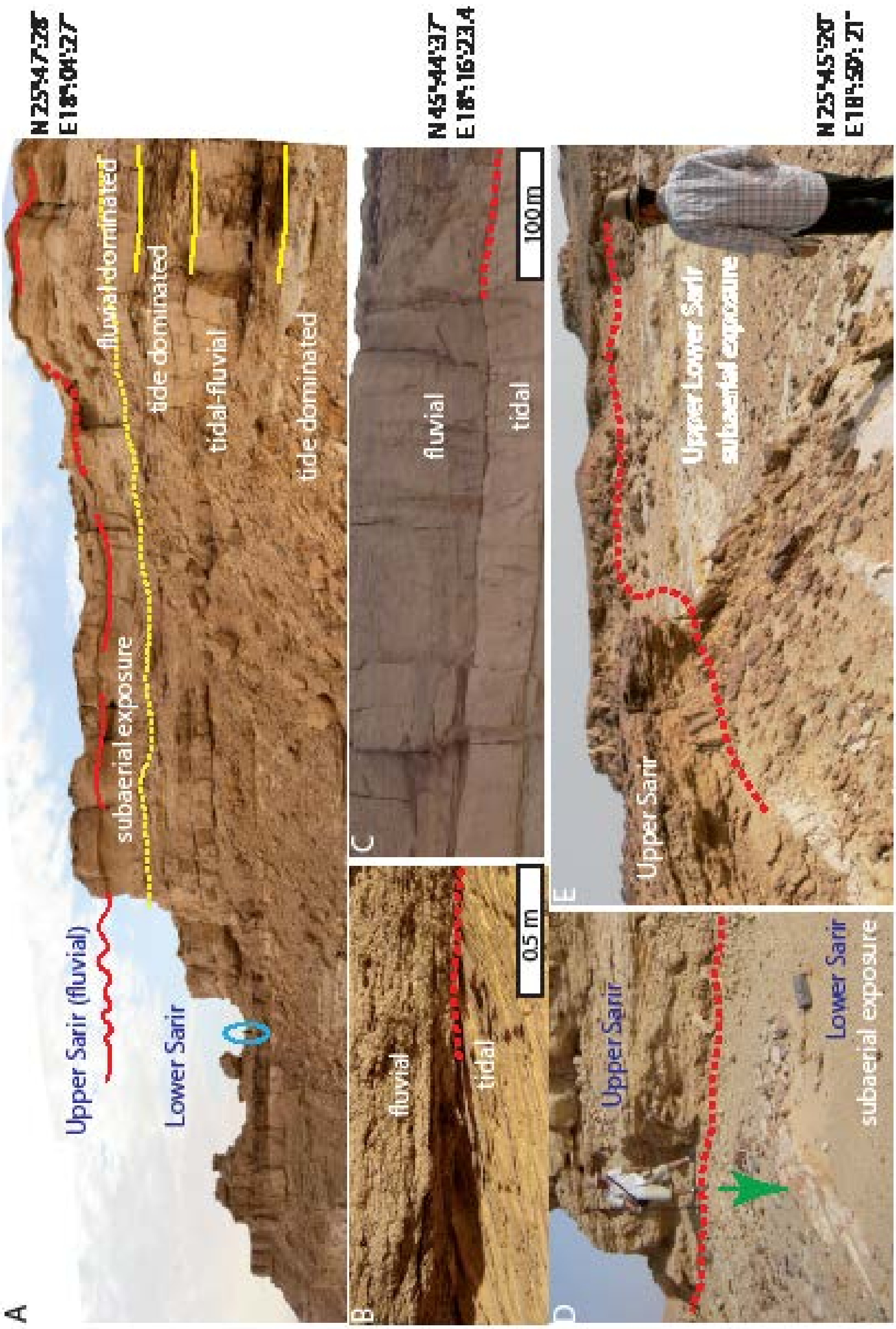


Fig. 6: Shows the unconformable contact between the medium grained (mixed fluvial-tidal) sediment of the lower Sarir and the very coarse-microconglomeratic fluvial sediments of the upper Sarir. A, B, C and D expose the differences of the rocks below and above the contact in three locations (B and C are close and far views in the same location) from west to east sides of the escarpment. The arrows in D point to the petrified trunk (common in the lower Sarir), which are absent in the upper Sarir).

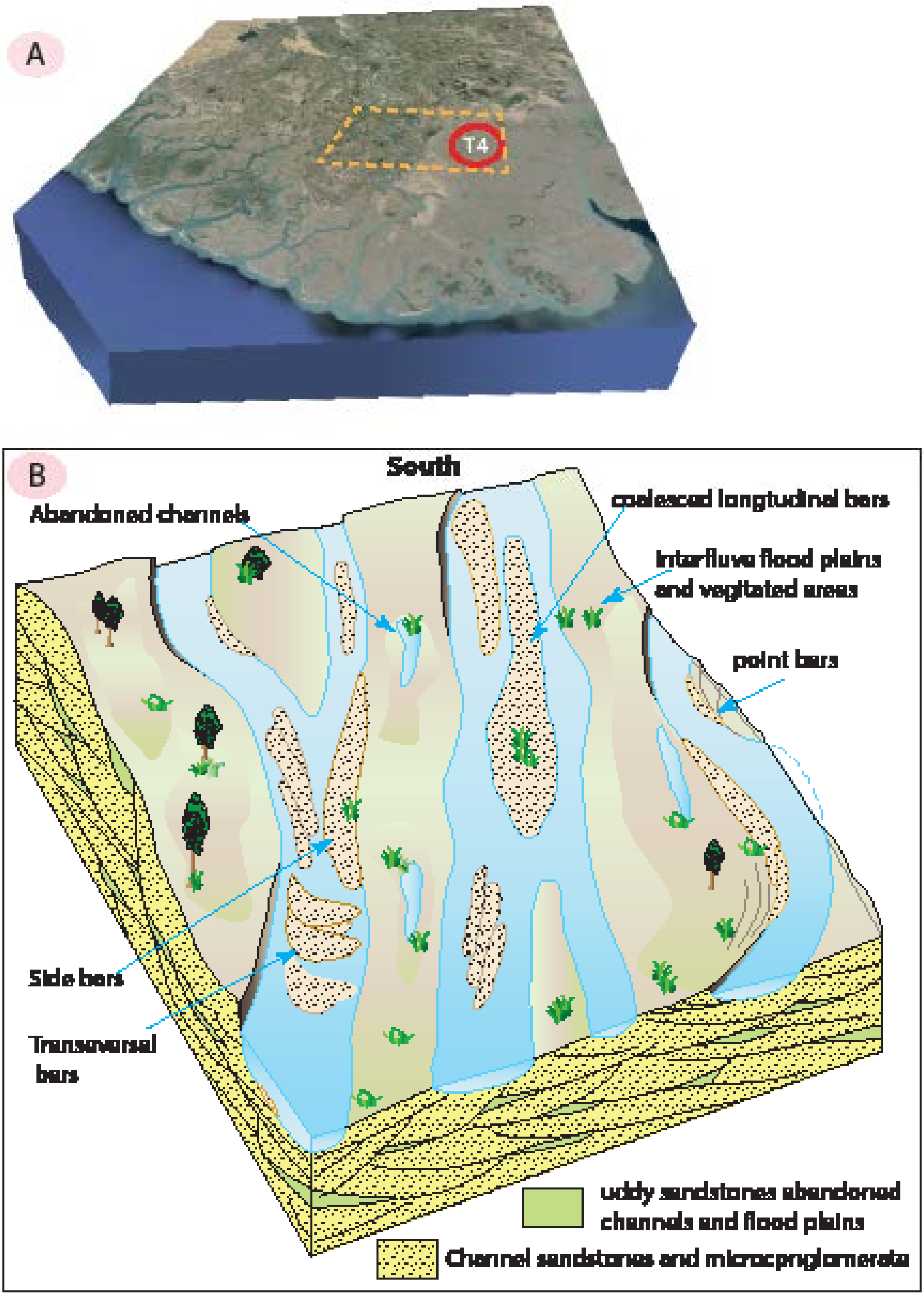


Fig. 7: Depositional model of the Upper Sarir fluvial system. Available informations suggest that this system is part of continental regime (detached or far to the South from the coeval shoreline) as suggested by T4 rectangle in block A. The time T4 refers to the youngest depositional interval of the Dur At Talah sequence; B) simplified representation of the fluvial system with the braided streams constitute the predominating component.

an independent system, probably detached from the shoreline. Because the fluvial system is very coarse grained and subaerially very broad, its chance of producing the low stand wedge is applicable.

IV) Matching the Dur At Talah sequence with the worldwide sea level curve

Sea level fluctuations in the Dur At Talah area during the depositional time of the studied succession has been deduced from the depositional pattern of the sediments. It is represented by overall shoreline backstepping (Fig. 8). Events of sea level fluctuation within this overall trend are recorded.

-Regressive phase expressed by progressive shallowing up depositional trend characterizes the New Idam Unit. Short pluses of sea level fluctuation are registered as several parasequences within the regressive phase. This phase is terminated by regional transgressive surface of marine erosion recorded as (sequence boundary) unconformity.

-Transgressive phase system tract (TST) is expressed by high energy tide dominated deposits characterize the lower part of the Lower Sarir subunit (LLS). This transgressive system tract lies immediately above the sequence boundary.

-Regressive phase (normal regression) expressed by mixed tidal-fluvial (progradational) deposits, took place in the Upper part of the Lower Sarir (ULS). This general regressive trend is culminated with regional emersion ending the marine history of Dur At Talah. The maximum flooding surface is located approximately between the lower and the upper parts of the lower Sarir (between LLS and ULS; Fig. 8). The Upper Lower Sarir is then belongs to the high stand stage of the sea level (HST).
The superjacent upper Sarir deposits start after an obvious erosion phase (fluvial incision/su-

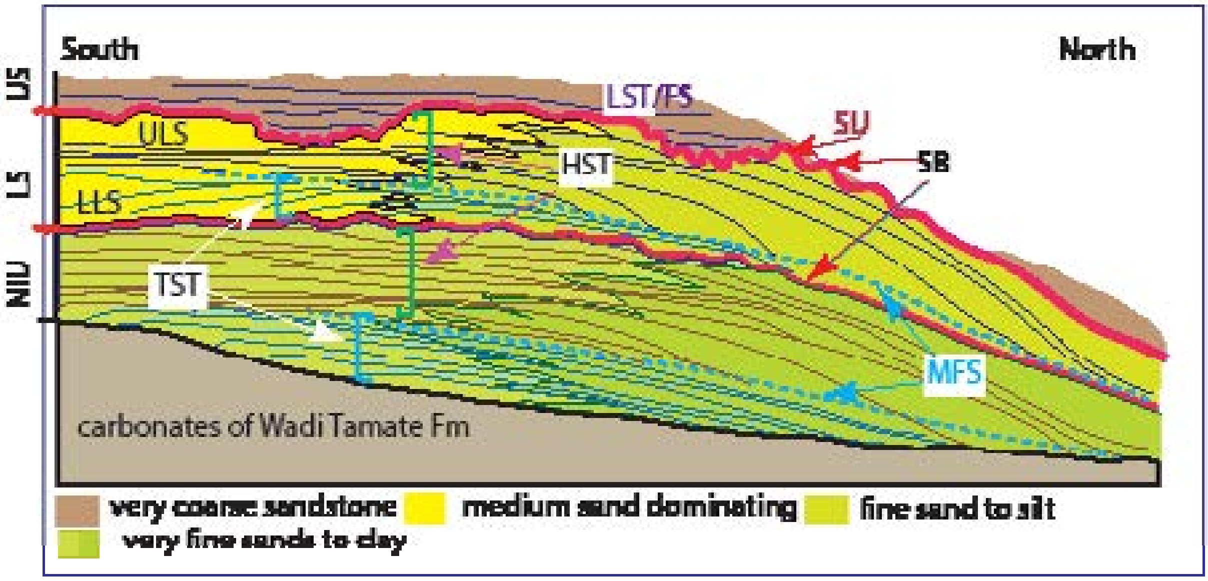


Fig. 8: 2D diagram presents an attempt of sequence stratigraphic interpretation for the entire sedimentary packages composing the Dur At Talah succession. The sequence overlies the Wadi Thamat Formation and consists of three main parts. This scenario locates sequence boundaries and system tracts according to the available date.

baerial unconformity), after a prolonged time (may be several thousands of years or more) of pedogenic processes. During this time shoreline was far basin ward and the relative sea level is lowered (forced regression). The fluvial LST is the consequences of this forced regression.
These phases of sea level fluctuation which are dated (39-38 My, Jaeger et al., 2010a,b) are in general fit with the world wide sea level curve (Haq et al., 1987; Hardenbol et al., 1998) during the Bartonian (Late Middle Eocene). The subaerial unconformity below the Upper Sarir meets with the relatively sharp sea level drop (after Haq et al. and the others) located between Bartonian and Priabonian (Fig. 9).
All this, as a matter of comparison, made the sediments of Dur At Talah older than the lithological and paleontologically very similar sediments of the Qasr El Sagha Formation of Fayum dated Late Eocene (Priabonian; e.g. Gingriche, 1992; Legler et al., 2013). In Fayum the sediments which are considered equivalent to New Idam Unit and Lower Sarir Unit is Priabonian and is overlain by the Gebel Qatrani fluvial deposits (Bown, 1982; Bown and Kraus, 1988; Abdelfatah, 2012 Gingriche, 1992) which is dated Rupelian (Said, 1990; Gingriche, 1992). Bearing this in mind, the age dating of the fluvial deposits of the upper Sarir is required to confirm whether these deposits are chronological and genetically attached to the Dur At Talah during Bartonian (39-38Ma) or it belong to Oligocene times.

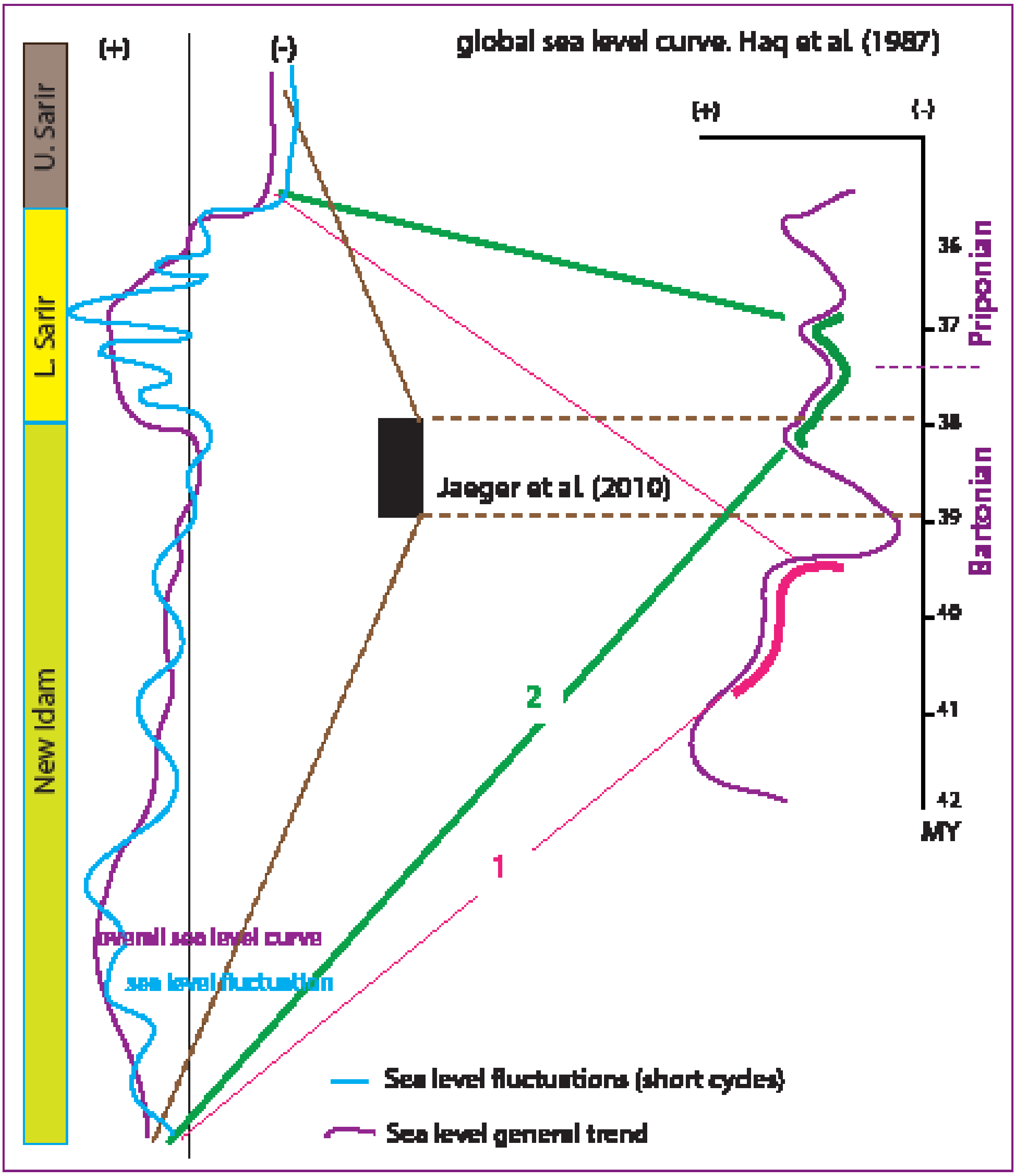


Fig. 9: Matching the Dur At Talah sea level changes with the global one (Haq et al. (1987). Two segments of sea level change are favorable for the Dur At Talah sequence. The red segment is slightly older than the age (by Jaeger, 2010) of the sequence. The green segment is in greatest part slightly younger. The younger segment is closer to consider the fluvial system above the subaerial unconformity as belong to the Oligocene.

The siliciclastic rock sequence of Dur At Talah escarpment (150 m thick) is built up by two different rock units: the New Idam Unit and the Sarir Unit. The oldest one (New Idam Unit; around 80 m thick) is composed of subhorizontaly stratified very fine grained sandstones and mudstones. This unit is marked exclusively at its base by intercalation of a half dozen of compact oyster beds (biostroms-like). New Idam Unit is erosively overlain by the Sarir Unit (around 50m thick), composed by coarser grained rocks. Cross bedded medium grained sandstones at the lower half, abruptly changing to very coarse and microconglomeratic sandstones at the upper half. Few subordinate intercalations of siltstones and mudstone interrupt these coarse sediments.

The fine grained sandstones and mudstones of the New Idam preserve indications for their deposition in shallow marine estuarine environment often dominated by well developed tidal deposits (evident at the base of the unit). Coastline attached outer estuarine environment dominates the lower 35 m of the outcrop. Whereas, inner estuarine setting dominating the upper 45 m of the unit. Intermediate transitional paleosoil interval (15 m thick) marks the contact between the outer and inner estuarine (i.e. between the lower and upper New Idam Unit). Evidences for the inner and outer estuarine setting are recorded as packages of multilateral sedimentary and biogenic indicators. These indicators point to the upward shallowness during the deposition of this estuarine system.

The richness of the lower part of the New Idam Unit in marine fossils and tidal structures gradually becomes weakness of tidal signature and absence of marine fossils at the upper part. Oppositely, fully terrestrial indicators exhibit obvious domination upward, recorded as an increase in the density and diversity of continental (both fauna and flora) fossils. For instance fossil proboscidean is more frequent and evident in the upper part.

Evidences of shallowing upward throughout the entire New Idam Unit is also presented by the unusual trace fossils. Cylindrical morphotype traces interpreted to be produced by freshwater decapod shows notable upward increase in their distribution toward the top of the Unit. In addition, some other terrestrial trace fossils such as burrows of turtles and lung fish were useful as a marker of shallowness.

Supplementary indicators of shallowness are provided by the increasing frequency and thickness of rhizoliths dominated beds with or without paleosoils development. This is supported by the appearance of penecontemporaneous termite burrows which are never observed in the lower part. This aspect is coupled with the existence of subaerial desiccation cracks, some of which are filled by reworked terrestrial fossils including rodents, carnivorous and primates. Moreover, ichnospecies known to occur in shallow marine conditions such as Teichichnus, Diplocraterion and Skolithos which are common in the lower part of the new Idam unit are absent even in the same lithofacies from the upper part.

Within the overall shallowness recorded by the entire New Idam Unit, the latest mollusks bank points to the isochronous time line between the increasing rate of sea level rise and the decreasing rate of sea level rise (i.e. MFS). This is equivalent to the time when the shoreline back stepping commenced. After this time there are neither marine fossils nor marine trace fossil in the New Idam Unit. And the conditions of increasing terrestrial influence in the expense of tidal influence are dominating above until the contact with the Sarir Unit.

The New Idam/Sarir Unit unconformable contact is marked by strong return of the shallow marine conditions characterized by diagnostic tidal dynamics. These are recorded as multiscale sedimentary structures, preserved in tidal dunes and megaripples as well as in tidal flats and point bars. These large bedforms resulted from stronger influx of sediments by proximal fluvial source. The uniquely strong tidal signature above the contact suggests tidal ravinment

surface (sequence boundary) underlies transgressive system tract (TST).
The tidal and fluvial interaction in the lower Sarir subunit is clearly evidenced by the existence of large tree trunks embedded in tidal mouth bars and tidal channel deposits. The degree of tidal fluvial mixing in the lower Sarir Subunit is fairly allowed to consider the lower (15-20 m) of the Sarir (LLS; Lower lower Sarir) as a tide dominated setting because it preserve strong tidal signature. And consider the succeeding (10-15 m; ULS; Upper lower Sarir) as fluvial dominated setting, with less ubiquitous tidal influence and more fluvial indications. Bearing this in mind, maximum flooding surface (MFS) is arbitrarily located between the two (LLS and ULS).

The lower lower Sarir (LLS) represent transgressive system tract and upper lower Sarir (ULS) represent highstand system tract. Moreover, indications of prolonged emersion started to show up above the maximum flooding surface, and gradually increase upward (in the ULS). It can be said with reasonable confidence that the duration of emersion is variably recorded. Aerial exposures are recorded as partially rootled sandstone bars in lower levels and as a heavily pedoturbated bars above. At the end, the fluvial sandstone of the upper Sarir subunit cut into these subaerially exposed lithologies.
By this end of the lower Sarir subunit, the sequence of events during the deposition of this unit is: TSE-TST-MFS-HST-SU. i.e. that the lower Sarir Subunit is commenced at transgressive surface of erosion, succeeded by the transgressive system tract which is culminated by the maximum flooding surface. The latter initiated the high stand system tract which is intruded by the subaerial unconformity. The entire subunit between the TSE (transgressive surface of erosion) and the SU (subaerial unconformity) is formed by continuous sedimentation in a progradational (delta complex) depositional system. The high influx of sediments in this system led to normal (shoreline back stepping) regression and to ending forever the marine phase of Dur At Talah.
The fluvial incision (SU) by the upper Sarir Subunit into the highstand deposits of the lower Sarir subunit is discontinuously but regionally recorded in 100 km wide escarpment. It is marked by profound change in the sedimentary facies. Microconglomeratic sandstone unconformably overlies different facies of the lower Sarir shallow marine sediments. The subaerial unconformity is introduced after a prolonged time of emersion known especially by the thick paleosoils and the occurrence of large-sized in situ trees. The fluvial system above the (SU) ends of the Dur At Talah sequence.
At present day there is no enough information to link the fluvial deposits with their coeval shoreline. But if we consider the 39-38 My as the age of the entire Dur At Talah sequence then there is a greater possibility to predict the occurrences of lowstand wedge ahead (north ward) of the fluvial system. Alternatively, if the fluvial system (upper Sarir subunit) is of Oligocene, than it is more likely to be independent from the shoreline. Worth mentioning in this position that the age (39-38 My) is in principle depends on fossils collected from the New Idam Unit. these fossils are absent in the Upper Sarir subunit.
Finally, when we started to study the Dur At Talah escarpment there was few sedimentological and paleontological studies. By the end of this research project many information have been revealed concerning architectural aspects (Pelletier, 2012) as well as about sedimentary and biogenic processes, facies and depositional environments (this thesis). In fact, these studies are a good start for better understanding of all about the sequence. In spite of these recent studies and the previous ones, many questions remain open and others arise, for instance:
Which is more important in the Dur At Talah sequence, the time of deposition or the time of non-deposition and erosion?

Being this study focus on the western (100 km) side of the escarpment, are there significant changes in the eastern side? For instance are there changes in the nature of the contact of New Idam with Sarir units and if there is changes in the consistency in New Idam Unit itself?
How much lacustrine environment contributes to the deposits of the New Idam Unit?
The fluvial system in the upper Sarir subunit requires more detailed study to emphasize whether the braided or the meandering system is more dominating? Or, in another words what is the degree of sinuosity of the upper Sarir fluvial system?
These perspectives arose from what we now know about Dur At Talah, what we do not know is still much more.

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Appendix (1)

1- Abouessa et al. (2012)

New insight into the sedimentology and stratigraphy of the Dur At Talah tidal-fluvial transition sequence (Eocene–Oligocene, Sirt Basin, Libya)

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New insight into the sedimentology and stratigraphy of the Dur At Talah tidal-fluvial transition sequence (Eocene–Oligocene, Sirt Basin, Libya)

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ABSTRACT

The Dur At Talah escarpment is exposed in the Abu Tumayam Trough at the southern part of the Sirt Basin, central Libya. The cliff (~145 m high and ~150 km long) is oriented along an E–W axis and faces southward. Only a few field studies have been previously carried out in this area, and these were mainly focused on the succession's famous vertebrate fossil-content. The reconstruction of the depositional environments, which is the purpose of this paper, remained poorly documented. In this study, the uppermost Eocene rock succession composing the Dur At Talah escarpment is divided into two stratigraphic units: the New Idam Unit at the base composed of highly bioturbated fine sand/claystone alternations, and the Sarir Unit at the top dominated by medium to very coarse grading sometimes to microconglomeratic sandstones. This complete succession is built up of shallow marine (New Idam Unit) to fluvial (upper part of Sarir Unit) deposits passing through a "marine/fluvial" transition zone (lower Sarir Unit). The stratigraphic succession suggests a global regressive trend. The marine part of the New Idam Unit is dominated by deposits attributed to tidal depositional environments including tidal flat, tidal channel and tidal bars as well as biostroms of oyster shells at the base of the unit. The lower part of the Sarir Unit appears to be deposited in a fluvial influenced, tide-dominated environment. The upper part of the Sarir Unit, made of coarse-grained to microconglomeratic sandstones interbedded with paleosoil horizons, is interpreted as being fluvial.

1. Introduction

The study area is located at the southern fringe of the Sirt Basin (Fig. 1). It corresponds to the southern, exposed part of the Abu Tumayam Trough. The outcrop can be described as a well pronounced E–W stretching escarpment about 150 km long by 100–150 m high. The age of the deposits forming this escarpment corresponds roughly to the Upper Eocene-Lower Oligocene transition. The deposits of the Dur At Talah cliff have received the attention of geologists because of their remarkable vertebrate content; especially mammals (rodents, primates, proboscidians), reptiles, sharks and fish (Arambourg and Magnier, 1961; Wight, 1980; Rasmussen et al., 2008; Jaeger et al., 2010a,b). The importance of the Dur At Talah area is increased due to the continuous exploration activities devoted to the discovery of more hydrocarbon occurrences in the Sirt Basin. Late Cretaceous and Early Cenozoic rocks of the Sirt Basin contain large accumulations of hydrocarbon which have been the target for the numerous exploration wells drilled in the region since oil discovery in 1957. Therefore, understanding this outcrop would certainly lead to a better understanding of its counterparts in the subsurface towards the basin centre.

First reports and descriptions about the geology of this area are attributed to Desio (1935), Bellair et al. (1954) and Arambourg and

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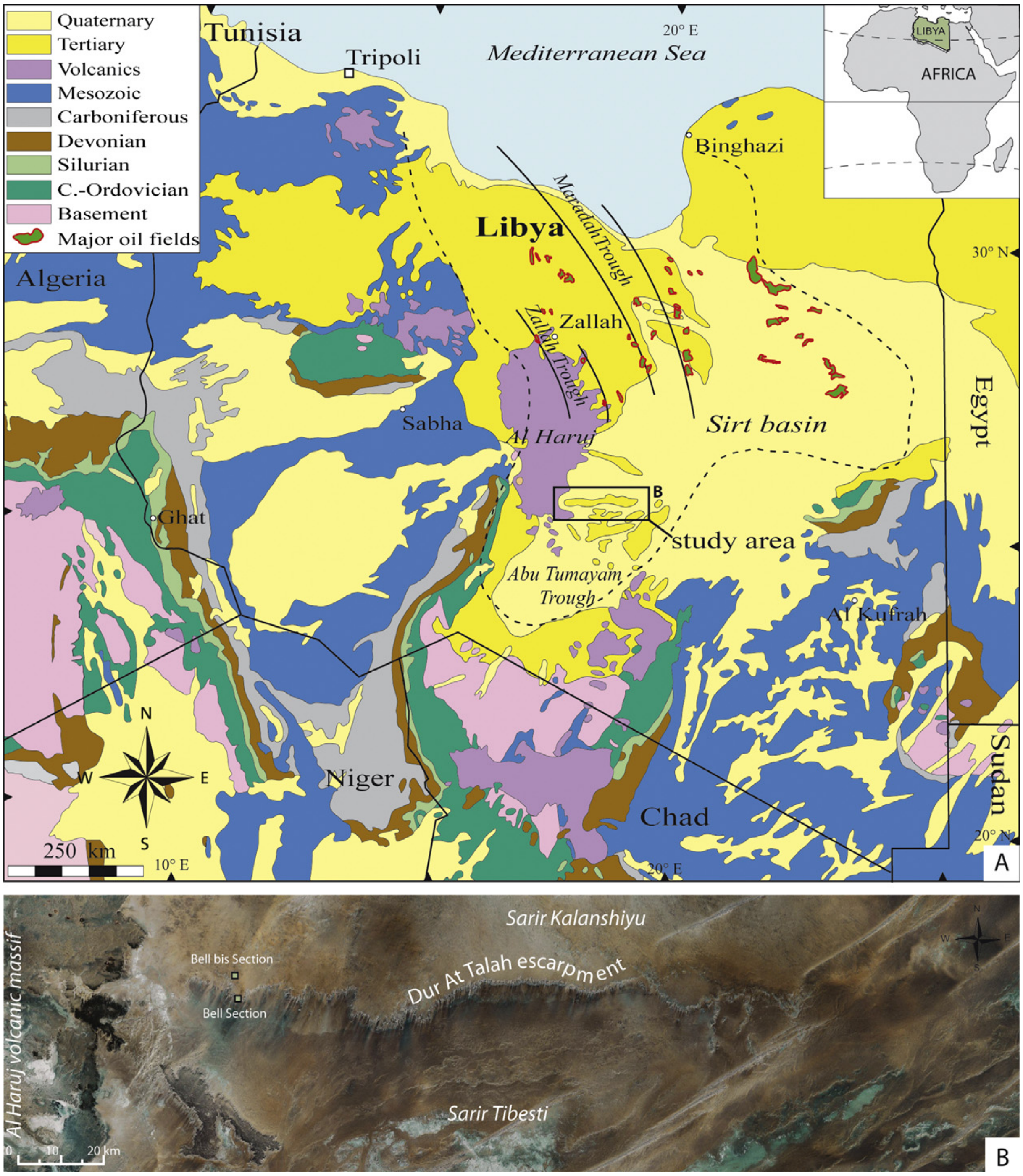

Fig. 1. Location maps of the study area. (A) General geologic map of Libya (modified after Rubino and Blanpied, 2000) showing the outline of the Sirt Basin (dotted line) and the location of the Dur At Talah escarpment (rectangle). (B) Satellite view (CNES/Spot Image, Google Earth capture) of the study area shows the East–West oriented escarpment, with the location of studied sections.

Magnier (1961). Recent geologic contributions at the Dur At Talah escarpment are attributed principally to Wight (1980), Vasic and Sherif (2007) and Jaeger et al. (2010a,b). The work of Wight (1980) is mainly focused on stratigraphy, paleontology and to a lesser extent on sedimentological aspects. The study by Vasic and Sherif (2007) provides the first geological map of the region including a new stratigraphic division; where the Dur At Talah sequence is assigned as a "Formation". The papers by Jaeger et al. (2010a,b) propose a reevaluation of the age of the deposits (Late Bartonian, between 39 and 38 Myrs) and reveal new paleontological assemblages (primates and rodents). Concerning the fossil content, close resemblance of the Dur At Talah sequence with Jebel Qatrani and Qser As Sagha formations of Fayum is reported (Savage, 1971; Wight 1980; Rasmussen et al., 2008; Jaeger et al., 2010a,b). The principal aim of this paper is to identify and describe the main facies assemblages including an attempt to interpret the depositional environments and their successions, which have until now received only scant attention. Micropaleontological investigations as well as organic matter analyses have been performed in order to support environmental interpretations. For the first time in

Dur at Talah, typical tidal depositional processes are evidenced and a close relationship between tidal, fluvial-influenced tidal and fluvial depositional environments is highlighted. As a result, the former stratigraphic subdivisions have been slightly modified.

2. Geological and stratigraphical aspects

2.1. Sirt Basin's hydrocarbon importance

The Dur At Talah outcrop is located at the south-eastern edge of the Al Haruj Basaltic complex. To the north it is bounded by the plateau of Sarir Kalanshiyu and by the plain of Sarir Tibesti to the south; these morphological elements (Fig. 1) belong to southern extremities of the Sirt basin. This basin or embayment (e.g., Conant and Goudarzi, 1967; Goudarzi, 1980) is one of the youngest sedimentary basins of the African craton (Gumati and Kanes, 1985). The Basin is well known as one of the world's largest hydrocarbon bearing provinces, located in the North African margin. It is one of the world's top 20 petroleum provinces (Abadi et al., 2008). Hydrocarbon is produced from reservoirs varying in age from Cambrian to Tertiary, from both horst and graben systems. Upper Cretaceous marine shales are the dominant source rocks. The basin's recoverable reserves are about 45 billion barrels of oil and 33 trillion cubic feet of gas (Abadi et al., 2008). Recent exploration suggests more hydrocarbon potential in the grabens, among which are the Marada, Zallah, and the Abu Tumayam (sometimes known as Dur At Talah) Troughs (Hallett and El Ghoul, 1996; Gruenwald, 2001; Hallett, 2002; Abadi et al., 2008). To date, exploration activities are still ongoing in many parts of the basin.

2.2. Tectonic setting of the Sirt Basin

The basin has long been considered as part of the Tethyan rift system (e.g., Hallett, 2002; Abadi et al., 2008; Capitanio et al., 2009). It reflects significant rifting in the Early Cretaceous and syn-rift sedimentary filling from Cretaceous to Eocene, and post-rift deposition in the Oligocene and Miocene (e.g., Ahlbrandt, 2002; Abadi et al., 2008). It seems that the accurate age for the Sirt basin is not yet precisely defined. Selley (1968) reported that the Sirt Basin developed at the end of the Cretaceous, but began to form in the Late Jurassic-Early Cretaceous. According to Goudarzi (1980), the Sirt basin generally remained a positive element until nearly the end of Cretaceous at which time movement and deformation (block faulting) took place. Then the Sirt area was generally submerged, probably for the first time since the Early Paleozoic area. The period of the Late Mesozoic-Early Cenozoic appears to have been relatively more eventful from the view point of tectonic evolution and the attendant sedimentational history (Sinha and Mriheel, 1996). The large scale subsidence and block faulting that began in the Late Cretaceous continued intermittently into the Miocene (Goudarzi, 1980). As a result, a complex structural pattern of northwest-southeast trending horsts and grabens was formed, and continued to develop until at least the Miocene (Selley, 1968). Ahlbrandt (2002) reports that rifting in the Sirt Basin terminated in the Early Tertiary.

2.3. Infilling of the Sirt Basin

In the troughs (i.e. grabens) of the basin, the thickness of sedimentary rocks to the basement exceeds 7000 m. This sedimentary infill ranges in age from Cambro-Ordovician to Quaternary (e.g., Sinha and Mriheel, 1996). The Early Paleozoic history of the basin reflects a relatively undisturbed intracratonic sag basin (Bellini and Massa, 1980) as part of the Gondwana continent. Cambro-Ordovician siliciclastic sedimentary rocks are only locally preserved (El-Hawat et al., 1996). These rocks occur today as erosional remnants occupying some parts of the basin floor. Rocks of Silurian-Devonian age are known only from few localities in the basin. Furthermore, there are no reports as yet of rocks of Carboniferous-Permian age (Sinha and Mriheel, 1996). Devonian to Triassic rocks are evident in some parts of the basin (Tawadros, 2001). The area was probably positive during these periods, attributed to the Hercynian Orogeny (Conant and Goudarzi, 1967; Bellini and Massa, 1980). Jurassic to Early Cretaceous sandstones known as "Continental Mesozoic" or "Nubian Sandstones" uncomfortably overlies Early Paleozoic rocks. Sediments of Late Cretaceous to Late Miocene age include marine carbonates, evaporites and shales, and paralic non-marine sandstones and shales, (e.g., Selley, 1968; Sinha and Mriheel, 1996). The basin witnessed several phases of marine transgressive episodes interrupted by periods of regression (Gumati and Kanes, 1985; Sinha and Mriheel, 1996).

The main source of clastic material supplied to the study area as well as to the Sirt Basin in general, was the higher hinterland to the south, around Tibesti Massif, where the basement as well as Paleozoic and Mesozoic rocks was continuously exposed (e.g. Barr and Weegar, 1972; Benfield and Wright, 1980; Hallett and El Ghoul, 1996; Ahlbrandt, 2002; Vasic and Sherif, 2007). A major marine transgression in Paleogene times extended southward, from the basin centre far into the embayment (epicontinental sea; Bradly et al., 1980; Gumati and Kanes, 1985). During the Late Eocene, this transgression had reached the Tibesti area and possibly beyond (e.g., Barr and Weegar, 1972; Benfield and Wright, 1980). This transgression is best recorded by the marine fossil dominated carbonate rocks (Wadi Thamat Formation) exposed beneath the Dur At Talah strata. Post-Eocene sediments in the basin were deposited in the period of overall regression which commenced with the onset of Oligocene (Benfield and Wright, 1980). In North Africa, Upper Eocene-Lower Oligocene sedimentary sequences resembling that of Dur At Talah are reported (Bown, 1982; Abdel-Fattah et al., 2010; Underwood et al., 2011) in the area of the Fayum depression (Egypt). Fossil assemblages of both sequences are also comparable (e.g., Savage, 1971; Wight, 1980; Jaeger et al., 2010a).

2.4. Dur At Talah geological setting

In the Dur At Talah escarpment three morphological elements can be distinguished (Fig. 3): (i) the low-relief plain to the South (Sarir Tibesti) covered by Quaternary loose sediments, (ii) the prominent slope (clay to fine sandstones) to the subvertical cliff (fine to coarse sandstones) which together form the core of the escarpment and extend East–West along latitude 25°45′N (Fig. 1), and (iii) the upper plateau, capping and extending to the North (Sarir Kalanshiyu), marked by scattered hills made of coarse to microconglomeratic sandstones.

For the Dur At Talah escarpment, a stratigraphic subdivision (Fig. 2) into three units was first proposed by Wight (1980): Evaporite Unit in the basal part, Idam Unit in the middle, and Sarir Unit for the top. Evaporite Unit was introduced because of apparently large occurrences of gypsum. However, field observations reveal that fibrous gypsum fills bedding planes and vertical cracks (Fig. 5B). Thus it is the result of post-depositional processes (i.e. secondary gypsum). Therefore, the pertinence of the term "Evaporite Unit" is questionable. Idam Unit, *sensu* Wight (1980), corresponds to fine arenaceous sediments that are rich in vertebrate remains. Sarir Unit *sensu* Wight (1980) refers to the cross-bedded sandstones that form the typical vertical cliff (~25 m thick). Conglomeratic sandstones (reported by the present article as the upper part of Sarir Unit) capping the cliff were not reported by Wight (1980). Recently, the "Dur At Talah Formation" has been introduced by Vasic and Sherif (2007) in the first published geological map of this area. This formation was split into two members by

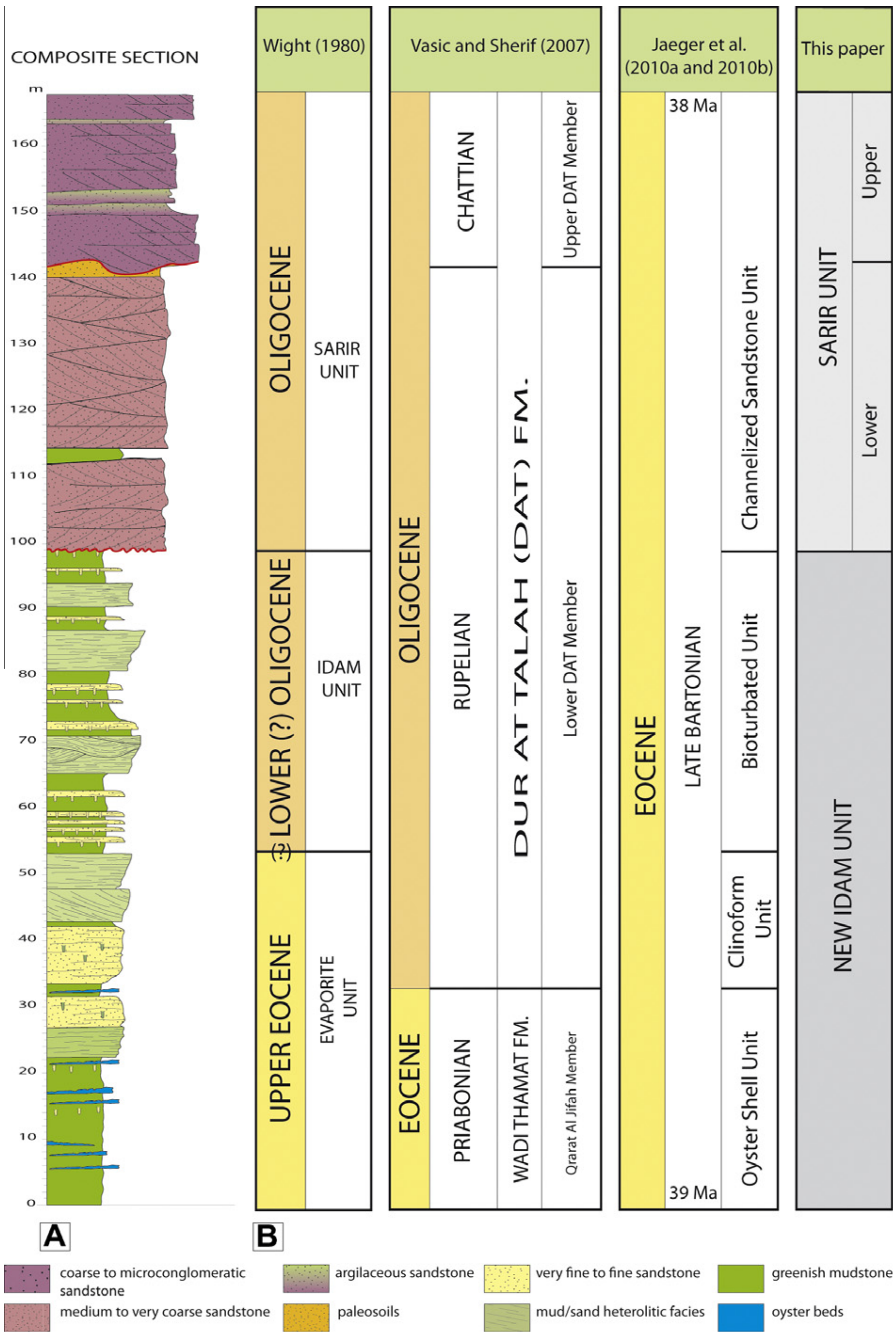

Fig. 2. Stratigraphy of the Dur At Talah megasequence. (A) Simplified sedimentological section. (B) Existing and proposed stratigraphic subdivision.

the same authors (Fig. 2): (i) the Lower Member starts above the uppermost observed oysters bed and is divided into two parts (lower part: dominated by fine clastics, rich in fossil vertebrates; upper part: dominated by medium grained cross-bedded sandstones, rich in petrified wood), and (ii) the Upper Member consists of coarse sandstones. A gradational contact separates the Dur At Talah Formation from the underlying carbonate rocks of the Wadi Thamat Formation. The latter is ended with interbeds of oysters and clay beds *sensu* Vasic and Sherif (2007).

In the present article a new stratigraphic subdivision into two units is proposed (Fig. 2) for the Dur At Talah sequence. The major morphological change happens at the transition from the prominent slope to the steep cliff (Fig. 3). Geologically this change corresponds to a sharp contact between claystones to poorly cemented fine sandstones below, and the overlying medium to coarse sandstones. Thus, practically two different units can be easily distinguished. Due to the facts that the Evaporite Unit (Wight, 1980) has no depositional meaning and that no significant lithological differences are evident with the Idam Unit, both Evaporite and Idam Units of Wight (1980) have been grouped in this article to form a single unit. This unit is named "New Idam Unit" (Figs. 2–4). For the upper part of the Dur At Talah sequence, the name "Sarir Unit" formerly proposed by Wight (1980) remains unchanged (Fig. 3). From a paleontological point of view, the New Idam Unit is characterized by fossils of vertebrates and the Sarir Unit is dominated by large silicified tree trunks. Similarities

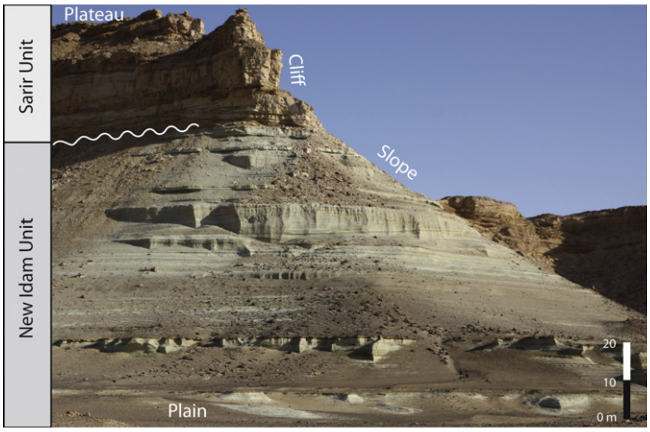

Fig. 3. General view of the Dur At Talah escarpment. Typical morphology is characterized by a vast plain below, a moderate slope in the middle part and a steep cliff followed by a plateau above. Morphologically, two rock units could easily be distinguished.

in paleontological contents between Dur at Talah and Jebel Qatrani have already been noticed (e.g. Savage, 1971; Wight, 1980; Rasmussen et al., 2008; Jaeger et al., 2010a). Striking similarities also exist when comparing the sedimentology of Dur at Talah with that recently reported from the Jebel Qatrani Formation (Abdel-Fattah et al., 2010; Underwood et al., 2011).

The age of the studied outcrop was assigned to the interval from the uppermost Eocene to the lowermost Oligocene by Bellair et al. (1954), based on paleontological assemblages. According to proboscideans remains (*Barytherium* and *Moeritherium*) Arambourg and Magnier (1961) assigned the Late Eocene (Priabonian) age for the lower part of the escarpment, as compared to the Fayum outcrop (Egypt). This age was accepted by Savage (1971). Thus, Upper Eocene to Lower Oligocene age was proposed for the sequence by Wight (1980), also by analogy with Fayum deposits. Vasic and Sherif (2007) acknowledged Lower Oligocene age assigned by Peregi et al. (2003) for equivalent rocks exposed in areas adjacent to the Dur At Talah. It is worth mentioning that in the subsurface of the Sirt Basin, the Oligocene-aged Arida and Diba Formations described by Barr and Weegar (1972) bear nearly similar lithological characteristics to those of the upper part of the Dur At Talah sequence. These two formations are known to be oil reservoirs. Recently, Late Middle Eocene (i.e. Late Bartonian, 38–39 Myrs) age for the Dur At Talah sequence has been proposed by Jaeger et al. (2010a, 2010b), based on rodent and proboscidean remains collected from the New Idam Unit, and supported by paleomagnetic investigations.

3. Depositional facies of the Dur At Talah escarpment

The Dur At Talah escarpment rock sequence is divided into two units (Fig. 4): the New Idam Unit (basal part) and the Sarir Unit (upper part). Three main facies associations characterize the New Idam Unit: (i) oyster shell beds/green clays alternation facies, (ii) very fine sand to mud alternation (tidalite) facies and (iii) green clays/sands alternation facies. Two main facies associations characterize the Sarir Unit: (i) medium grained cross-bedded sandstone facies association and (ii) very coarse sandstone (fluvial) facies association.

3.1. Facies associations of the New Idam Unit

This unit has a total thickness of at least 90–100 m., and it overlies the marine carbonates of the Wadi Thamat Formation. The New Idam Unit (Figs. 2–4) displays a thinly stratified nature formed by green to grey claystones and siltstones, alternating with fine grained, poorly cemented sandstones having light grey to white colour. This unit occupies the foot of the escarpment until the base of the sandstone ledge of the overlying Sarir Unit. The greatest part of the facies associations composing the New Idam Unit displays sedimentary and biogenic features characteristic of a shallow marine environment. Lots of facies show strong evidence for tide processes. Bioturbation is common, occurring in variable densities at many levels of this unit.

3.1.1. Oyster shell beds/green clays alternation facies

Prominent oyster banks (Fig. 5A and B) are exclusively exposed all along the base of the scarp and characterize the bottom of the section (Fig. 4). The section consists of a repetition of oyster banks interbedded commonly with green clays. Oyster beds are laterally discontinuous. However, several vertical cross-sections allow reckoning up to sixteen successive beds. The oyster banks seem to form more or less lenticular "patches" with flattened bases, and are moderately thick (60–70 cm for maximum thickness). The lateral maximum extension observed generally does not exceed 1 km. Based on their size and morphology, oyster shells can be subdivided into two types. The most common one is dominated by small oysters (centimetric scale; Fig. 5C and D), and the second is dominated by large oysters (decimetric scale; Fig. 5E and F). According to Vasic and Sherif (2007), the small oysters are *Ostrea (Lopha) nicasei* and *Ostrea (Lopha) morgani*. The large oysters are *Ostrea roncana*. Ceriths (*Serratocerithium serratum*) and turitels (*Turitella sp.*) are uncommonly associated with oyster shells beds. Oyster shells commonly occur with both valves preserved and are obviously fixed one on each other thus forming reef-like constructions. *Ostrea roncana* (large oysters) are often bored by organisms such as pholads and sponges (*i.e.* T*rypanites* ichnofacies; Fig. 5F) and in seldom cases, encrusted by small barnacles.

The oyster banks are interbedded with green claystone levels (from centimetric to plurimetric scale) with a sharp contact. Some remains of plants can be found in the green clays and some remains of vertebrates (fish, proboscideans, crocodilians and turtles) are embedded in both green clays and shell beds (Fig. 6). Contrary to the oyster shell beds, green clay levels have a good lateral continuity and can be traced over few kilometres. The green clays and oyster bank alternations attain a total thickness of about 20 m. Some brown sandstone layers are interbedded with the oyster shell beds and are strongly bioturbated. The bioturbation is sinuous in the bedding plane view and shows, in vertical section, a strong vertical adjustment (retrusive spreiten) that is typical for *Teichichnus sp.* (Fig. 7).

Biostromal organization of the shells, welded together, as well as the occurrence of oysters with both of their valves, suggests that the oyster beds are mainly the result of autochthonous deposit rather than being accumulated after transport. It is particularly obvious for the largest oysters preserved in living position. The occurrence of T*rypanites* ichnofacies is characteristic of shallow marine conditions (e. g., Bromley, 1992). The corresponding depositional environment could be foreshore to backshore, possibly lagoonal, as suggested by the presence in the same units of vertebrate remains (fish and crocodilians); some of them being continental like the proboscideans (*Barytherium* and *Moeritherium*; Arambourg and Magnier, 1961; Savage, 1971; Wight, 1980; Rasmussen et al., 2008; Jaeger et al., 2010a,b).

3.1.2. Very fine sand to mud alternation facies (Tidalite)

This facies is identified in beds (packages) that have a thickness varying from 2 to 9 m. Each bed is composed of very fine sand to mud alternating layers. Internal individual layers have a thickness ranging from few mm to few cm. This facies displays many

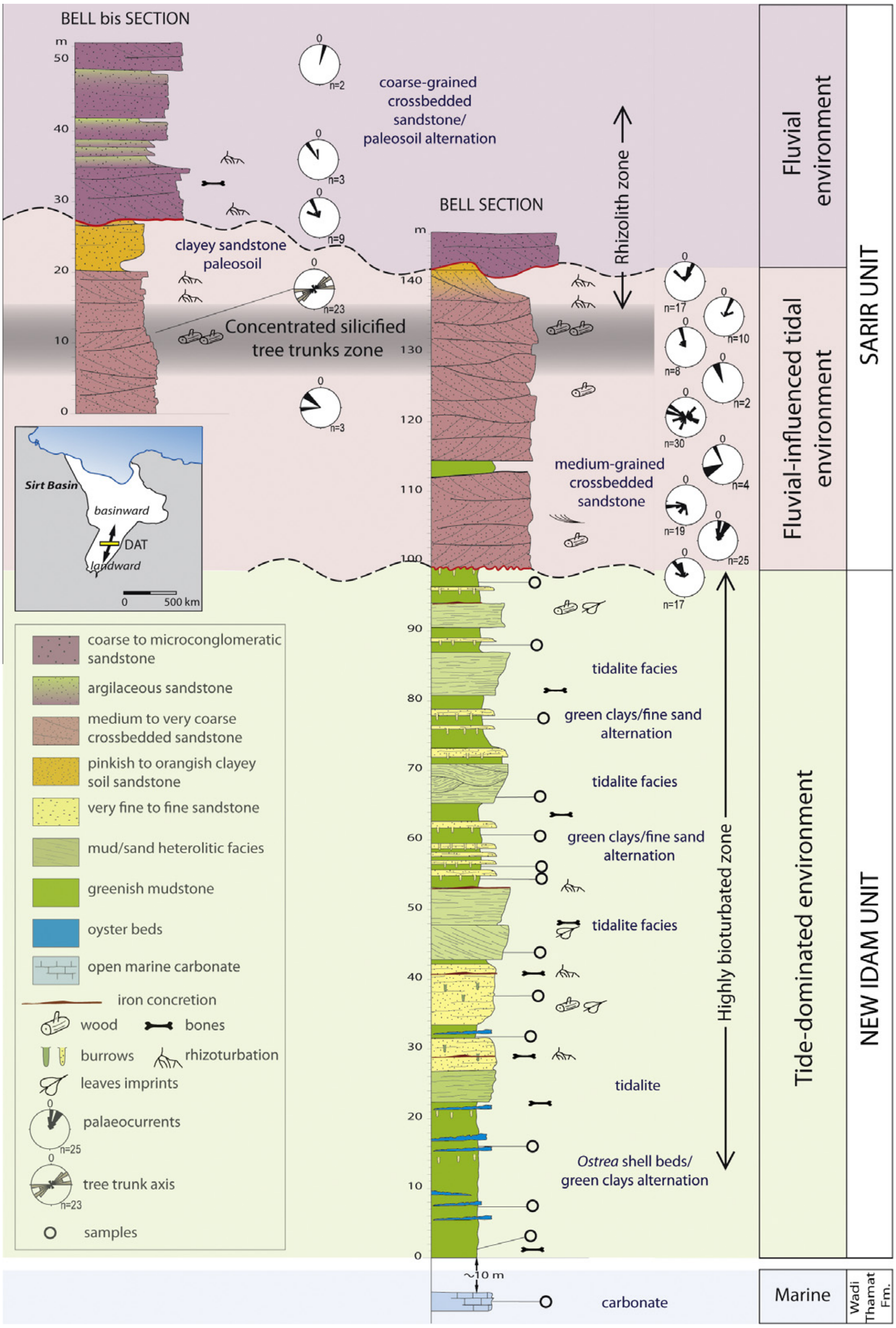

Fig. 4. Representative geological section pieced together from two locations (Bell and Bell bis; Fig. 1B) showing main facies, lithologies, common sedimentary features, and locations of the samples analysed for micropaleontology and biomarkers.

sedimentary features that are typical of tidal deposits. Generally, in the sedimentary record, the most important criterion to recognize tidalite is millimetric to centimetric vertical mud-sand alternations, double mud-drapes, combined sometimes with current reversal (e.g. Klein, 1970, 1971; Allen, 1980; Dalrymple et al., 1991; Lanier et al., 1993; Tessier, 1998). Other diagnostic tidal criteria are the occurrence of current/wave ripples associated with mud drapes as well as vertical laminae thickness increasing/decreasing attributed to neap-spring tide alternation (e.g. De Raaf and Boersma, 1971; De Boer et al., 1989; Choi et al., 2004).

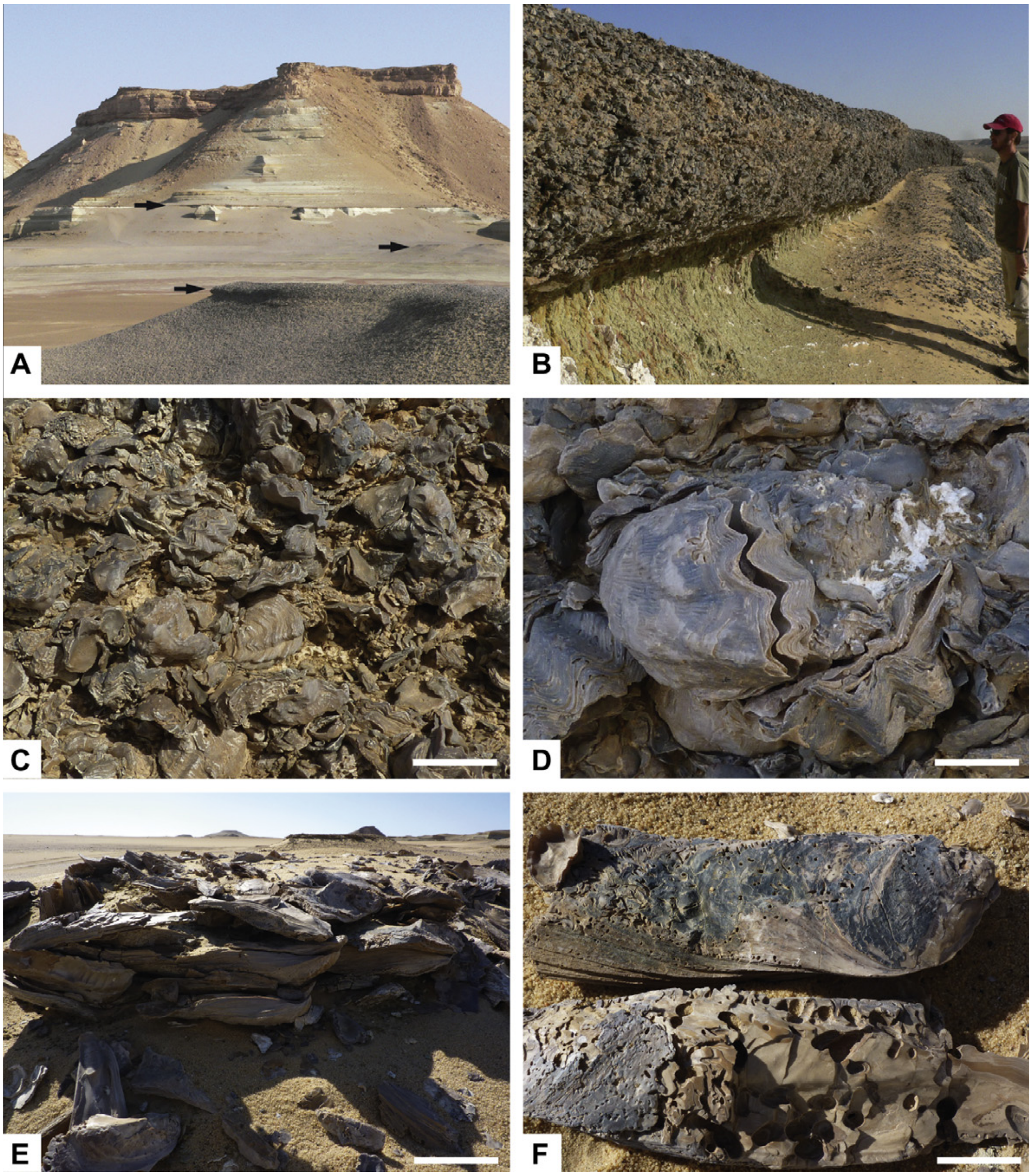

Fig. 5. Oyster beds from the oyster shell beds/green clays alternation facies. (A) Large scale view showing several fossil oyster banks (black arrows) at the base of the scarp. (B) Close view of one prominent oyster bank, overlying green clays, with fractures in the green clay filled by secondary gypsum (white colour at the bottom left of the photo). (C) Shells of small oysters (*Ostrea nicasei*?) (scale bar: 4 cm). (D) Close view showing both valves joined together (scale bar: 2 cm). (E) *In situ* large oyster shells (*Ostrea roncana*?) (scale bar: 10 cm). (F) Large oyster shells showing perforations caused by various organisms such as pholads (biggest perforations), annelids and sponges (scale bar: 5 cm).

Current ripples associated with mud drapes are widely observed here, and display a rhythmic alternation of sand and clay drapes (Fig. 8). The wavelength of these ripples varies from <10 to 25 cm. The current ripple cross laminations often reveal a palaeocurrents bidirectionality. Combined with mud deposits, they form typical flaser/wavy/lenticular beddings, such as those described by Reineck (1963) and Reineck and Wünderlich (1968). These characteristic features are directly driven by the periodic alternation of high (flood and ebb) and low (slack time) energy in tidal regime. Occasionally, it is possible to observe opposite palaeocurrents forming "herringbone" structures (Fig. 8A and B).

Thickness variations of the sand layers indicate flood-ebb asymmetry of tidal currents. Taking into consideration that north is the basin ward (e.g., El-Hawat et al., 1996; Abadi et al., 2008; Rasmussen et al., 2008), most of the time the ebb seems to be the dominant current whereas the flood is the subordinate current. Moreover, the asymmetry between flood and ebb tides and the number of mud couplets (double drapes) within neap-spring cycles indicates that the nature of the tidal regime seems to be semidiurnal (i.e. two tides a day; e.g. Kvale and Archer, 1991).

A rhythmical vertical variation in thickness of the sand/clay alternations is also a blatant outcrop feature frequently observed in this facies (Fig. 8C). Indeed, when the thickness of the sandy levels dilates, lamina or clay drapes become thinner or do not exist. On the contrary, when the sandy levels are very much contracted, clay drapes are thicker, flat and directly stacked. This dilation/

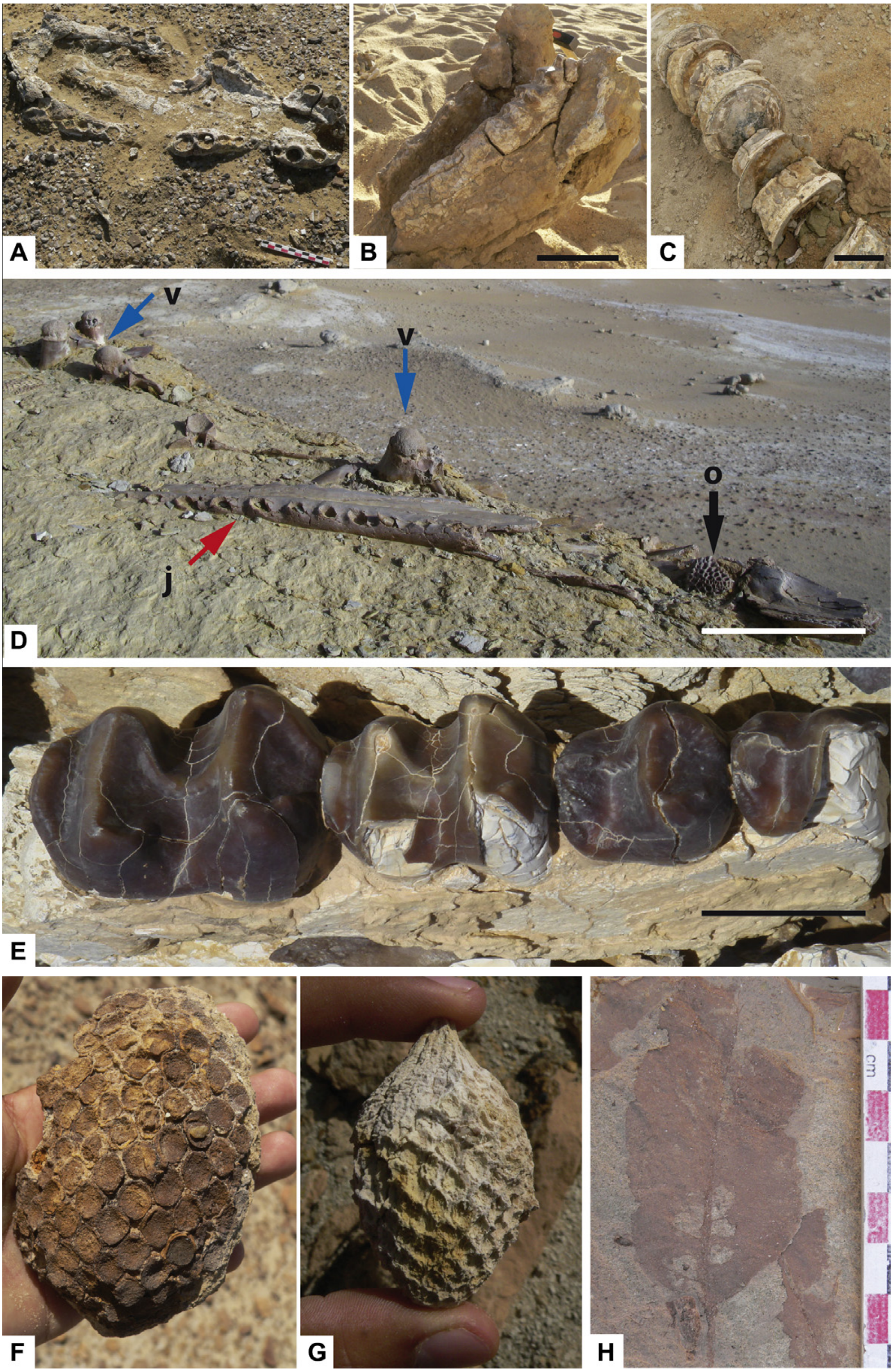

Fig. 6. Various vertebrate and flora remains from the New Idam Unit. (A) Mandible of crocodile found in green clay/oyster banks facies (scale is 10 cm long). (B) Mandible of *Barytherium sp*. (scale bar: 20 cm). (C) Backbone, probably shark, (scale bar: 3 cm). (D) Gavialid crocodilian remains including vertebras (v), jaw (j), osteoderm (o) (scale bar: 30 cm). (E) Jaw of proboscidean with well-preserved teeth (scale bar 5 cm). (F and G) Examples of fossil fruits. (I) Example of leafs imprint found in some green clay and silty clay levels.

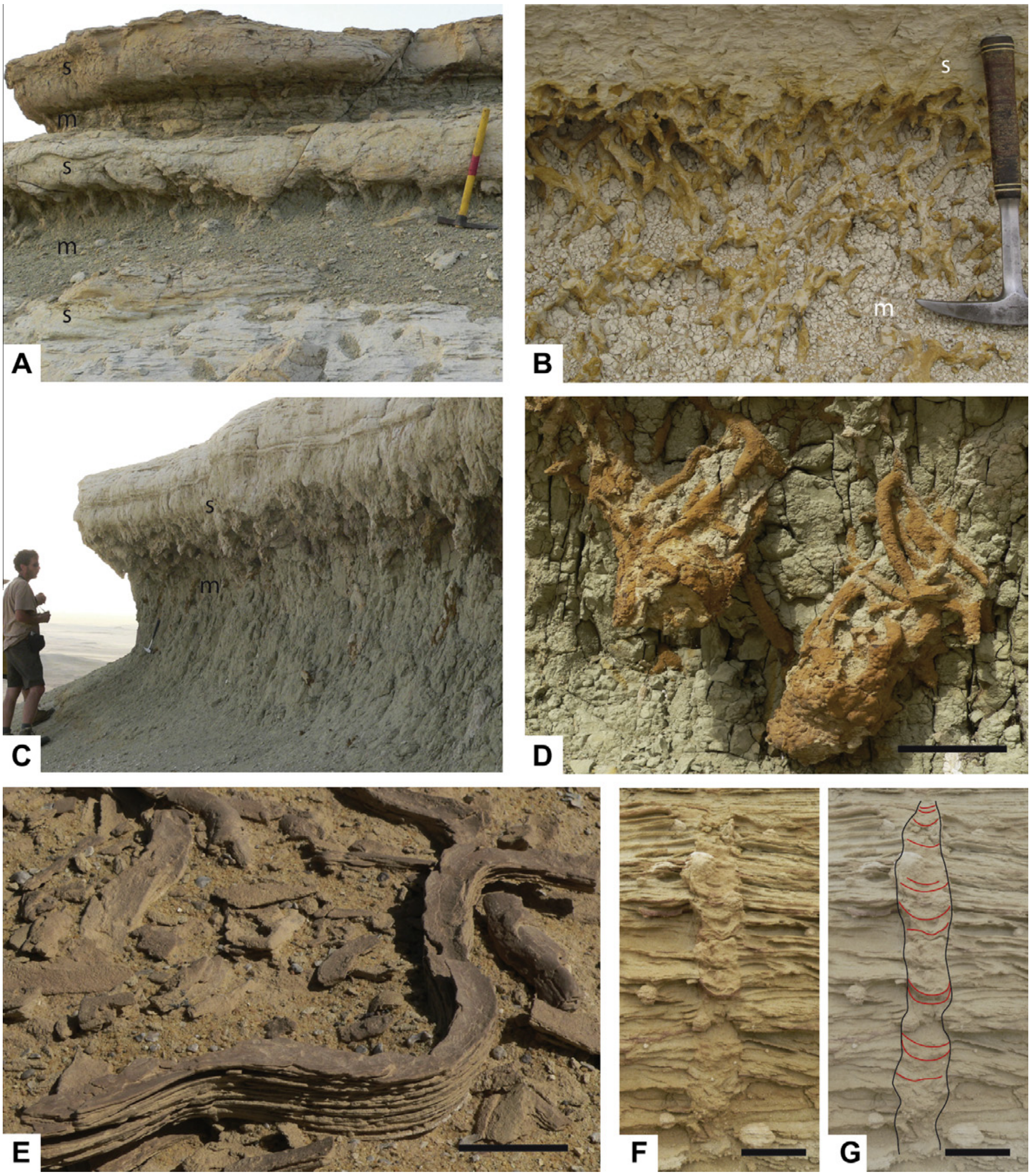

Fig. 7. Characteristic trace fossil from the New Idam Unit. (A) Repetitive sequences of bioturbated sand (s)/mud (m) cycles (hammer for scale). (B) Close view of the intensively bioturbated (mainly *Thalassinoides isp*) sand (s)/mud (m) contact zone. (C) Large bioturbations in sand (s)/mud (m) sequences. (D) Close up view of the bioturbation from (C): showing large burrows filled by small burrows (*Thalassinoides isp.*). (E) Bedding plane view of sinuous *Teichichnus isp*. (scale bar: 3 cm). (F) and (G) Vertical view of *Teichichnus isp*. showing vertical adjustment of the burrows (scale bar: 2 cm).

contraction in the thicknesses (Fig. 8C) is another criterion typical for tidal rhythmicity. It seems to correspond to neap-spring periods generated by longer wavelength lunar cycles (Lanier et al., 1993). Observation from different outcrops show that this facies is either dominated by the sandy fraction (in current ripples), or dominated by the clayey fraction (with finely laminated drapes). The clayey fraction is often dark, fissile, and contains imprints of plants (leaves and small plant fragments; Fig. 6H) suggesting a terrestrial proximity. These tidalites contain also *Teichichnus isp.* (Fig. 7E and F) showing a strong vertical adjustment (retrusive *spreiten*) that suggests a high sedimentation rate.

In terms of geometry, the outcrops where tidalite facies occur are characterized by tabular stratification evolving laterally into large clinoforms. These later appear in packages of inclined strata (Fig. 9) with an average inclination of the master bedding up to 15°. These clinoforms can be traced laterally over at least several hundred of metres for heights up to 15 m. The clinoform morphology is the most common and fascinating large-scale structure from the New Idam Unit. Two types of clinoform can be distinguished according to the relative orientation of the internal current ripples to master bedding. When current ripples are more or less perpendicular to the dip of the master bedding, structures can be considered as the result of lateral accretion, which probably corresponds to inclined heterolithic stratifications (IHS) of point bars in a meandering tidal channel system (e.g., Thomas et al., 1987; Choi et al., 2004). When current ripples are pointing in the same direction

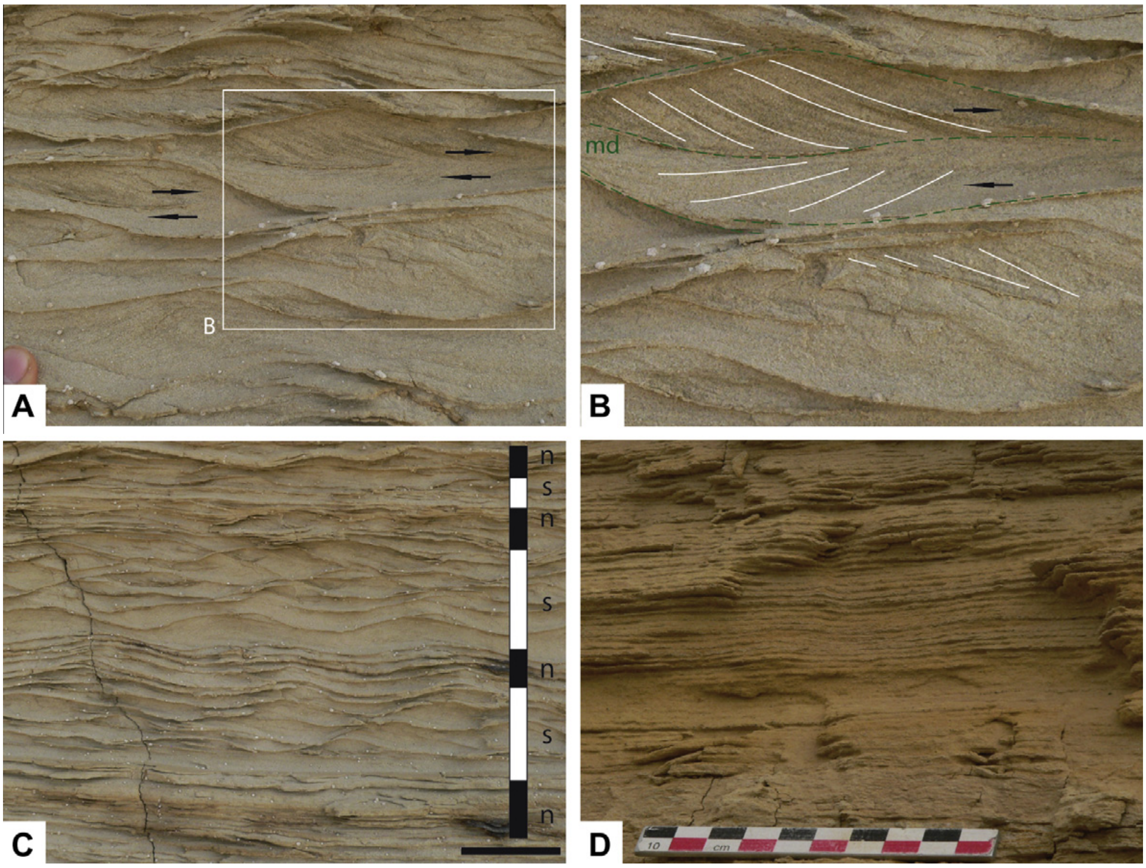

Fig. 8. Diagnostic tidal sedimentary structures commonly found in the New Idam Unit. (A) Current ripple laminations in fine sand interrupted by well-preserved mud drapes (finger at the lower left corner for scale). (B) Close view from (A): illustrating the bipolar current structures "herringbone", (black arrows indicate palaeocurrents) reversal, opposite ripples are separated by discontinuous mud drapes (md: green dotted lines). (C) Tidal rhythmicity preserved as neap (n) spring (s) cycles, displaying climbing current ripples laminations (scale bar: 15 cm). (D) Typical vertical accretion of tidal rhythmites.

as the dip of the master beddings, the clinoform then reflects progradation processes (tidal bar system). Both types of clinoforms pass laterally into the tidal flat. Most probably, they represent two types of tidal bars: point bar and longitudinal bar.

3.1.3. Green clay/fine sand alternation facies

This facies corresponds to an alternation of whitish, fine, well-sorted sandstone (20 cm to 1 m thick) and green clay beds (up to 3 m thick). The clay/sand alternation forms small repetitive sequences. A sharp contact often separates green clays from the overlying sand which is highly bioturbated, whereas the transition from sand to clays is often gradational. This sequential rhythmic repetition (Fig. 7A) is observed principally in the median part of the New Idam Unit. The sands display current ripple laminations, sometimes with interbedded mud drapes (very similar to those represented in Fig. 8A–C). Opposite current ripples (herringbone) are also frequent. Regarding the sedimentary structures, this facies is not that different from those described in the previous tidalite facies (Section 3.1.2 above). Proportionally, sand is more abundant in this facies than in previous tidalites facies. In each sand/clay sequence, the thickness of the current ripples become thinner upward, the grain size decreases and the clay/sand ratio increases to become pure clay. The base of the sandy beds is sometimes marked by a centimetric, microconglomeratic lag with clay pebbles, fossil teeth and bone fragments. These surfaces could correspond to a transgressive lag surfaces expressing flooding events (ravinment surface). Worth mentioning here that the fossils used by Jaeger et al. (2010a,b) for the age dating of the Dur At Talah sequence are collected from such conglomeratic lag. The green clays sometimes display subtle bedding plane polygonal structures (30–70 cm wide), suggesting possible desiccation cracks. These structures are filled with sand, and occasionally by with gypsum. Furthermore millimetric scale root marks are evident in some sandy levels.

Bioturbation is very frequent in this succession (green clay/sand alternation facies) especially at the base of the sand. Locally it causes total destruction of the primary sedimentary structures. Bioturbation consists of sand-filled vertical burrows starting from the sand bed and penetrating into the underlying clays (Fig. 7A–D). Two common sizes of burrows exist. The most plentiful burrows (Fig. 7B), are about 1 cm in diameter and up to several tens of centimetres long. They show box work framework with numerous dichotomies characterized by a typical enlargement at the intersection knots. The larger sized burrows (Fig. 7C and D) measure around 10–20 cm in diameter and are up to 80 cm long. They often display an obvious funnel-like shape. In many cases, these big bioturbations are filled by an intertwined network of smaller burrows. For the latter, the complicated organization of the burrows in all directions (as well as the typical enlargement at the intersection, signal the ichnogenus *Thalassinoides* that could be interpreted as the burrow of crustaceans (crabs, mud shrimps, and prawns; exceptionally, one claw of crab has been found in this facies). The interpretation of the large bioturbation is not yet well established. The funnel-like shape could correspond to the external mould of a root of a medium size plant (possibly main roots of mangrove) that could be reused by crustaceans.

The sedimentary features observed in the sand of facies are very similar to those from the tidalites facies described above. This

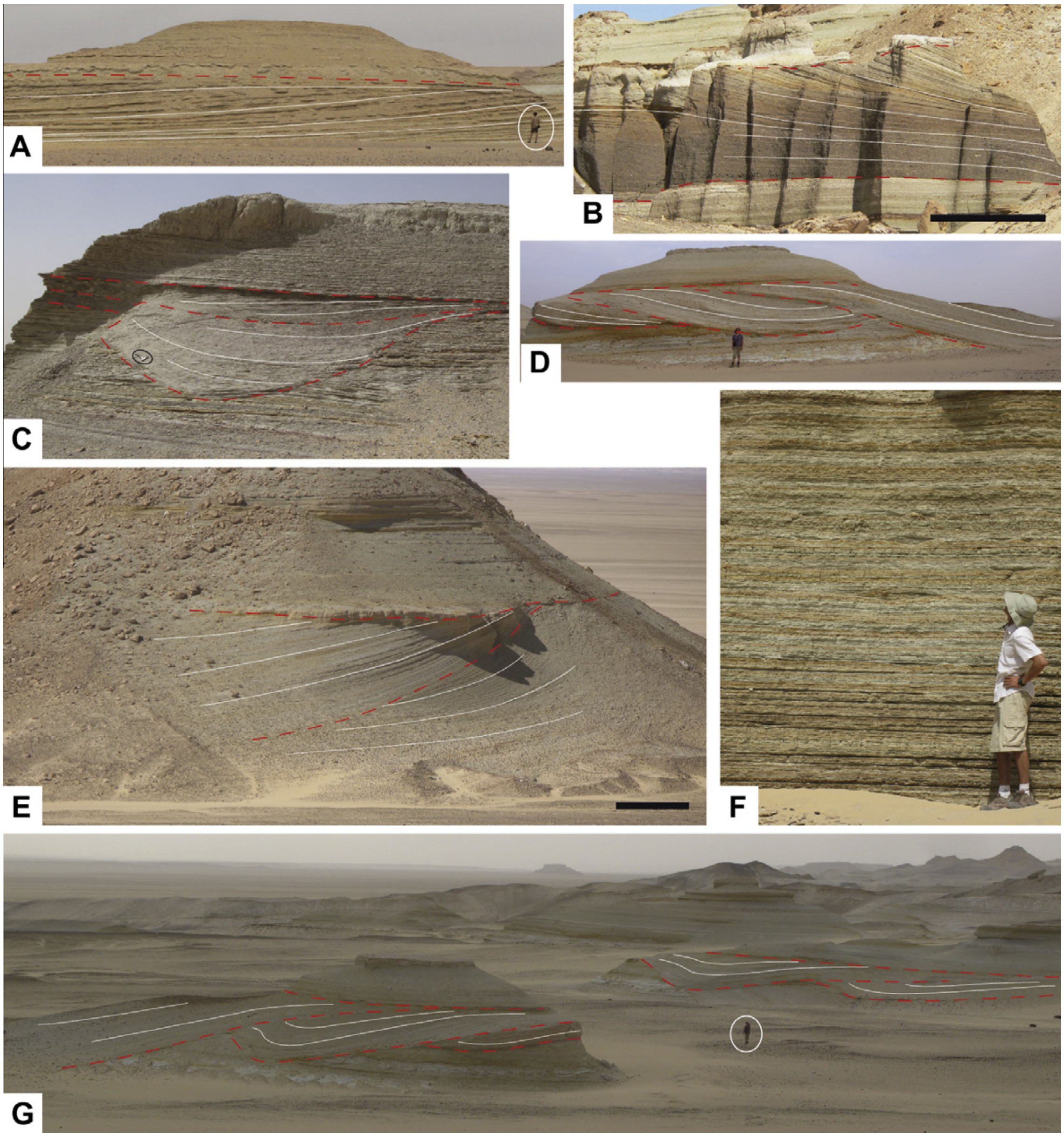

Fig. 9. Large scale geometries (clinoforms) of the New Idam Unit. (A) Lateral accretion in tidal channel point bar where mud/sand ratio variations generate inclined heterolithic stratifications (red dotted line: erosive upper contact; geologist for scale). (B) Tidal channel filled by dark muddy tidalites (scale bar: 5 m). (C) Cross section of typical tidal creek infilling (hammer for scale). (D) Amalgamated tidal channels complex (geologist for scale). (E) General view of clinoform truncated by horizontal whitish sandstone strata (horizontal dotted line) and inclined internal truncation (inclined dotted line; scale bar: 5 m). (F) Horizontal heterolithic stratification from tidalites facies (geologist for scale). (G) General view shows the spatial distribution and the relationship between amalgamated channel bodies (geologist for scale).

asserts that tidal environment is also prevailing during the deposition of the green clay/fine sand alternation facies. Features of subaerial exposure suggest interplay between intertidal and supratidal conditions. The sand beds appear as discontinuous layers embedded within the clay-dominated, broad tidal flat. A shallow marine, tide-dominated bay margin system, locally interrupted by mangrove, can be emphasized as a depositional environment for the New Idam Unit.

3.2. Facies associations of the Sarir Unit

The Sarir Unit (50–70 m in thickness) overlies the New Idam Unit. An erosional contact separates the thinly stratified clay/fine sandstone of the New Idam Unit below from the coarse cross-bedded sandstone above. The contact is best pronounced at the western part of the escarpment. Sedimentary structures as well as grain size suggest that the Sarir Unit should be split into two different parts: a lower characterized by medium grained cross-bedded sandstones with common silicified tree trunks, and an upper part made up of coarse to microconglomeratic sandstones, often with abundant rhizoliths.

3.2.1. Medium grained cross-bedded sandstones facies association (Lower part of the Sarir Unit)

This facies constitutes most of the cliff-ledge, and has a persistent thickness of about 25–30 m along the escarpment. The contact between this facies and the underlying unit is marked by a break in the slope; from gentle below the contact, to steep and cliff forming above (Fig. 3). This facies is essentially composed of fine to medium, occasionally coarse cross-bedded sandstones, commonly moderately sorted. It possesses mostly yellow and white colours, often weathered to brown and pink. This sandstone is often intercalated with subordinate occurrences of thin, sometimes lenticular, beds of light grey to white silt and mudstones; thickness varies from few centimetres to few decimetres. Cross-bedding (Fig. 10A and B) is the prevailing sedimentary structure in this facies association. Features of soft sediment deformations such as water escape structures, overturned lamina, and convolute structures are commonly observed at all levels of this facies association. Mud rip-up clasts have also been observed in many levels, and in the basal part of these sandstones they seem to be reworked from the underlying tide-dominated unit. The size of these mud clasts range from granules to boulders of up to 25 cm. occasionally the mud clasts appear as an erosional lag.

In many outcrops the sandstones of this facies show repetition of two slightly different packages. One is dominated by the cross-bedded sandstones, and the other is dominated by cross-laminated sandstones. Individual packages ranges from 3 to 8 m in thickness. Packages are usually separated by erosional surfaces. Each package is composed of amalgamated megaripples and sigmoidal sandstone bars. The prevailing sedimentary structures of these sandstones are trough cross-bedding and, to a lesser extent, planar cross-bedding (Fig. 10A and B). Occasionally, individual sets exceed 50 m in length and are up to 1 m in thickness. Most Paleocurrent measurements indicate water flows from south to north, but with a dispersion of about 40° (Fig. 4). Thick beds presenting nearly southerly palaeocurrents are occasionally observed at the lower part of this facies.

Unlike the tide-dominated facies below, this sandstone-dominated succession includes only very scant bone fragments (possibly of *Barytherium sp.*) that are possibly reworked from the New Idam Unit. Commonly, this succession also includes silicified tree trunks (Fig. 11), embedded mainly in the sandstone with trough cross-bedding, and tree trunks are more frequently observed upward. Apparently the tree trunks are exceptionally well preserved and more prevailing in a several metres thick interval in the uppermost part of these sandstones. Lots of trunks are complete with their stump preserved; many of them having their long axis orientated N–S. Local assemblages display nearly E–W orientations. Some trunks exceed 15 m in length and 0.8 m in diameter. A few

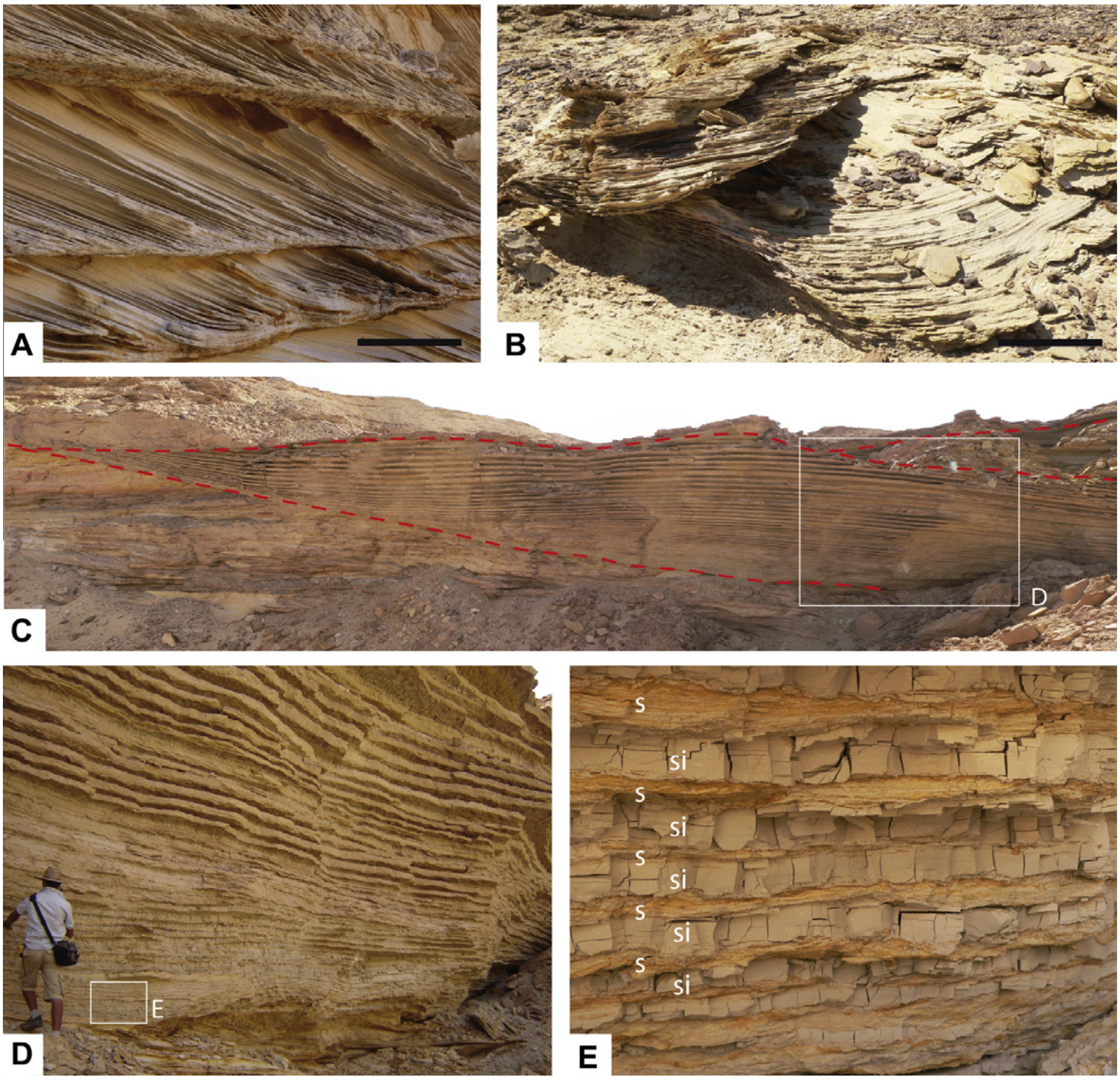

Fig. 10. Medium grained cross-bedded sandstones facies (lower part of the Sarir Unit). (A and B) Planar and trough cross-bedded sandstones (scale bar: 60 cm). (C) Trough-shaped (channel-fill) geometry intersected into the cross-bedded sandstone (width of the photo is ~50 m). (D) Close view of (C) showing systematic thickening and coarsening upward sequences infilling the trough (geologist for scale). (E) Detailed view exhibiting well-organized interbedding of rippled fine sand (s) and laminated silty mud (si) (width of the photo: 1 m).

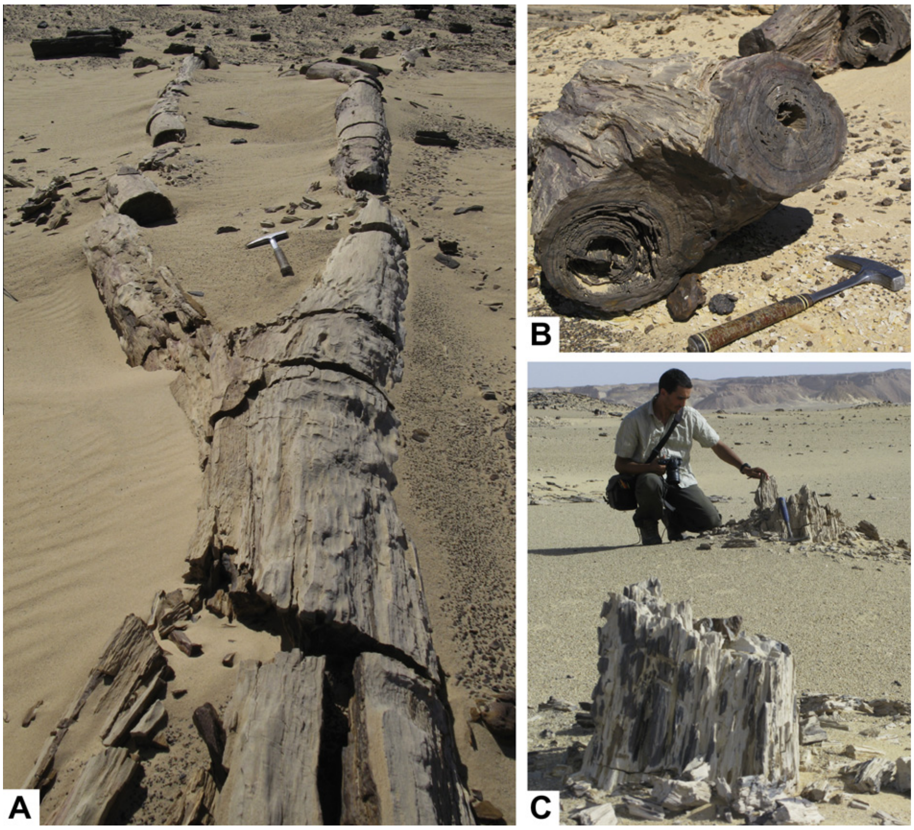

Fig. 11. Silicified tree trunks characteristic of the medium grained cross bedded sandstones facies. (A) Complete and intact tree trunk (hammer for scale). (B) Cross sectional view of silicified trees (hammer for scale). (C) Vertical silicified tree trunks, likely in living position (geologist for scale).

of them are vertical and could be regarded as being fossilized in living position. Levels with small root marks are also frequently observed in this facies.

At many locations along and across this facies (medium grained cross-bedded sandstone), it is intersected by large scale trough shaped bodies, of variable dimensions, and possibly corresponding to large channel-fills (Fig. 10C). The largest ones are up to few hundred meters wide and up to 12 m. thick. These large channel-like bodies are commonly filled with well-organized heterolithic beds (Fig. 10D and E), composed of interbedded fine sand and silty mud. In frequent cases these beds display a well-preserved characteristic thickening upward (Fig. 10D; thickness of single bed ranges from few to 25 cm). In these trough-shaped bodies, internal sedimentary structures observed are principally current ripple laminations, which occasionally grade laterally into small scale low angle cross bedding. The silty mud beds are commonly laminated. The heterolithic nature of the infilling reminds the *Inclined Heterolithic Stratifications* described from point bars (e.g., Thomas et al., 1987).

The dominance of large scale trough and planar cross-bedding associated with the presence of well-preserved petrified wood, as well as the presence of channelizing bodies, all point to a fluvial origin of this succession, as formerly proposed by Wight (1980). Unexpectedly, this facies also exhibits subtle evidence of tidal influence (Fig. 12). Most evident is the bimodal current directions recorded on ripple lamina associated with bundled foresets (Fig. 12A and B); the latter is attributed to the alternating neap-spring tides.

Current bidirectionality is, in modern tide-dominated environments, attributed to changing tidal current directions (e.g., Dalrymple and Choi, 2007). The oppositely directed current ripples are interpreted as the deposit of reversed subordinate current (flood or ebb). Additionally, in these sandstones, one of the best criteria for tidal activity is the presence of mud drapes deposited onto the toe of the foresets of the megaripples (Fig. 12C and D). Many outcrops show the mud drapes combined with reversed ripples (Fig. 12B). Sets with double mud drapes characteristic of a semi diurnal tidal regime are also observed (Fig. 12F). Foresets are formed during flood or ebb, and mud is then deposited during quiet periods (slack water phase). The alternation of such sandy foresets and the mud deposited on its toe has long been described as a conclusive criterion for tidal deposit (e.g., Allen, 1980; Visser, 1980; Dalrympe, 1984; Selley, 1992). Large-scale cross bedded units with mud-draped bottom sets and foresets are present in several shallow-marine sands attributed to tidal sand bodies (Allen, 1982). Associated with these sand/mud couplets are the occurrences of perpendicular current ripple laminations at the toe of the foreset laminae (Fig. 12E). Perpendicular current ripples are typically form at the foot of megaripple foresets in intertidal zone, during ebb tide draining stages (Féniès et al., 1999). Cross-bedded sandstones in this facies display numerous reactivation surfaces which are also common tidal features (Klein, 1970), though not diagnostic. Furthermore, in finer sandstone intervals, flaser, wavy, and lenticular bedding similar to those described in modern tidal environments (e.g. Reineck and Wünderlich, 1968; Ashley, 1990) also occurred.

3.2.2. *Very coarse sandstones facies association (upper part of the Sarir Unit)*

This facies represents the uppermost part of the studied sequence. It attains a thickness of at least 35 m, occupies the top of the escarpment and extends above into the capping plateau as isolated hills and discontinuous mesas. The upper limit of this facies is not detected in the study area. The lower contact commences with a sharp erosional surface incising into the lower part of the Sarir

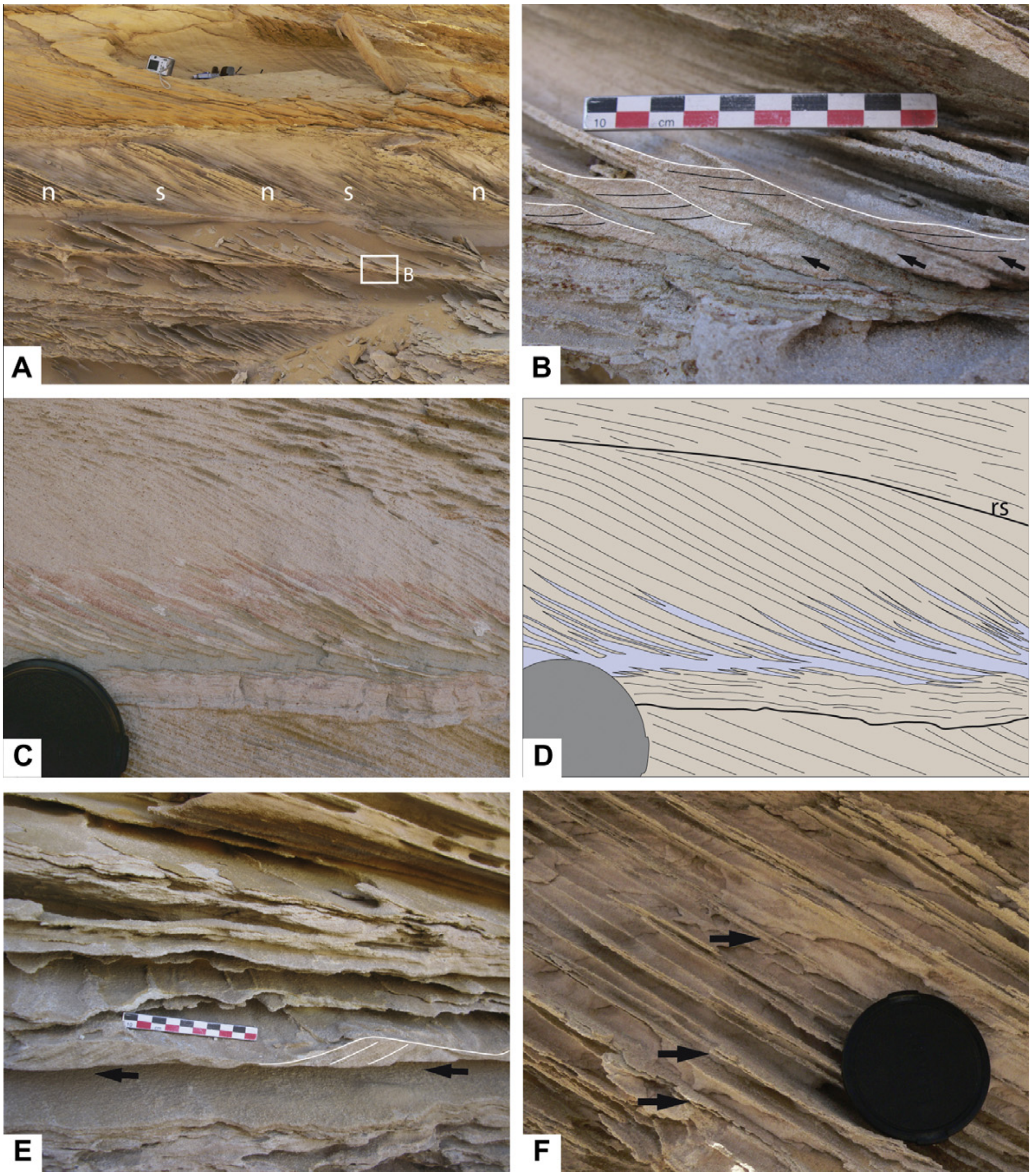

Fig. 12. Diagnostic tidal sedimentary structures in the medium grained cross-bedded sandstone facies. (A) General view of cross-bedded sandstone with regularly spaced, bundled foresets, attributed to neap (n) spring (s) tidal cycles. (B) Close view from (A) showing current ripple lamina (black arrow) climbing on the toes of a megaripple (foreset), the opposite direction records tidal current reversal. Drapes of light green mud can also be noticed. (C) Tangential cross bedding with mud drapes (green colour) laid down on sandy foresets during slack water. (D) Schematic representation of (C), dark line corresponds to reactivation surface (rs). (E) Preserved morphology and internal laminations of draining ripples, flowing perpendicularly to the foresets dip (dip: toward the photographer; arrows for the ripple's direction of migration). (F) Cross section view of foresets displaying subtle double mud drapes (arrow), known for semi-diurnal tidal regime.

Unit. This surface is often strewn with pebbly and granularly lag sediments of quartz composition. The contact is not always well exposed but coincides with the top of the silicified trees interval capping the sandstone underneath. This facies is characterized by coarse grain size, from coarse grained sandstones to microconglomerates. Granules and less commonly pebbles are found as disseminated quartz grains, or commonly as a basal lag. Pure clay and mud layers have not been observed in this unit. Grain size criteria allow subdividing this part into two distinctive alternating lithofacies: (a) very coarse-grained cross bedded sandstone facies (Fig. 13), and (b) poorly sorted sandy mud facies (Fig. 14). The former constitutes the major component of this succession, and the latter occurs as a subordinate element. Although the outcrop is discontinuous, both facies are broadly distributed along the escarpment, and they also seemed to be laterally interplaying. Rhizoliths are common features of this part of the Sarir Unit.

3.2.2.1. In the very coarse grained cross-bedded sandstone lithofacies, cross-bedded sets are variable in thickness, from 20 cm to few metres thick. In some places individual sets measure up to 4 m. Rhizoliths in these sandstones (Fig. 13A) are well preserved, dominantly a few millimetres to 1 cm in diameter, and are sometimes

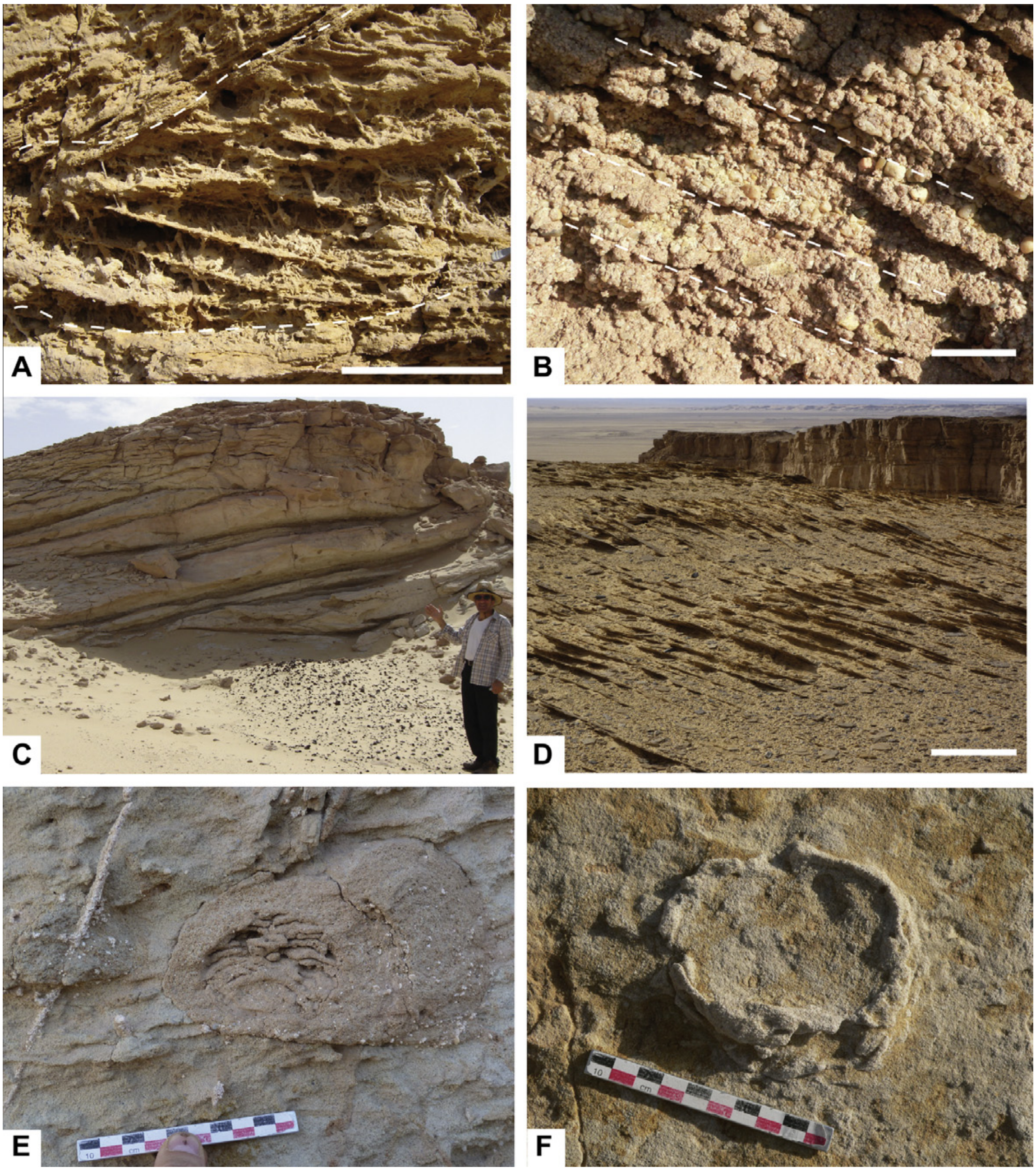

Fig. 13. Sedimentary structures preserved in the fluvial sandstone, the Upper part of Sarir Unit. (A) Cross bedded sandstone with abundant rhizoliths. In many occasions, root tracks are intersected by foresets, indicating syndepositional occurrences (scale bar: 1 m). (B) Quartz granules and pebbles in the cross bedded microconglomeratic sandstone (basal lag). (C) Low angle master beds attributed to the lateral accretion in a meander point bar. (D) Surface view of sandstone shows large cross bedding with sets dipping to the north (away from the photographer, scale bar 1 m). (E and F) Cross sectional view and plane view respectively of termite nests, embedded in the hosting sandstone, with fungus comb preserved in (E).

truncated by the foresets. Cross-bedded sandstone bodies often display a trend of fining upward grain size within sets. Cross-bedded sets frequently commence with a microconglomeratic lag dominated by rounded to subrounded granules and pebbles of quartz (Fig. 13B). Sandstone bodies occur in variable scales and geometries. Sometimes they show components of lateral and vertical accretion, resulting in few meters thick sequences (inclined heterolithic stratifications), made up mainly of very coarse sandstone, intercalate with finer sandy mudstone beds (Fig. 13C). A few well exposed locations show repetition of the fining up cycles. Characteristic sedimentary structures fascinating this very coarse sandstone facies are the large scale unidirectional (mainly northwards) trough and planar cross stratifications (Fig. 13D). In some places, sets can be traced up to several tens of metres and display characteristic graded bedding. In some cases, beds do not show any distinguishable sedimentary structures. In these cases, the lack of sedimentary structure could be attributed to biogenic activity (roots). The large scale unidirectional cross stratifications probably represent in-channel migration of bed forms.

In this facies, distinctive ball-shaped structures have been observed (Fig. 13E and F). Their diameters vary from 5 to 15 cm and they show concentric internal laminations. They are filled with material from the hosting sandstones. Most probably, these structures correspond to bioturbation by termites. They are very similar

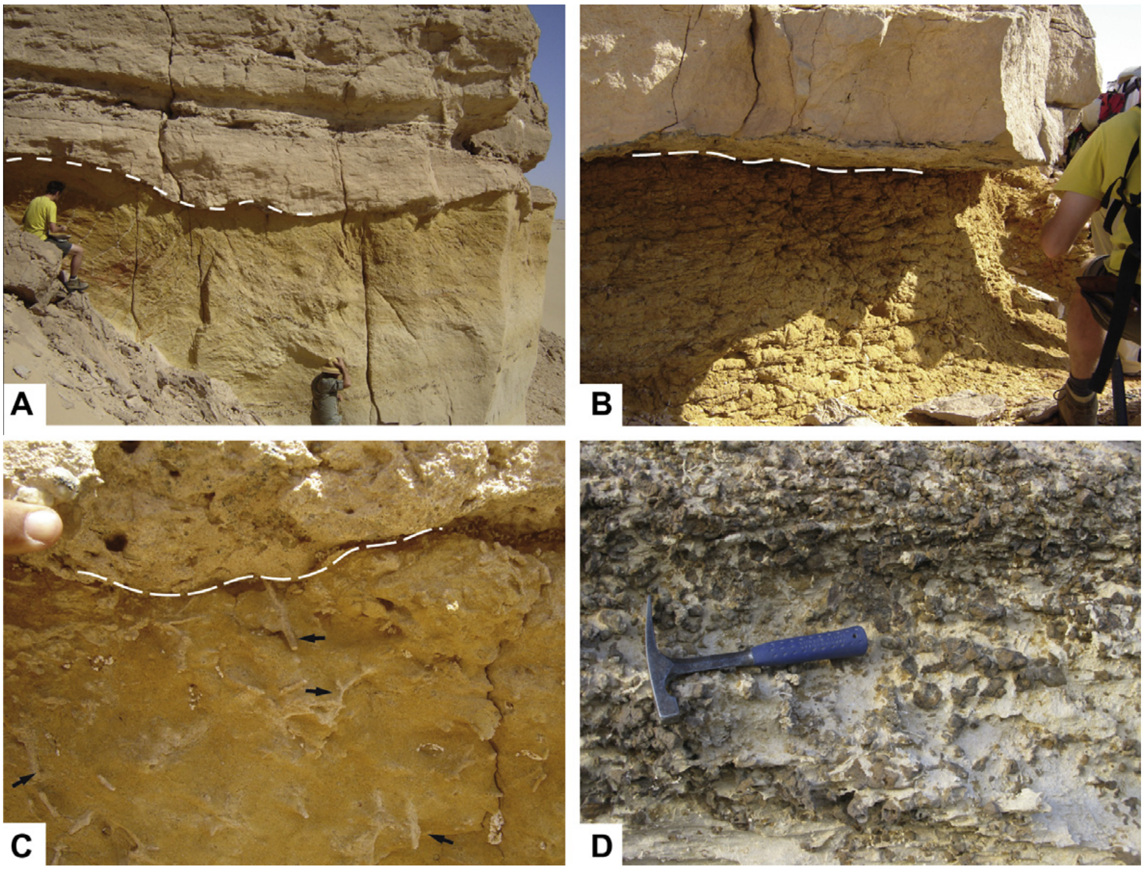

Fig. 14. Sandy mud (paleosoil) facies in the upper part of the Sarir Unit. (A) Sharp contact separates the orange (mottled) paleosoil and the overlying microconglomeratic sandstone. (B) Close up view of paleosoil horizon totally churned due to intensive biogenic activities. (C) Close view show root marks (rhizoliths; e.g., arrows) occasionally dominate the paleosoil horizons. (D) Abundant concretions of iron and manganese oxides, attributed to extensive pedogenic processes.

to the fossils *fungus* comb chambers, from *fungus* growing termites described by Duringer et al. (2007) from Neogene continental sandstones of the Chad Basin. At Dur At Talah, the ball shaped structures show the same degree of cementation as that of the hosting sandstones, and they intersect and are intersected by the associated rhizoliths. This bioturbation, which is likely being produced by termites, appears to be penecontemporaneous with the deposition of the sandstones. However, obviously younger (Quaternary?), weakly cemented termite nests have also been observed in several places in various facies of the Dur At Talah sequence. Fossil termite nests described in the upper part of the Sarir Unit show close resemblance with those described by Bown (1982) and Bown and Kraus (1988) in fluvial sandstones of the upper part of Qasr Asagh Formation (Oligocene, Egypt).

The coarse grained to microconglomeratic sandstones, the lack of fossil, and the abundance of root marks from base to top of this facies, as well as the large scale cross bedding with basal lags, suggest strongly a fluvial origin for this part. At many outcrops, the occurrences of low angle master bedding (inclined heterolithic stratifications, IHS) that displays internal cross-bedding, associated with fining upward into muddy sandstone suggest a meandering point bar deposits (e.g., Thomas et al., 1987). The presence of poorly sorted microconglomeratic layers and the lack of clear mudstone layers could be attributed to a high energy braided fluvial regime (Collinson, 1986). Large scale planar and trough cross-bedding in coarse grained sandstones is also considered as a criterion of braided streams (e.g., Reinek and Singh, 1980). Penecontemporaneous termite nests also emphasize the terrestrial origin of these sandstone facies.

3.2.2.2. The poorly sorted sandy mud lithofacies occurs as thick (1–6 m), flat and lenticular horizons, sometimes they can be laterally traced for few hundreds of meters, according to the outcrop conditions. The lithofacies is composed of poorly sorted argillaceous sandstones to sandy mudstones, comprise small proportion of disseminated quartz granules and occasionally small pebbles. Uniquely, this lithofacies displays a variety of colour mottling (Fig. 14A–D) going from orange to pale green and purple in some places, such a colour mottling being typical for paleosoil horizons (Retallack, 1988). In many outcrops the contact between this sandy mud facies and the coarse grained sandstone is erosional (Fig. 14A), often being marked with conglomeratic sandstone lag. Dark and brown diagenetic iron and possibly manganese concretions commonly occur in this facies. In some horizons, these concretions (Fig. 14D) dominate over the original constituents. The sandy mud lithofacies appears also structureless in many locations, probably because of biogenic activity and dominance of concretions. This apparently structureless, motley coloured facies, rich in fossil root marks occurring above the fluvio-tidal facies, and alternating with the fluvial facies, is interpreted as paleosoils (e.g., Retallack, 1988; Bridge, 2003). Root-dominated paleosoil horizons indicate a flood plain or abandoned channel colonization (e.g., Cant and Walker, 1978).

3.3. Micropaleontological contents and organic matter analysis

In order to bring complementary information about paleoenvironments and stratigraphy, fourteen samples (Fig. 4) of clays from the New Idam Unit have been tested for micro/nanofossils (nanofossils, dinoflagellates, palynomorphs and foraminifera) and for molecular fossils (biomarkers).

3.3.1. Micropaleontology

Contrasting with the richness of the macropaleontological content of the Dur At Talah outcrop, the micropaleontological content is extremely poor, probably due to weathering as well as diagenetic processes. No palynomorphs (spores and pollens) and no dinoflagellates have been detected, probably due to the oxidation of the clays (most of them being green). Except for one sample collected at the top of the wadi Thamat Formation below the New Idam Unit, no nanofossils could be detected. For this sample, the relative frequency is very poor (3%) but two species have been found: *Reticulofenestra pseudoumbilica* and *Cyclycargolithus floridanus.* These have no accurate stratigraphic value, however a biozone can be proposed: zone NP16/NN7, middle Eocene to middle Miocene (i.e., Bartonian/Serravalian). The lack of nanofossils all through the remaining part of the sampled section (New Idam Unit) could be interpreted as an indication for a semi-open marine environment.

3.3.2. Biomarkers

The molecular fossils (or biomarkers) from the solvent extract of a series of selected green clay samples from the "Bell" profile (Fig. 4) have been analyzed by coupled gas chromatography-mass spectrometry (GC–MS) in order to investigate the origin(s) of the organic matter. In most samples, the amounts of extractible organic matter are extremely low, except in some samples containing macrofossil remains (plant debris). In the latter case, the biomarker content consists almost exclusively of straight-chain lipids in the C_{12}–C_{36} range (mainly *n*-alkanoic, α–ω–*n*-alkandioic acids, and, to a lesser extent, *n*-alkanes) showing an even over odd (acids) or odd over even (alkanes) carbon number predominance, generally considered as characteristic of leaf plants (epicuticular waxes). Surprisingly, the solvent extracts were devoid of di- and triterpenoids indicative of higher plants, and despite a specific search for taraxerol derivatives (indicators of mangrove environments), these compounds could not be observed. Similarly, biomarkers specific of paleoenvironments of deposition, notably those which could indicate hypersaline (evaporitic) conditions, have not been detected. This validates the abandonment of the term "Evaporite Unit" originally proposed by Wight (1980).

4. Discussion

4.1. Stratigraphy

In this article, the Dur At Talah escarpment is subdivided into two stratigraphic units (New Idam and Sarir). "New Idam" is proposed to replace both "Evaporite" and "Idam" units of Wight (1980). Given the similarities in lithofacies, ichnofacies and in the depositional environments, both units have been combined. Furthermore, there is no obvious boundary separating "Evaporite" and "Idam" units *sensu* Wight. The name "Evaporite Unit" was proposed by this author because of the occurrence of gypsum. In fact, here, the evaporites (mainly gypsum) are obviously of diagenetic origin. Gypsum appears not in primary strata but only as pure fibrous crystals infilling fractures. In addition, all evidence points to a shallow marine environment (tidalites, marine fauna), rather than a sabkha. Furthermore, biomarker analysis of the organic matter does not show evidence for such restricted environments. The proposed new unit name refers to the pioneering work of Wight (1980). "New Idam Unit" encompasses both the "Evaporite Unit" and the "Idam Unit". The term "Sarir Unit" assigned by Wight to cover the (25 m) sandstone that lies above the New Idam Unit, is maintained unchanged. Meanwhile, in this article "Sarir Unit" is used to include all the exposed (50 m) sandstones above the New Idam Unit.

In the New Idam Unit, vertebrate remains can be found in two distinct contexts. Firstly, bones in anatomical connections (crocodiles, proboscideans, fish) occur in the green clays, more commonly at the lower part of the New Idam Unit. They also occur at the flanks of tidal channels of this unit. Secondly, accumulations of fragmentary bones and teeth occur commonly at the base of (sand/clay) parasequences, as microconglomeratic lag (placer). Bones and teeth fragments are thought to have been accumulated during the small regressive/transgressive pulse.

4.2. Depositional environments

4.2.1. The green clays

All facies described in the New Idam Unit are associated with beds of green clays. The interpretation of these clays remains speculative because of their lack of sedimentary structures. To explain their origin, several depositional environments can be considered. As presented above, evaporitic environments can be excluded. The frequent alternation of green clays with oyster beds, the shallow marine bioturbations and the continental vertebrates (proboscideans) as well as the tidal channels and tidalites, support nearshore rather than offshore environments. Nevertheless, the lack of fresh water fauna inside of the clay allows the exclusion of lacustrine settings. The most probable environment is a broad muddy tidal flat interrupted by tidal channels. Sandy and muddy tidal flat juxtaposition is reported from many modern tidal environments such as in the Bay of Mont Saint-Michel (e.g., Tessier et al., 2010). In Late Holocene, muddy sand interbedded with clay is reported from the Bay of Bengal where the largest tide-influenced mangrove swamp on Earth is located (Allison et al., 2003). In ancient environments, sand-clay parasequences showing a very close resemblance to those discussed here are reported by Abdel-Fattah et al. (2010) from the Qasr El-Saga Formation (Fayum, Egypt). They are interpreted as being deposited in a marginal-marine lagoonal environment. Underwood et al. (2011) report that the lower part of the Qasr el-Sagha Formation comprises marine mudstones alternating with thin marine to quasi-marine shell beds, which might be correspond to the green clay/oyster shell facies at the base of New Idam Unit.

4.2.2. The clinoforms

The two types of clinoform described from the New Idam Unit are supposed to reflect two types of depositional systems. The first type of clinoform is interpreted as the result of lateral accretion of point bars within meandering tidal channels. Many outcrops show that clinoforms are part of channels of decametric to hectometric scale. Nevertheless, in many places, the high inclination of the master bedding (up to 15°) is uncommon in modern analogues where the inclination is around 5° (e.g., Thomas et al., 1987; Hovikoski et al., 2008). Moreover, the shape of the clinoforms sometimes appears slightly concave up whereas it is usually convex up in modern point bars (Choi et al., 2004). One alternative interpretation is an overlapping infill of a preexisting channel (Fig. 9C). The second type of clinoform is likely to correspond to a prograding sedimentary body that is best explained as a distal part of deltaic mouth bars, such as those described from the Eocene Great River Formation (e.g., Schomaker et al., 2010).

4.2.3. The tidal-fluvial transition zone

In the lower part of the Sarir Unit the high influx of terrigenous material supplied to the basin, as well as the onset of cross-bedded sandstones laden with significant amounts of silicified wood, led Wight (1980) to interpret these sandstones as fluvial. However, several discrete sedimentary features that are typical for tidal setting have been ascertained. Nevertheless, the tidal signature is not as ubiquitous as for the New Idam Unit below, which is clearly tide-dominated. Inversely, the common occurrence of large silicified tree trunks in the cross-bedded sandstones, and some levels with small root marks, fingerprints a clear continental contribution. In these sandstones, both the abrupt decrease in the intensity of marine bioturbation and the lack of marine fossils also support an upward increase of continental/fluvial influence. Thus, rather than being purely fluvial, the Sarir Unit records a transitional zone from tidal to fluvial environments. Comparable systems are known from modern environments such as that of the Rhine and Meuse mesotidal estuarine (Van den Berg et al., 2007; Hijma et al., 2009) where the diagnostic features of the fluvial-tidal zone are described, and ancient examples such as those described by Shanley et al. (1992) from the Cretaceous strata exposed in the Kaiparowits Plateau (USA).

The local accumulation of silicified trunks along 150 km remains unclear. The first impression in the field is that this concentration represents a lag surface. In fact, the occurrence of the silicified trunks is very variable. The wood is originally embedded inside the sandstone as a result of increasing terrestrial influx, which is thought to be concomitant with shoreline regression. The tree trunks are generally scattered in the section. Most of their concentration could be attributed to deflation during Quaternary time, which gives the impression of primary lags. The increasing of silicified tree trunks abundance, as well as the occurrence of vertical trunks in living position at the top of lower Sarir Unit, confirms the hypothesis of a progressive emersion and a termination of marine phase associated with the development of wooden areas.

4.3. Sequence stratigraphic aspects

Facies succession composing the Dur At Talah sequence records an example of transition from tidal dominated nearshore marine environments to continental environments. Basin ward (North) shoreline migration is deduced from the vertical succession of the three environments (tidal, tidal-fluvial transition, fluvial). This overall regressive sequence could correspond to the general regressive trend established by Haq et al. (1987) in their worldwide eustatic curve, for the Late Bartonian. Eocene–Oligocene regressive event is suggested also for adjacent basin (Fayum basin, Egypt) (e.g., Bown and Kraus, 1988; Rasmussen et al., 2008). The overall regressive event is interrupted in the New Idam Unit, by small scale marine transgressive pulses recorded as repetitive parasequences.

5. Conclusion

The exposure of the Dur at Talah is attributed to the late Eocene (38–39 Myrs). It displays a coarsening up sequence, dominantly composed of siliciclastic rocks, that evolves from a tide-dominated environment at the base to a fluvial system at the top, with a transitional zone in between. The sequence of Dur at Talah records the last major basin ward migration of the coastline of the paleosirtic embayment.

New sedimentological observations allowed subdividing this sequence into two main stratigraphic units; the lower being called ‘‘New Idam Unit’’, and the upper one is ‘‘Sarir Unit’’. The New Idam Unit encompasses both the ‘‘Evaporite Unit’’ and ‘‘Idam Unit’’ formerly proposed by Wight (1980). The Sarir Unit remains unchanged, despite the fact that it is now extended much higher thanks to complementary outcrops at the capping plateau, and despite that its paleoenvironmental interpretation is reconsidered.

The New Idam Unit corresponds to a tide-dominated environment, built up as a wide mud-dominated tidal flat, marked by oyster-rich bioclastic bars and intersected by variable-sized tidal channels. This unit is intensively bioturbated; associated ichnofacies are typical for shallow marine environments (*Thalassinoides, Teichichnus, Trypanites*). Phases of emersion are suggested by root marks and surfaces with desiccation cracks. Most of the vertebrate remains are derived from the New Idam Unit.

For the first time, tidal processes are evident from the deposits of the Dur at Talah. A nice diversity of tidal features has been identified from the base of the New Idam Unit up to the end of the lower part of the Sarir Unit.

The Sarir Unit was previously interpreted as exclusively fluvial. It appears now that its lower part corresponds to a transition zone from a tidal to a fluvial depositional environment showing an upward increasing of fluvial influence and a concomitant decreasing of tidal influence. Large *in situ* silicified tree trunks at the top of the lower Sarir Unit announce the onset of continental conditions characterized by fluvial sandstones (microconglomeratic basal lags, sub-aqueous dunes, point bars) and by paleosoil development (rhyolites, pedoconcretions, mottling, termite nests).

The rocks succession of Dur at Talah is penecontemporaneous with the one of the adjacent Fayum basin (Egypt). Preliminary comparisons between Dur at Talah and Fayum suggest comparable depositional environments and climatic conditions. Further detailed comparison would bring indications about the paleogeography and the evolution of Paleogene basins in North Africa.

This contribution to the knowledge of the Dur At Talah area leads to a better understanding of the geology of the Sirt Basin, one of the most important oil bearing basins in North Africa. The sandstones of Sarir Unit have a good lateral extent, low clay content, generally a weak cementation and a good sorting, and thus it can be highlighted as a good reservoir.

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Appendix (2)

Abstracts (oral presentations)

***Abouessa** A., Duringer Ph., Pelletier J., Schuster M., Salem M.J., Hlal O. Tidal influenced Eocene deposits of Dur at Talah (Libya) compared with present-day tidal sediments of the bay of Mont Saint Michel (France). (oral)*

The 5th Technology of Oil and Gas Forum (Tripoli, 12-14/10/2010)

TOG (October 2010)

Tidal influenced Eocene deposits of Dur At Talah (Libya) compared with present day tidal sediments from the Bay of Mt St Michel (France)

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ABSTRACT

Dur At Talah escarpment is located in south central Libya, the southern peripheries of Sirt Basin. The escarpment (height ≈ 130m and length ≈ 150 km.) can generally be considered as the exposed part of Abu Tumayam Trough. The outcrop is built up with marine to deltaic clay, silty clay and various sandstones, it is attributed to the Upper and uppermost Eocene time. Only a few field studies have previously been carried out to this area, those were mainly attracted to its vertebrate fossil-content. For the moment, sedimentology and depositional environment are poorly documented.

Taking into consideration the importance of Dur At Talah escarpment outcrop, at the southern fringes of the large hydrocarbon bearing Sirt Basin, this paper aimed at defining the main facies, encountered in the exposed sequence. Sedimentological investigation suggested that the greatest part of the outcrop, which is the lower and the middle (approx. the lower 100 m.) parts, are strongly tidal dominated. The upper part therefore, appears to show smooth changing from tidal to ‘pure’ fluvial, probably includes mouth bar environments. In order to compare the Libyan tidal facies exposed in this outcrop, to modern ones, several field trips were conducted to the modern “macrotidal” environment of the Bay of Mont St Michel, France. The comparison would contribute to the understanding of the sedimentological sequence encountered in Dur At Talah area. Main results, especially the comparison between fossil and modern environments are presented in this paper.

Key words: macrotidal, tide-dominated facies, comparing sedimentary structure, Mont Saint Michel, Dur At Talah Escarpment

Appendix (3)

Abstracts (oral presentation)

Abouessa *A., Pelletier J., Duringer Ph., Schuster M., Rubino J.-L. 2011. Characteristic sedimentary structures of a fluvial-tidal transitional zone (Dur at Talah sequence, upper Eocene, Libya). Livre des résumés 68, 1-2. (oral)*

The 13ème Congrès Français de Sédimentologie (ASF), Dijon (14-16/11/2011)

Characteristic sedimentary structures of a fluvial-tidal transitional zone (Dur At Talah sequence, Upper Eocene, Libya).

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Dur At Talah escarpment displays 145 m thick siliciclastic megasequence, stretching E-W for more than 140 km. The outcrop is located at the southern peripheries of Sirt Basin, south central Libya. This basin is known as one of the largest and youngest hydrocarbon-bearing basins in Africa. The megasequence records transition from marine to fluvial deposits and is subdivided into two subsequences. The lower one (New Idam Unit: is made up of ~ 90-100 m thick of thinly stratified fine sandstones to mudstones dominated by bioturbation. The upper subsequence (Sarir Unit: is composed of ~ 50 m thick sandstones with subordinate intercalations of mudstones horizons.

Regarding both, grain size and sedimentary structures, the upper subsequence (Sarir unit) is divided into two parts. The lower one is made up of medium to coarse grained well sorted sandstone exhibits broad spectrum of trough and planer cross bedding, intercalated by mudstone beds. Some cross beds therefore, display discrete but evident tidal features. Among these features are the regularly spaced, bundled foresets, attributed to neap-spring tidal cycles. One of the most demonstrative tidal features are tangential cross bedding with mud drapes occurred on sandy foresets attributed to deposition during slack water. Furthermore, such structures are associated with features of current directions reversal and draining ripples frequently observed at the foot of foresets.

The contact between lower and upper parts of Sarir Unit is marked by few meters thick sandstone bed characterized by intensive occurrences of silicified tree trunks. The upper part (above this bed) is composed of coarse to microconglomeratic sandstone displaying large scale cross stratifications and graded bedding alternated with thinner horizons of paleosoil. Primary sedimentary structures in this unit are often obliterated by biogenic activities, particularly rhizoliths associated occasionally with termite nests. Accordingly upper part is interpreted as fluvial deposit.

Thus Dur At Talah megasequence represents a regressive sequence (shoreline retreat) showing a well-developed transition from marine to fluvial. The lower part of Sarir Unit records a good example of tidal-fluvial transitional zone, overlying the tide-dominated (new Idam Unit). The Upper Sarir Unit at the top demonstrates the pure fluvial dynamic.

Fig. 1. Show cross bedded sandstone from lower part of Sarir unit. Mud of greenish color drapes the pinkish sandstone foresets. White line tracing the mud drapes, and yellow line follow reactivation surface.

Appendix (4)

Abstracts (oral presentation)

30th meeting of the International Association of Sedimentologists (IAS), Manchester (2-5/09/2013) .

Abouessa*, A., Duringer, P., Schuster, M., Pelletier, J., 2013. Identification and implication of emersion phases in a tidal-fluvial depositional system: lessons from the sedimentary facies and bioturbations of the Dur at Talah (Eocene, Sirt Basin, Libya). (oral)*

T4S3_O2 30 IAS (September 2013)

"Identification and implication of emersion phases in a tidal depositional system: lessons from the sedimentary facies and bioturbations of the Dur at Talah (Eocene, Sirt Basin, Libya)."

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The studied succession (New Idam Unit, 60-80m thick) constitute the lower part of Dur At Talah Escarpment (150m thick, 150 km long), exposed in remote desert south central Libya. The importance of the escarpment comes from its location at the southern fringe of the hydrocarbon mega-province of Sirt Basin, and from the richness of the New Idam Unit in vertebrate fossils of Late Eocene time. The Unit is composed of siliciclastic rocks, claystones to very fine grained sandstone. It is erosively overlain by medium grained, crossbedded sandstone preserve unmistakable tidal sedimentary structures (Sarir Unit).

The New Idam Unit preserves remarkable tidal sedimentary structures (Abouessa et al., 2012), especially in its lower part. Diagnostic structures include mud drapes and double drapes, daily tidal bundle, neap-spring-neap cycles, and oppositely organized current ripples. Other structures, which are not unique for tidal processes include flaser, lenticular and wavy bedding. *Thalassinoides* are variably preserved from base to top of the succession; these intersect and are intersected by larger cylindrical burrows. Marine Invertebrates exist at the basal part.

The diagnostic tidal structure and the marine fossil, the domination of *Thalassinoides-like* bioturbation, and the evident tidal structure in the overlaying unit led to interpreting the New Idam unit as being deposited in tide-dominated environments, composed of tidal mud-flat to tidal channels system. New field data revealed that this interpretation is not accurate for the entire unit. This data is mainly concerned with the recurring evidences of prolonged phases of subaerial exposure. Some of these evidences are strong, others are arguable. Remarkably, these immersion surfaces express obvious increasing toward the top of the unit. Combinations of paleontological and sedimentological immersion evidences are recognized.

The paleontological evidences include: the presence of fossil bones and teeth of rodents and primates (Jaeger et al, 2010a,b), observed in at least two levels in the upper half of the unit. Terrestrial vertebrate also includes large bones of proboscideans and other large mammals. Moreover, fossil flora is also common, of which a variety of petrified plant remains and fossil fruits, coexisting with trace fossil of terrestrial origin. Nests of termite associated with possible root marks are usually culminating a shallowing up sequences. Most disputable of the trace fossils are the existence of the cylindrical (30-200cm deep, 5-15cm diameter) burrows, which could be attributed to fresh water crayfish. There morphology and behavioral features are comparable with their modern counterparts.

The sedimentological criteria of emersion include: thick paleosoil horizons characterized by variegated colors, succession of sand beds colonized by millimetric-scale roots. Similar sand bed in another locations are showing subtle characteristic of aeolian sandstone. The most evident of the sedimentary features of emersion is the desiccation cracks, some of which are filled with the terrestrial fossils. Many of the listed features of subaerial exposure are certainly syndepositional others seem to occur shortly after the deposition. Despite this, they always provide evidence of aquatic-terrestrial rather than marine proximity.

Though tidal structures and marine fossils are well preserved in the New Idam Unit, the terrestrial and emersion features present considerable increase toward its top. Considering these new facts, interpreting the New Idam Unit as entirely tidal is inaccurate. Alternatively, this unit represents coastal, tide dominated environment at its lower part, grading toward its top into fluvial-dominated, tide-influenced environment.

Résumé

La séquence sédimentaire du Dur At-Talah, située dans la partie sud du bassin de Syrte au centre de la Libye, est composée de 150 m d'épaisseur de roches principalement siliciclastiques (grès, siltites et argiles). L'importance de cette séquence est liée en partie à l'importance du bassin de Sirt qui est un des plus grands réservoirs d'hydrocarbures de Libye. La séquence est également un des plus important site de fossiles de vertébrés de l'Eocène supérieur, l'âge de la séquence.

Les études antérieures, bien que très limitées par rapport à l'importance de cette zone, se sont concentrées principalement sur le contenu paléontologique de la séquence. L'étude sédimentologique n'avait été jusqu'à ce jour que très peu abordée. Cette thèse est un travail basé sur l'examen des affleurements et où l'accent est mis sur les structures sédimentaires et biogéniques (traces fossiles), visant à définir et à interpréter les faciès sédimentaires qui ont construit la séquence du Dur At Talah.

L' étude de la séquence a conduit à diviser la totalité de l'affleurement en trois intervalles génétiquement liés. Le plus ancien que nous avons appelé la « New Idam Unit » (environ 80 m d'épaisseur), est composé de grès très fins, de siltites et d'argiles. Cette unité (New Idam Unit) est recouverte en discordance par la « Sarir Unit » (environ 50 m d'épaisseur), composée de grès fins à moyens à faisceaux de litages entrecroisées dans sa partie inférieure (environ 25-30 m d'épaisseur) et de grès grossiers à microconglomératiques dans sa partie supérieure (environ 20-30 m d'épaisseur). La « Sarir Unit » est ainsi divisée en « Sarir inférieur » et « Sarir supérieur ».

La « New Idam Unit » présente des dépôts qui sont attribués à un milieu main estuarien. La série débute par des dépôts d'environ 35 m d'épaisseur typiques d'un estuaire externe. Les 45 mètres qui lui font suite passent progressivement à des dépôts tidaux caractéristiques d'un estuaire interne. La Surface d'inondation maximale se situe entre les deux intervalles. Au-dessus de cette surface les indicateurs fluviaux augmentent et les indicateurs de marées diminuent progressivement, offrant ainsi un indice pour la migration de la rive de rivage vers le bassin (vers le Nord).

La sous-unité du Sarir inférieur qui avait été interprétée avant ce travail comme dépôts fluviatiles, préserve pourtant des structures sédimentaires multi-échelles qui sont le résultat incontestable de processus de marée. Ceci est particulièrement évident dans la partie inférieure de l'unité « Sarir inférieur » (la Lower Lower Sarir Unit ; LLS). Dans la partie supérieure de l'unité Sarir inférieur (Upper Lower Sarir; ULS), les indicateurs de dynamique fluviale dominent largement sur ceux de la marée. Le Sarir inférieur est donc interprété comme un système deltaique mis en place lors d'une régression normale. Cette fois-ci, la surface maximale d'inondation se situe entre le LLS et ULS.

Le « Upper Lower Sarir » (ULS) se terminée par une discordance subaérienne, avec de nombreuses traces d'émersion conservées au sommet de l'ULS. Celles-ci sont recoupées par le « Upper Sarir » qui montre des marqueurs fiables d'environnement de dépôt strictement fluvials.

Les dépôts du « Upper Sarir » enregistre la séquence de bas niveau marin. Cette étude fournit des informations précieuses concernant le dépôt des séquences dans le bassin de Syrte au cours de la fin de l'Éocène. Elle fournit également une étude originale sur la dynamique tidale dans des milieux marins margino-littoraux.

Mots clés: Dur à Talah, Eocène supérieur, indicateurs de marée, bassin de Syrte, structures sédimentaires, traces fossiles, terriers d'écrevisses, bioturbations

Abstract

Dur At Talah sedimentary sequence, located at the southern side of the Sirt Basin in central Libya, is composed of 150 m thick of mainly siliciclastic rocks. The importance of this sequence is linked to the importance of the Sirt Basin as one of large hydrocarbon reservoirs in Libya. The sequence is also an excellent site for vertebrate fossils of Late Eocene, the age of the sequence.

Previous studies, though very limited compared to the importance of this area, are focused on its paleontological content. Sedimentology received only scant attention before this project. This thesis is an outcrop based study in which the focus is given to the sedimentary and biogenic (trace fossils) structures, aiming at defining and interpreting depositional facies which building up the sequence. The study is mainly based on field data which are analyzed on the light of related published literature and on the comparison with modern sedimentary environments.

Results of facies analysis have led to splitting the entire sequence into three genetically related intervals. The oldest, we called the New Idam Unit (around 80m), is composed of very fine sandstones to mudstones. New Idam Unit is unconformably overlain by the Sarir Unit (around 50m), composed of medium grained cross bedded sandstones (the lower 25-30 m) changes up to very coarse and microconglomeratic sandstone (the upper 20-30 m). Thus, the Sarir Unit is split into the lower Sarir Subunit and upper Sarir subunit.

The New Idam Unit presents both classical and unusual sedimentary and biogenic indicators that attribute this unit to estuarine depositional environment. It starts with outer estuarine (the lower 35 m) and ends up with inner estuarine (the upper 45 m). Maximum flooding surface is located in between. Above this surface the fluvial indicators increase and tidal indicators decrease, thus providing clue for basinward (North) migration of the shoreline.

The lower Sarir subunit which was previously interpreted as fluvial deposits, preserves multi-scale sedimentary structures that undoubtedly belong to tidal processes. This is especially evidenced at the lower part of the lower Sarir Subunit (LLS). Fluvial indications over dominates the tidal ones in the upper part of the lower Sarir (ULS). Due to this configuration the whole lower Sarir subunit is interpreted as shallow marine, deltaic, depositional system, occurred during sea level ¨normal¨ regression. This time, maximum flooding surface is located between the LLS and ULS.

The lower Sarir subunit is terminated by subaerial unconformity, with evidences of subaerial exposure preserved at the top of the ULS. These are intruded by the upper Sarir subunit which presents clear evidences of strictly fluvial environment of deposition.

The deposits of the upper Sarir subunit record the low stand system tract part of the Dur At Talah sequence. In addition to the outlined results, the sequential pattern of the depositional events is suggested for the entire sequence of Dur At Talah. This study provides a valuable information regarding the depositional and sequential aspects of the Sirt Basin during the late Eocene, it also provide an unique case study for the better understanding of the shallow marine tidal deposits.

Key words: Dur At Talah, Late Eocene, Tidal indicators, Sirt Basin, sedimentary structures, trace fossils, burrows of crayfish, bioturbation