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The macroscopic Paleo-pedogenic features and their significance in deducing the continuity of sedimentation and the climatic changes during the Eocene/Oligocene transition, Dur At Talah sequence, central Libya

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Abstract: The studied sequence is 150 m thick of siliciclastic strata, well-exposed as a prominent escarpment that extends along 25°:45"N at the southern flank of Sirt Basin and dated as of Late Eocene age. It is built up from the base to top by three sedimentary units: (i) very fine sandstones and mudstones called New Idam Unit (NIU), (ii) medium-grained sandstones called Lower Sarir Unit (LSU) and (iii) very coarse to microconglomeratic sandstones called Upper Sarir Unit (USU). Pedogenic modifications which are differentially recurring from the base to the top of this sequence have not been paid sufficient attention in the previous studies. This study benefited the widespread macroscopic pedogenic features, introduced them and discussed their usefulness for estimating the continuity of the sedimentation and thus inferring the paleoclimate responsible for their formation.

The exposed-pedogenic features characteristic of each unit are described and then discussed in light of the documented modern and ancient analogues and case studies in order to comprehend the depositional continuity through time. The discussion is passed via analysing the prevailed climate because it is the fundamental factor controlling the formation of these features. Ultimately, this research allowed, for the first time, the recognition of a major (end Eocene) unconformity embedded within the sequence. This is certainly of interest for the hydrocarbon exploration in and around the basin

Keywords: pedogenesis, paleoclimate, pedo-features, late Eocene-Oligocene, Dur At Talah, Sirt Basin

1. Introduction

This research is an outcrop study of 150 m thick siliciclastic sedimentary succession that recurrently embeds pedogenically modified strata. It is well-exposed in a remote area of central Libya (Fig. 1A) called Dur Atalaha. The importance of this outcrop is owed to being part of the southern flank of the giant Petroleum-bearing Sirt Basin, which is one of the world's top 20 petroleum provinces (Abadi et al., 2008; Hallett and Lowes, 2016). The age of the entire succession is presumed either Late Eocene (Jaejer et al., 2010a, b) or Oligocene (Vasic and Sherif, 2007). Both assignments are dependent on fossils uniquely from the Lower Unit (NIU), which is exceptionally very rich in fossils. The Eocene/Oligocene boundary, which is of crucial importance for the oil exploration in the basin, is poorly defined (Bezan and Malak, 1996; Yanilmaz et al., 2008; Abualkhir, 2019).

In this work, analysing the sequence's pedogenically modified strata (Fig. 1B) compared to their counterparts that are not subjected to pedogenesis allowed the recognition of intervals of short sedimentation pauses and another of a very long gap (unconformity). As the understanding of the duration of the pedogenesis is dependent on the recognition of the climate responsible for their formation, the study is then implied analysing the paleoclimate concomitant with the deposition. The objective of the study is achieved through correlating the macroscopic paleo-pedogenic features to their modern (e.g., Morrison, 1978; Arnold, 1994; Yaalon, 1983; Brinkman and Brammer, 1990; Bockheim et al., 2014) and ancient (e.g., Yaalon, 1970; Kraus, 1997; Catt, 1990; Wright and Marriott, 1996; Kraus, 1999; Hasiotis, 2004; Targulian and Goryachkin, 2004; Tabor and Myers, 2015; Tabor et al., 2017; Badawy, 2018) case studies. Further citations are in the two paragraphs underneath, which are suggested as a substantially relevant refreshment.

Soils (which would become paleosols) form as a product of physical, chemical and biological activity at the outermost veneer of the Earth's surface (Beverly et al., 2018). Parent materials, biota, topography, climate, and time are the five soil-forming (pedogenesis) factors that determine what type of soil will form in a particular area (Jenny, 1941; Duchaufour, 1983; Retallack, 2001). These factors determine specific soil processes and therefore the characteristic products (features). Actually, soil features are among the tangible indicators of climate on the earth's surface (Harden and Tylor, 1983;

Solleiro-Rebolledo et al., 2013). Besides climate, parent sediments also affect the rate of soil (maturity) development. This is because different materials have different sensibilities to bioclimatic factors (Targulian and Sokolov, 1978; Bockheim et al. 2014). Thereafter, it is mainly by reference to the parent material as a starting condition that the degree and nature of soil development can be assessed (Birkeland, 1974; Retallak, 1983; 2001).

For the objective of this research, it is essential to bear in mind that the results of the pedogenesis comprise a range of soil features/structures that indicate the maturity and the relative age of the soil (e.g., Jenny, 1941; Nettleton et al., 2000; Retallack, 2001; Retallack et al., 2001; Driese and Ashley, 2016). Moreover, soil structures can be developed by changing pedogenic factors on different time scales. Taking into consideration that the soil age (the duration of pedogenesis) is the time at which the parent material is exposed before burial, Targulian and Krasilnikov (2007) concluded that pedogenic processes mostly occur on three time-scales. While rapid pedogenic processes (e.g., salinization, vertic features, bio-pedo-turbations) happen in tens to hundreds of years, there are also medium (10^3 – 10^4 years; e.g., leaching, humification) and slow rate (10^5 – 10^6 years; e.g., ferallitization, homogenization) processes. Based on this and on many other pieces of research (e.g., Yaalon, 1970; Alexandrovskiy, 2007; Sauer, 2010; Sauer et al., 2015), it can be concluded that a period of several hundred years of surface stability is enough for a weakly mature soil horizon of up to few tens of cm to occur, whilst, a homogenised few metre-thick soil might take more than 1 Myr to develop (Fig. 2).

In this Libyan outcrop, investigating the exposed paleo-pedogenic features together with the associated ichnogenic and biogenic climofunctions is proven very useful for the better understanding of the Dur At Talah succession, both in terms of the presence/absence of unconformity (appraise paleosol as a stratigraphic marker) and in highlighting the prevailed paleoclimate and its changes along with the time of the deposition (around 39–37 Myr ago).

2. Geological context

The Dur At Talah sequence (Fig. 1B) is exposed as a prominent escarpment, stretching east-west along $25^{\circ}45'N$ for more than 100 km. It is almost entirely composed of siliciclastic sediments. Geological mapping by Vasic and Sherif (2007) named it the Dur At Talah Formation and assigned it for the Oligocene age. Macro-scale sedimentary and biogenic structures, grain size and geomorphology allowed its subdivision into three units: (i) The basal gently sloping, fine-grained and intensely fossiliferous New Idam Unit (NIU), (ii) the steeper sloping and medium-grained Lower Sarir Unit (LSU) at the middle and (iii) the scattered-hills-forming, very coarse to microconglomeratic sandstone Upper Sarir Unit (USU), topping the escarpment (*for attention, the term “Sarir” is used elsewhere as a name for a Lower Cretaceous formation*). The NIU has been assigned to an estuarine environment (Abouessa et al., 2012) and occupies the lower 80 m. It is built up as alternations of very fine sandstone, siltstone and mudstone. Based on the fossil assemblages at the middle of this Unit, the entire sequence is dated 39–38 Myr by Jaeger et al. (2010a, b; Bartonian/Priabonian). 37 Myr is suggested by Otero et al. (2015) based on fossil fish as well as in comparison with the nearly identical strata of Qasr El Sagha Formation of the Fayum sequence in Egypt. The contact of the NIU with the overlying LSU (35 m thick) is sharp-erosional in the western side and appears gradational eastwards. Besides the omnipresent terrestrial indicators, the two units preserve evident tidal sedimentary structures (well-illustrated in Abouessa et al., 2012, 2014; Pelletier et al., 2016). Meanwhile, the intensity and diversity of the biogenic structures are contrastingly greater in the NIU. Because of its content of tidal and fluvial proxies, the LSU is assigned to a transitional, marine-to-continental, deltaic environment. The sandstones of LSU are culminated by an exclusively thick and well-developed paleosol that is erosively truncated before the deposition of the contrastingly coarser-grained USU (available thickness ~30 m). The latter is assigned to braided fluvial by the ubiquity of fossil roots and termite nests coupled with the definitive absence of marine indicators. The strata of the three units are variably intervened by pedogenically modified intervals. These pedogenically modified intervals are different in their spatial distribution, thickness, degree of development and their associated biogenic features.

3. The description of the pedogenic modifications

Sedimentary strata of the three units composing the Dur At Tallah sequence enclose recurring intervals that are evidently modified by pedogenesis. The frequency and maturity of the modified intervals are contrastingly different from one unit to the other (Fig. 1C – H). Essentially, differences in pedogenesis appear in the thickness and the stacking patterns of paleosol horizons as well as in the associated bio-pedogenic features.

3.1. The pedogenic modifications of the New Idam Unit (NIU)

The NIU is built up mainly as fine heterolithic sediments on which pedogenic modifications to their strata are not very striking. Nevertheless, they are able to split this Unit into three intervals: the basal (30–35 m; Fig. 3), the middle (5–10 m; Fig. 4), and the upper (35–40 m; Fig. 5). Pedogenic developments are moderate and are closely spaced in the lower two intervals. In the upper interval, pedogenesis is relatively weak and vertically widely-spaced. The three intervals are frequented by almost identical lithology, represented by the lateral and vertical interplay of beds of very fine sandstone, siltstone and mudstone.

3.1.1 Pedogenic modifications of the basal interval of NIU

Sediments of this interval are represented by lateral and vertical interplay of four lithostrata (Fig. 3A): channelled fine sand/siltstone alternations, flat beds of mudstone, white-coloured aeolian sandstone beds and local lenses of marine mollusk (mainly oysters; see Wight, 1980; Abouessa et al., 2012 for more details). Pedogenic modifications are intermittently affected all but the oyster's banks. In the aeolian sandstone beds, pedogenesis is preserved as subparallel levels with millimetre scale rootlets which are presented in white colour (Fig. 3B) as that of their hosting sand. Larger centimetric to decimetric fossil roots are also commonplace; these exist in white as well as red (Fig. 3B). The latter are usually descended from a variegated reddish pedohorizon of ~30 cm in thickness. Bioturbations similar to that of turtles (Fig. 3C) are found to be associated with these roots. Burrows of crayfish and/or lungfish cannot be excluded. Similar horizons are recurrently observed but are thinner and weakly developed (Fig. 3D) and are of limited lateral extent. Within the channelled sandstone sequences which often preserve tidal sedimentary structures, pedogenesis is almost absent. Small millimetric rhizoliths are the only trustful pedo-features, restricted to the topmost layers of some channels. Hoofed ground is evident in many surfaces, seen with many fossilized excrements that belong to grazing animals and possibly to crocodiles. In the mudstone beds which are up to 2 m in thickness, pedogenic developments are comparatively weak, of which vertic features such as soil peds, slickensides and shrinkage cracks are unmistakable, as fully illustrated in Abouessa et al. (2020).

3.1.2. Pedogenic modifications of the middle interval of NIU

This interval (5 to 10 m thick; Fig. 4A, B) is a succession where most of the sedimentary layers are, influenced by pedogenesis. Paleosols here are stacked as centimetric to decimetric-thick discernible horizons (Fig. 4A – F). Profiles with surface soil (A) and subsoil (B) horizons are expressed by a gradual (downward) increase in the intensity of the colours such that changes in Fe-oxides concentration are expressed in the same horizon by darker-colour-down (Fig. 4C and E). Overlapping of horizons is distinguishable in some profiles. This is subtly expressed as a mixed colour zone between two superposed horizons (Fig. 4C) and as roots and burrows that penetrate two or more horizons (Fig. 4F). As a lateral change and for further illustration, a distinctive stack of multiple horizons is presented in Figure (4D); seven horizons can be distinguished in this succession of at most 2.5 m in thickness. Centimetric-size desiccation cracks and terrestrial body and trace fossils are remarkably associated with such succession (Fig. 4E – G). Bedding planes with fossilized excrements belonging to grazing animals are not exception (Fig. 4H). Despite all the mentioned obvious pedogenesis, relicts of sedimentary interfaces and internal laminations can always be discerned.

3.1.3. Pedogenic modifications of the upper interval of NIU

The top 40m part of the NIU is made of fine sandstones and mudstones alternations, same as that of the underneath intervals. Contrarily, this one show less colour variability and thus less pedogenized strata (Fig. 5A). The dominating colours are light greenish-grey and light green for the mudstones—and whitish-grey/greyish-white for the sand and siltstones. Pedostrata here are often

separated by thick (up to 9m), channelled (heterolithic) strata that are mostly not subjected to pedogenesis. Like in the entire NIU, the channelled strata are only slightly altered (the original stratifications are only partially disturbed) at their uppermost layers. Here, it appears that fossil roots with or without crayfish burrows (Fig. 5B – E) are the only frequent pedo-features. Centimetre-scale root casts are overwhelming, and decimeteric ones are occasional (Fig. 5C). Crayfish cylindrical burrows are observed as moulds and as casts that measure 10 cm in diameter in average and exceed one metre in their depth of penetration (see Abouessa et al, 2015 for details). Successive beds with truncated cylinders are widely preserved vertically and laterally in this interval. These pedo-features are recurrent until the erosional contact with the overlying Lower Sarir Unit (LSU; Fig. 5B). In the mudstones, pedogenic modifications are mainly presented as vertic features, mottling and cutans, slickensides and small-scale mud cracks (few cm wide and several cm deep). The latter are found to be associated with thin pedo-horizons (Fig. 5E) that exhibit a faint change in colour. Fossil fruits of exotic trees (Fig. 5F, G) are frequent enough to be seen attached to many depletion surfaces over the entire area. Some of these are of genus *Pandanus* and are seen together with medium-to-large-sized fossilized trunks and upright stumps.

3.1.4: Discussion: The NIU

Not many strata of the NIU are pedogenically modified, but modified strata are recurrent from the base to the top of this Unit. Sedimentation phases are interrupted by pedogenic ones, suggesting that sedimentation and pedogenesis have occurred simultaneously. As compared to documented modern and quaternary soils (Harden and Tylor, 1983; Birkeland, 1999; Buol et al., 2003; Muhs and Bettis, 2003; Tabour et al., 2017), the paleosols of the NIU are visibly weakly developed (entisols/inceptisols). Even for the apparently more pedogenized intervals (5 to 10 m; Fig. 4A, B) at the middle of the Unit, individual horizons (argillic, oxic and humic) are thin, vertically isolated and laterally discontinuous. Similar quaternary horizons of at most 40 cm in thickness are known to occur in <1 to 10 kyr (examples and case studies are given by: Alonso Zarza et al., 1992; Buol et al., 2003; Yaaloon, 1983; Temgoua et al., 2005; Kraus and Hasiotis, 2006; Kaczorek and Zagorski, 2007; Targulian and Krasilnikov, 2007; Birkeland, 1999; Nehren et al, 2016).

Concerning the relatively better-developed paleosols at the middle (5–10 m) interval and despite their better maturity, bedding interfaces and internal lamination are only partially masked, thereby attesting to short-lived soil. Comparable pedogenized intervals are explained by Kraus (1999), Hembree and Hasiotis (2007) and Hembree (2018) by the closeness of such soils to the active channel. Thus, as the 5 m successions of superposed horizons are distal (flood plain), the less mature 10 m successions are proximal to the active channel. That is to say, pedogenesis outpaced sedimentation in the first case and vice-versa. Altogether, this suggests that the NIU was deposited as one-sedimentation continuum. The more developed horizons are most likely reflecting a local topography where pedogenesis is more favourable rather than a regional cessation in sedimentation. The weaker development and wider-spaced pedogenesis at the upper interval certainly attest to sedimentation outpacing pedogenesis. This is thus in accordance with the obvious gradual increase in coarseness that persists until the top of superjacent LSU (Abouessa et al., 2012). Eocene-Oligocene comparable case studies are presented in Prothero and Berggren (1992), Kraus (1999), Sheldon and Retallack, (2004) and Hembree and Hasiotis (2007).

Consequently, and admitting the same parent sediments, this renders climate as the main player in the formation of the paleosols of the NIU. Climate here is mirrored firstly by the region-wide domination of fully terrestrial body and trace fossils. The fossil roots of different sizes and the crayfish burrows together imply that rainfall complied with their living requirements. The depth of the penetration of crayfish corresponds directly to the water table depth, i.e., very close to the surface (Crandall and Templeton, 1999; Smith et al., 2008); it thus attests for high precipitation. Secondly, the oxic and the organic horizons preserved by this Unit are also evidence for high rainfall, as rainfall is needed to provide enough vegetation and to induce the physicochemical conditions that are necessary for the dissolution and dislocation of oxides and clays (Brinkman and Brammer, 1990; Arndorff, 1993; Retallack, 2001). In this context, the lack of carbonate nodules has also been considered elsewhere (Brinkman, 1970; Van Breemann, 1988; Parrish 1998; Retallack 2005, Retallack and Huang, 2010) as

reliable evidence of high precipitation. Altogether, coupled with the domination of different varieties of exotic fruits in this Unit, it is suggested to be located in a near-equator tropical climate belt.

3.2. The pedogenic modifications of Lower Sarir Unit (LSU)

This sandstone (35 m thick) represents a shallow marine-to-continental regressive sequence (Abouessa et al., 2014) where pedogenic influence (Fig. 6) becomes gradually more impressive towards the top. It remarkably ends up with an exclusively mature ~7m thick paleosol that marks the appearance of the superjacent (USU) (Fig. 6G). The contact of this Unit with the underlying NIU is in part gradational, marked by upward coarseness and sometimes erosional with lithology jumped from mudstone to medium-grained sandstone. Excluding the mature paleosol at the topmost 7m, pedogenic indications in this sandstone are weak and are mainly of biogenic origin. They exist as discontinuous patches of rhizoliths, petrified trees and termite nests and galleries (Fig. 6A – F). The petrified trunks, of which many are in living position, are found as fossil forests of variable species in different sizes and with different bark ornamentations (Fig. 6A – C; see Abouessa et al., 2012, 2014 for more illustrations). Large trunks associated with small rhizoliths are obvious (Fig. 6B); others coexist with their fruits (Pandanus and pine cones; Fig. 6C) and are ubiquitous. When approaching the top of the Unit, these pedo-features become more and more frequent such that thick cross bedded cosets (up to 5 m) are totally colonised with root casts and/or termite nests (Fig. 6D – F) and can be traced for a few kilometres at once. Despite these biogenic pedo-features, cross laminations here are always discernible.

These pedogenic features are culminated by the exceptionally well-developed paleosol that terminates this Unit (Fig. 6G), and marks the erosional contact with the overlying microconglomeratic sandstone of USU. Of this paleosol, the sediments are completely homogenised such that the original stratifications are totally masked. Pedogenesis here is principally exhibited as a successive stack of several, barely discernible, overlapped horizons (Fig. 6G). These are distinguished by subtle differences in their colours, presence/absence of nodules, mottles and rhizoliths. Fe-Mg-nodules are found scattered in the matrix and as continuous horizons. There are also locations where Fe-Mn nodules form an over-thickened horizon (may exceed a thickness of 2m) that seems to be overprinting precedently existing horizons (Fig. 14D in Abouessa et al., 2012). Contrarily, carbonate nodules in this thick paleosol are uncommon. They are seen locally scattered as white-coloured grains of a few mm to few cm in diameter. A notable feature about this mature paleosol is that the horizon subjacent to the contact with the USU is somewhat laterally variable (Fig. 6G – K) concerning their preserved pedogenic features.

3.2.1. Discussion: the LSU

The evident upward increase in the intensity, repeatability and spatial distribution of the pedogenic modifications of LSU sandstones is in accordance with the regressive nature (Abouessa et al., 2014) of this Unit. The 7 m thick extremely mature paleosols culminating this Unit (Fig. 6D) should then announce a regional subaerial exposure and cessation of the sedimentation. Thus, until this strongly mature paleosol, a rapid and continuous sedimentation could be suggested. This is because the pedo-features below the mature paleosol are local and are mainly biogenic, i.e., of short duration such that the time spans for forest trees are few tens to few hundreds of years (Lieberman et al., 1985; Martínez-Ramos and Samper, 1988) and that of termites are as short as several years to few tens of years (Whitford and Eldridge, 2013; Ahmed and Pradhan, 2018). As the pedo-features are of a short duration, they are also presumed by their weak effect on the sedimentary structures which are only slightly disturbed. Moreover, the good preservation of the tree trunks itself attests that they are rapidly buried by the subsequent episodes of sedimentation. In fact, the sites where these biogenic features colonise lack any evidence of long-duration pedogenesis such as physiochemically developed horizons. That is to say, the intervening of the weakly pedogenized cosets with the adjacent non-pedogenized ones concludes that the pedogenic modifications were simultaneous with the sedimentation. This is applicable for the whole but not the terminal paleosol of this (LSU) Unit.

Regarding their paleoclimatic implications, the described bio-pedological features are the only visible climate proxies. The remarkable variability among the petrified tree trunks largely mirrors today's conifer forests. Meanwhile, the adjacent colonisation with rhizoliths and termites fits well with today's grasslands. Accordingly, recalling the overall upwardly decreased biodiversity, an increased continentality over that of the NIU could confidently be suggested. For instance, the crayfish burrow in

NIU is replaced in this Unit by the termites, which are more adaptable to lesser precipitation and higher temperature (Hasiotis and Platte, 2012; Martin, 2013). Thus, although the climate during the LSU epoch was not as wet as that of the underneath NIU, the preserved indications can certainly be used to eliminate the occurrence of arid and semiarid climatic conditions.

As for the thick terminal paleosol at the top of the LSU, a strong maturity is initially deduced from its thickness and total disappearance of the sedimentary structures (homogenization) in favour of the pedogenic ones. This is in addition to the occurrence of the uninterrupted stack of several mature horizons which are known (by comparison; Kraus, 1999; Tabour et al., 2017) to take a very long time to develop. Furthermore, the overprinting by Fe/Mg nodules on soil horizons, is known (Rosenau et al., 2013) to be a clue for multiple phases thus very long-duration pedogenesis.

3.3. The pedogenic modifications of Upper Sarir Unit (USU)

This Unit (at least 30 m) constitutes quartz-dominated microconglomeratic sandstones with subordinate alternations of muddy sandstones. It is installed as flat and lenticular bedforms of up to 2 m in thickness (Fig. 7). The sandstone beds are brownish-greenish-grey and light grey (Fig. 7A, B). The muddy ones are variegated, greyish-brown – brownish-yellowish-green (Fig. 7C, D). This Unit has been interpreted as braided fluvial deposits (Abouessa et al., 2012). Unlike the NIU and LSU, almost all beds of this Unit are pedogenically altered. Together with physicochemical (horizons) pedo-features, biogenic ones (mainly termites and rhizoliths) are spatially widespread. Of the abiotic features, mottlings are overwhelming in the muddy horizons. They occur as light grey and/or light brown spots in a prominently greenish-yellowish-grey matrix (Fig. 7C, D). In the sandstones, the mottles are of biogenic origin, caused as a result of bioturbations by termites (Fig. 7E) and rhizohaloes. Moreover, nodules of Fe/Mn oxides are common in this Unit, particularly in the muddy sandstones. They are preserved as discontinuous granular horizons of a few tens of cm in thickness (Fig. 7F, G). These nodules are generally rounded and up to several centimetres in size, and their colours are dark brown and reddish-brown. Carbonate nodules are also present but are relatively less abundant, found scattered in both the sandy and the muddy beds, and their diameter is up to few centimetres. Unlike Fe/Mn nodules, those of carbonates are not sufficient to form traceable (calcrete) horizons.

In addition to the presence of the mottlings and nodules, the described horizons are also discernible by a gradual change in the colour (Fig. 7F, G) which coincides with a slight downward increase in the intensity of Fe/Mg nodules. Besides, the average thickness of a single horizon (between two visible sedimentary interfaces) is up to several tens of centimetres. Thicker horizons are seen in some isolated outcrops but are not thicker than the beds' thickness (~ 2 m). Another remarkable physical pedogenic feature recorded only by the muddy horizons is the large, orthogonal desiccation cracks. These reach up to ~20 cm wide and ~ 2 m deep (Fig. 7D). Again, what is regionally remarkable about this Unit compared to the underneath LSU is its entire occupation by fossil termite traces and roots. Termites are often rounded and up to 20 cm in diameter (Fig. 7E). Rhizoliths are of centimetric scale in their length and millimetric in diameter and are repeatedly truncated by the cross-set lamina (Fig. 7B). They exist also as rhizohaloes of light grey colour (e.g., Fig. 7H). Larger traces of roots are not observed in this Unit.

3.3.1. Discussion, the USU

Admitting that the sediments of USU are of continental origin (Abouessa et al, 2012) explains their repetitious modifications by pedogenesis and vice versa. The described abiotic and biotic pedo-features, in comparison with documented cases (Harden, 1982; Busacca, 1987; Sauer et al., 2015; Celarinoa and Ladeirab, 2017; Tabor et al., 2017), are equivalent to rapid duration pedogenesis – particularly, the occurrence of the only thin horizons and the absence of the duripans. The bio-pedological features (termites and rhizoliths) are also known for short-lived features. Present-day ones can colonize soil in a period as short as decades (e. g., Alexandrovskiy, 2007). The horizons' maturity and thickness (representing the relatively longest soil-forming process; Sauer et al., 2007) of this Unit suggest < 1 to 3 kyr time of pedogenesis. Such a period is in phase with the expected time of the fluvial channel adjustment to a new course – a period that is approximately in the order of 10^3 years or maybe fewer (Stouthamer and Berendsen, 2001; Hartley et al., 2013). The Ganges fluvial system provides a comparable modern example (Steven and Goodbred, 2003) of the rapid shift between areas of

sedimentation and those of pedogenesis. Together (the preserved features and the correlation with the modern example), they conclude that the USU is a continuum that has experienced no regional long-term break in sedimentation.

Concerning the depositional climate, The USU pedo-features are also proven useful as climofunctions. Similar cases, studies and explanations are ubiquitously documented (Bown and Kraus, 1988; Parrish 1998; Retallack, 2001; Retallack et al., 2004; Hasiotis 2004; Kraus and Hasiotis 2006; Hembree and Hasiotis, 2007; Tabor and Myers, 2015; Fischer and Hasiotis, 2018; Gelybó et al. 2018). The direct climate proxy of the USU is essentially given by its regional occupation by dense rhizoliths and termites. In the first place, domination of termites would eliminate ever-wet (equatorial), ever dry (desert) as well as cold (boreal) paleoclimates. In such climatic regimes, termites either cannot survive or are not obliged to forage (Krishna and Weesner, 1970; Hasiotis et al., 2007; Whitford and Eldridge, 2013). Basically, all these (fossil termites and rhizoliths) are known for the present-day Savannah grassland ecosystem (Retallack, 1988; Bredenkamp et al., 2002; Whitford and Eldridge, 2013; Tagesson et al., 2014). Moreover, the preserved depth of the mud cracks (2 m), the repeatability of the rhizoliths and the Fe/Mn horizons are attributed by many researchers (Nahon, 1980; Morris et al. 1992; Zhang and Karathanasis, 1997; Gasparatos, 2007; Gasparatos et al. 2005) to a climatic seasonality. For instance, Fe and Mn are reduced and easily dispersed in the soil during the wet seasons. During the dry seasons, the soil gets more oxidized and thus leads to the reprecipitation of Fe and Mn along the planes of sheet silicates or within the matrix pores (White and Dixon, 1996; Vepraskas, 2001). In this context, Schwertmann and Fanning (1976), Bourman (1993), Stiles et al. (2001) and Yu et al. (2020) found that the pedogenic Fe/Mn nodules occur particularly under subtropical (rather than arid) temperature regimes.

4. Comprehensive discussion: The position of the unconformity/the paleoclimatic changes

For any thick sequences, the duration of individual events of sedimentation are generally insignificant (10^6 –100 yr; Sadler, 1981) compared to the duration of the intervening periods of soil formation (10^1 – 10^6 ; Birkeland 1974; Harden 1982; Retallack, 1984; or more years; Retallack 2001). For the Dur At Talah sequence, with the exception of the only extremely mature paleosol (indicative of unconformity) at the top of the LSU, the pedogenesis is always relatively weak (indicative of short pause or slowness of sedimentation). The short-lived pedogenesis is suggested first: by the rapid repeatability of the identical sedimentary events (lithostrata) that are not pedogenized and second: by the fact that the degree of the pedogenic modifications compared to the intervening unmodified sediments is undoubtedly mild. Starting from these facts and referring to (section 3) above, the stratigraphic position and the duration of the proposed unconformity can be worked out. This requires the analysis of the prevailed climatic conditions, because the impact on the soil of the climate and the duration of this impact are effectively interdependent.

With this regard, the entire sequence (late Eocene or Oligocene?) records two obvious trends; (i) an upward increase in the recurrence of the pedostrata over the lithostrata (Fig. 1B) and (ii) an obvious decrease in the associated biodiversity (Fig. 8). Likewise, the sequence also records two inferior trends: A) a slight decrease in the bio-pedogenic features from its base just until the top of the LSU, B) a striking decrease from the LSU to the USU (Fig. 8). Taking the trends (i, ii) into consideration, an upwardly increased paleoclimate aridity can be deduced. This is quite evident when comparing the pedo-horizons in the NIU to that of USU passing through LSU. The terrestrial trace fossils (crayfish and termites) are certainly unable to survive today's climatic conditions beyond $\pm 40^\circ$ N/S (Krishna and Weesner, 1970; Hobbs, 1981, 1989). Therefore, they provide the first climatic boundary; the crayfish dominated the NIU, and the termites dominated the USU. This distribution ascertains an overall wetter-to-dryer climate, as there are no other features in-between to refute this conclusion. The same argument eliminates ever-wet (equatorial; 0° – 10° N) and ever-dry (arid; beyond today's 25° N) climates. Neither the crayfish nor the termites can survive these conditions (e.g., Hobbs, 1981; Hasiotis et al., 2007; Martin, 2013). A supplementary climate boundary is suggested by the absence/presence of pedogenic carbonates (calcrete, widely known for semi-arid to arid climates beyond today's 20° N (Wright and Tucker, 1991)). Carbonate nodules are absent in the NIU, appear in the LSU and are better developed in the USU. Consequently, they also attest to the upwardly increased aridity.

Therefore, pedogenic combinations such as those of the NIU are most likely to coincide with today's wet climate between 10° and 15°N. The absence of the pedogenic carbonates from NIU paleosols confirms its position in a climate zone where precipitation exceeds evaporation. Carbonates are leached away under such conditions (Birkeland 1999; Retallack, 2001; Retallack, 2005). Compared to the NIU, the diminution of the pedo-features at the LSU to only patchy occurrences of rhizoliths, termites and tree trunks attest to the unfavourable environmental conditions of the ecosystem of the NIU to wholly persist. The organic horizons and their associated exotic fauna and ichnofauna disappear in the LSU. Coupling this with the disappearance of the crayfish burrows and the appearance of termite traces in the LSU, are ascribed elsewhere (Hasiotis et al., 2007; Retallack 2001; Fischer and Hasiotis, 2018) to increased temperature and decreased precipitation. These inferences thus place the LSU in a climatic belt slightly drier than that of NIU. The combination in the LSU of the termites-domination with the presence of patches of grassland and others of woodland together with the absence of calcrete and gypcrete are in accordance with today's climate between nearly 15° and 20° N.

In the USU, the low occurrences of carbonate (only scattered nodules) can be interpreted in two directions: 1) It attests to the (upwardly) increased temperature/decreased precipitation and 2) It subtracts the possibility of the occurrence of the arid climate during USU as well. This is explained by the basis that most modern calcic horizons are known to develop in areas receiving precipitation less than 80 cm/yr (Retallack, 2005). Consequently, and together with the other climate proxies, this places the USU in a rainfall belt greater than 80 cm/y (but less than that of the underneath units). In subtropical Africa and Australia, this range of precipitation is accomplished in less than two degrees of latitude (Strahler and Strahler, 1992). This, along with recalling the Savana ecosystem proposed by the regional domination of rhizoliths and termites, suggests locating the USU at a paleo-latitude approximately equivalent to today's 20 °N. Further, the occurrences of Fe/Mn nodular horizons in the USU, together with the large desiccation cracks, also informs us about more dryness and higher seasonality compared to the lower two units. With this background in mind, the slight decrease in the bio-pedogenic features between the lower two units (NIU and LSU; both are tidally influenced) is in agreement with the continuous sedimentation. Meanwhile, the abrupt decrease in the bio-pedogenic content between the LSU and USU (entirely fluvial) can confidently be considered as supplementary evidence of a durable unconformity between the two units. Eventually, and as the age of the entire sequence (39–37 Myr) is based on fossils restricted to the NIU, coupled with the deduced unconformity that ended the LSU, all of this provides strong reasons to date the USU as post-Eocene (Oligocene) rather than late Eocene.

An identically correlatable Eocene-Oligocene transition is documented for the well-studied (Bowen, 1982; Bown and Kraus, 1988; Rasmussen et al., 1992; Gingerich, 1992, 1993; Abdel-Fattah et al., 2010) siliciclastic succession of Fayum outcrops in Egypt. At Fayum (located 29° N, 31° E), the fossil fauna and flora that are almost identical to that of the NIU and LSU dominate the Middle-Late Eocene sediments of the Qasr el-Sagha Formations. Meanwhile, lithostrata and pedostrata (termites and rhizoliths; Bown and Kraus, 1988; Gingerich, 1993), very similar to that of USU, dominate the Oligocene (Bowen, 1982; Gingerich, 1993) Gebel Qatrani Formation. In the sequence of Fayum (and recalling our LSU/USU unconformity), Gingerich (1993) reported that the Oligocene Gebel Qatrani Formation is separated from the underlying marginal marine late Eocene sediments by a major unconformity, with a minimum of 76 m of the section being missing due to erosion and/or non-deposition. Accordingly, the correlation with Fayum succession supports not only the occurrences of the very long unconformity between the LSU and USU but it also attests for the wide geographic extent of this unconformity. Comparable end-Eocene unconformities are reported in other regions in Africa (Sullivan and Holman; 1996; Noubhani et al. 2008; Guiraud et al. 2005) and Asia (Swezey, 2009). All of this attests to a regional (end Eocene) fall in the eustatic sea level and thus provides an explanation to the climatic changes.

5. Conclusions

Investigating the exposed pedogenic features throughout the Dur At Talah sedimentary succession revealed crucial information concerning the continuity of the sedimentation and the prevailed depositional climate:

Sedimentation and pedogenesis acted almost simultaneously across the New Idam and Lower Sarir Units. The study confirmed that there are no visible indications of long pauses in sedimentation

within and between the two units. Meanwhile, the exceptionally mature paleosol recognized between the Lower Sarir and the Upper Sarir Units suggests a very long unconformity. It relatively displays striking indications that the time of non-deposition between them exceeds one Myr. As a consequence, it is not correct to include the Upper Sarir Unit as part of the Dur At Talah formation. It rather belongs to a post-Eocene episode. The widely pedogenized sediments of this Unit are certainly correlatable in terms of lithostrata and pedostrata to the Oligocene Gebel Qatrani Formation, in Egypt.

As paleoclimatic indicators, the preserved paleosols of the Dur At Talah sequence are proven useful by two tracks: first, the thickness and degree of development of the paleosol horizons and second, the variations in the intensity and diversity of the associated trace and body fossils. Relatively high precipitation and low temperature are recorded by the paleosols of the New Idam Unit, with a mild increase in aridity toward the Lower Sarir Unit (Late Eocene). Remarkably lesser precipitation and higher temperature are recorded by the Upper Sarir Unit (Oligocene). This remarkable change likely coincides with the long-time lost in the unconformity between Lower and Upper Sarir Units. Overall, the paleoclimate, as mirrored by the Dur At Talah sediments, is suggested to be equivalent to today's African climate between approximately 10° and 20° North.

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Figures caption

Fig. 1: Location and geological section of Dur At Talah; A) location map shows the position of the area of study (white rectangle); B) geological log highlights the distribution of the pedo-features; C to F) images illustrating the overall appearance of the pedogenic modifications across the sequence.

Fig. 2: Rough illustration of soil maturity versus time. It simplifies possibilities of the pedogenic progress over time. Such that a simple soil horizon could be initiated in years and reaches steady state (horizontally flattened curve) in several hundreds of years. Multiple horizons need several thousands to possibly millions of years. After Birkeland (1999).

Fig. 3: Paleosols of the lower part of NIU; A) general view (foreground ~10 m, background ~500 m) shows the spatial distribution of the major lithofacies: channelled strata (Ch), aeolian sandstone (AeS; arrows point to their position in the outcrop), mudstone beds (MS); B) a close view of paleosols associated with the aeolian sandstones; C) the burrows of turtles (dashed line); D) weakly developed oxic horizon associated with rootlets and burrows of probably crayfish (red rectangle in A for the location of D; the green arrow is to indicate the downward leaching of Fe-oxides).

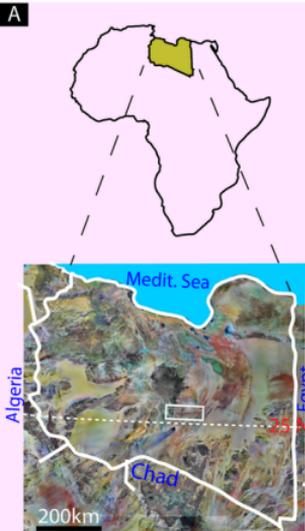
Fig. 4: Paleosols of the middle NIU; A and B) show lateral changes in thickness and maturity of paleosols succession (the two images is several kms apart). Horizons in both locations are thin and discernible suggesting a short duration pedogenesis; C) shows superposed (1 to 5) oxic/argillic horizons of which horizon no. 4 is partly overprinted by no. 3 as seen by their colour mixing. Burrows penetrating several horizons (dashed yellow lines) indicate contemporaneity with the sedimentation; D) lateral changes (several tens of Km from A and B) show stacked horizons that can be disassembled as: 1) organic (O; ~50 cm); 2) organic rich surface horizon (Ao ~30 cm); 3) mineral horizon (A; ~35 cm), underlain by; 4) pale white (eluviation; E ~20 cm) horizon; 5) greenish gray (probably B2; ~40 cm) horizon, it erosively truncates the underneath horizon; 6) truncated, brown coloured (A2o; >10 cm) horizon; 7) whitish gray clayey (probably E2; 30 – 40 cm) horizon. Regardless of the accuracy of this disassembly, there is no indication of strong multiphase pedogenesis; E) intense fossil roots associated with weak soil development; F) weak horizon, as indicated by short thickness, incomplete oxidation, undestroyed sedimentary structures and by the crayfish burrows; G) paleosol with roots and horizontal crayfish, suggesting shallow water table; H) fossilized excrements of grazing animal, (plan view).

Fig. 5: Pedo-features of the upper NIU; A) outcrop view shows the two major facies, the channelled rarely bioturbated strata (Ch) and the flat bioturbated strata (Bi). The inset image (a) provides a close view of crayfish burrow as the most dominant bio-pedogenic feature; B) crayfish burrow below the contact (red line) with the overlaying LSU, examples of the burrows are illustrated by dashed lines; C) fossil roots of medium-size; D) small rhizoliths (arrows) with the sedimentary interface and laminations still well exhibited (sign of weak pedogenesis); E) small mud cracks (dotted lines) in association with thin paleosol profile (the arrow points to a trace of root); F and G) varieties of fossilized fruits of exotic trees, which are exceptionally dominate the NIU.

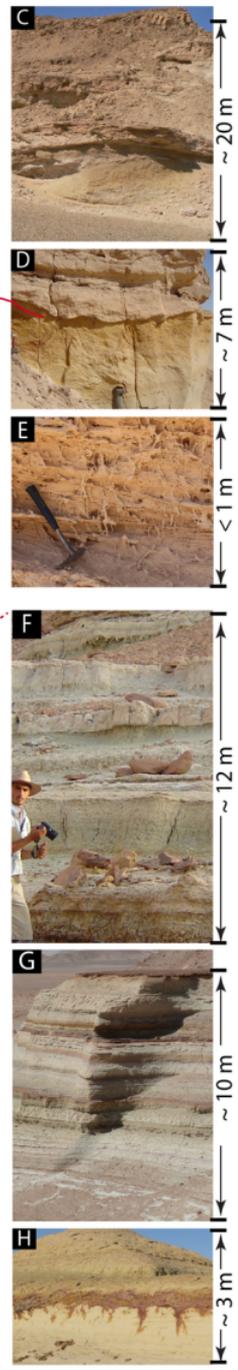
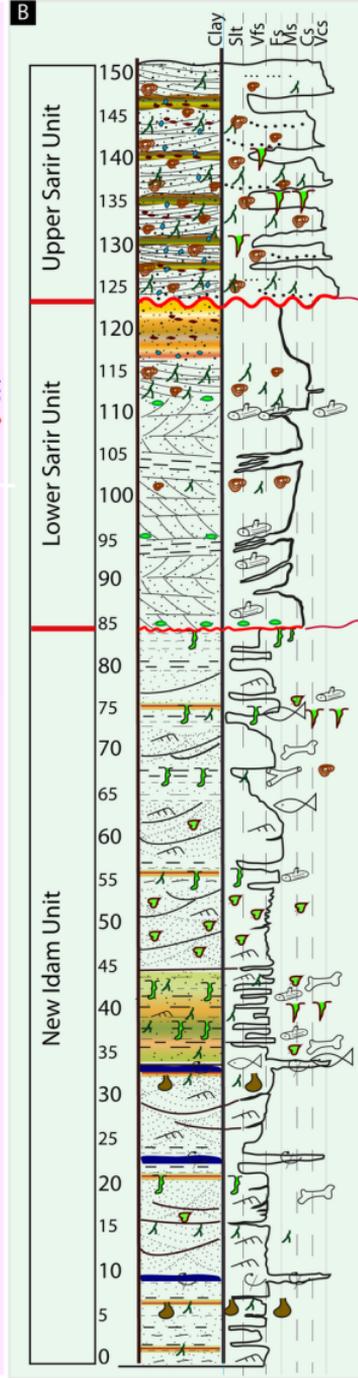
Fig. 6: Pedo-features of the LSU; A to F) show the biogenic pedo-features that are associated with weakly modified sandstones: upstanding trunks in A; large trunks associated with small roots (the dashed circle) in B, and with their fruits in C; and different occurrences of termites in D to F. The original sedimentary structures are remarkably well preserved; G) shows the strongly mature paleosols at the top of LSU, red line is for the contact with the overlying USU microconglomerate. The dashed lines separate the discernable paleosol horizons; H to K) presents the changeable nature of the paleosols subjacent to the contact (the red line) with the USU, this might suggest a prolonged period of nondeposition and erosion

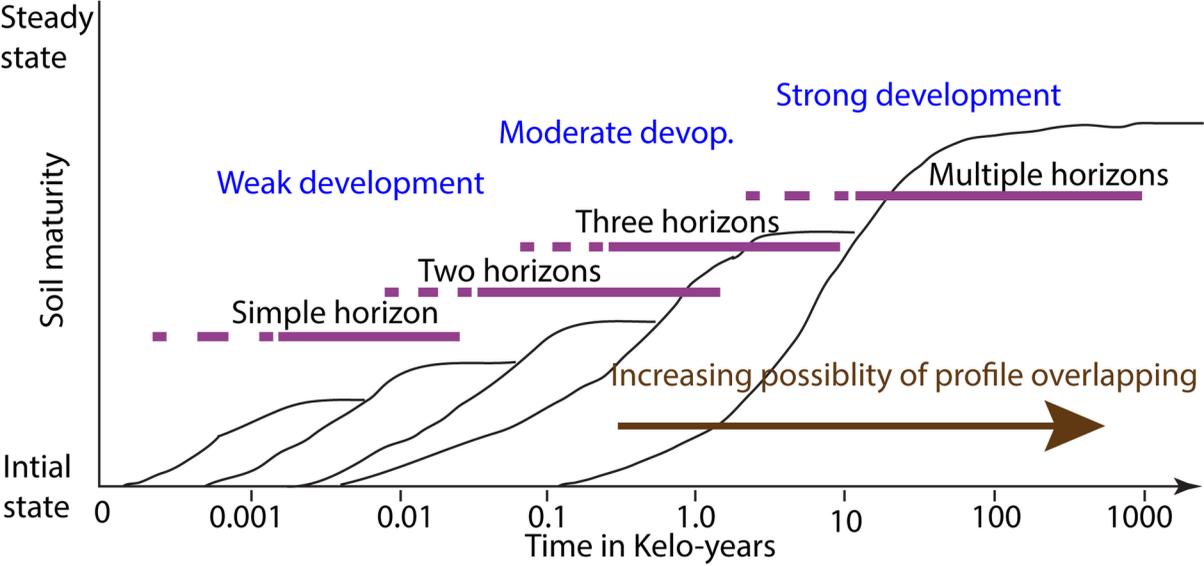
Fig. 7: Pedo-features of the USU; A) the dominant lithology, very coarse sandstone (Sst) and muddy Sst; B) rhizoliths dominating the sandstone beds and truncated by the subsequent foresets; C) variegated paleosols dominated by termites (arrows); D) variegated pedogenized muddy sandstone characterized by large orthogonal desiccation cracks (straight lines); E) top view of biogenically-mottled sandstone, ascribed to its domination by the termites nests (arrows) ; F and G) paleosol profiles characterized by the occurrences of Fe/Mg nodular horizons. The white arrows points to termite nests; H) bioturbated horizon dominated by small scale rhizohaloes (arrows). Solid and dashed lines for the evident and inferred (obscured) sedimentary interface, respectively.

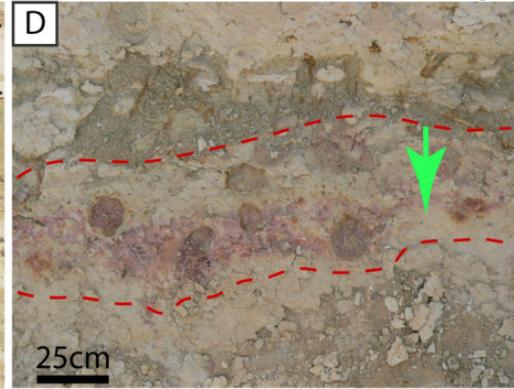
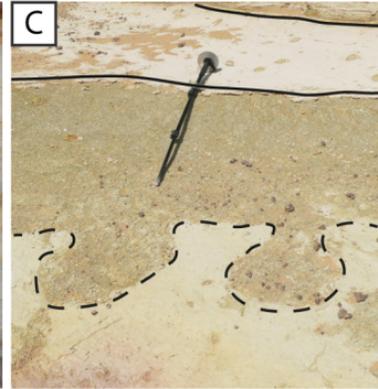
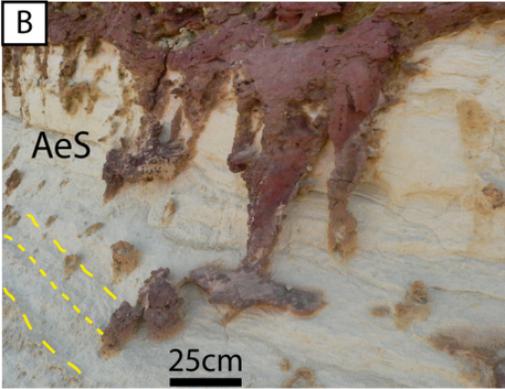
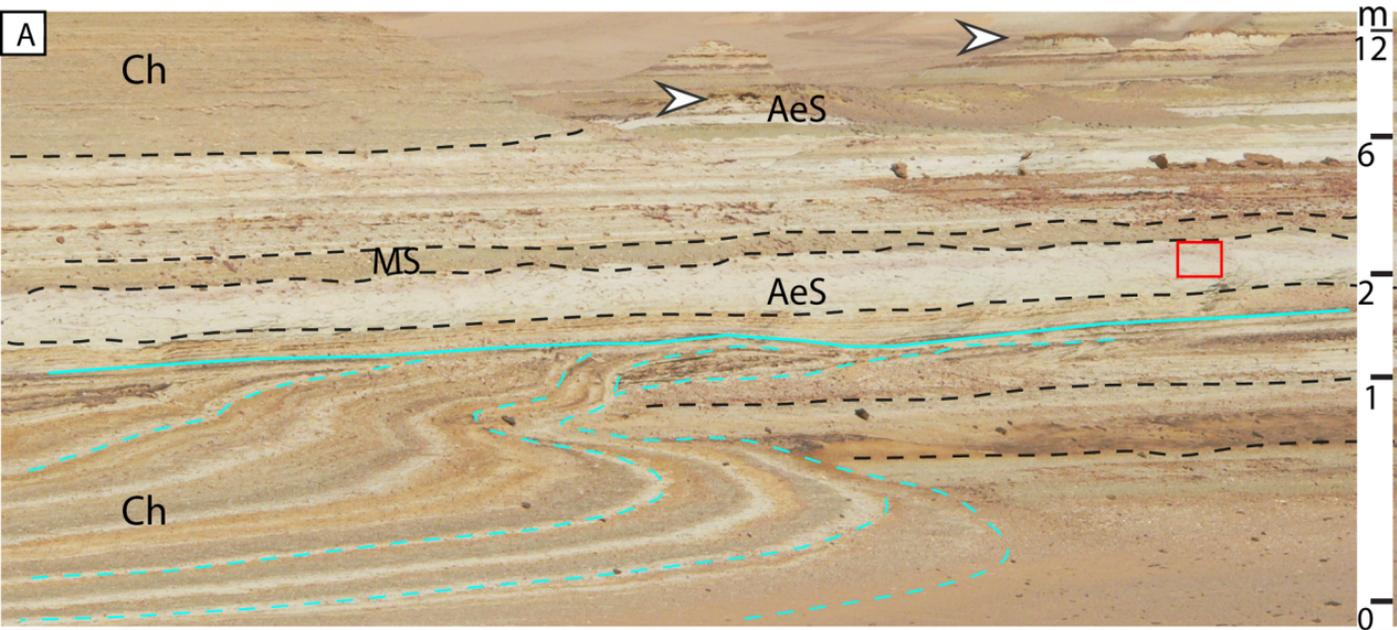
Fig. 8: The distribution of the most common bio-pedogenic features across Dur At Talah sequence. Decreasing in the associated biodiversity can be clearly noted, it is normally coincided with an overall increase in the temperature and decrease in the rain fall. A minor decrease in the biodiversity could be noted between the NIU and LSU compared to a major decrease at the USU. The latter is attributable to the presence of unconformity between the LSU and the USU.

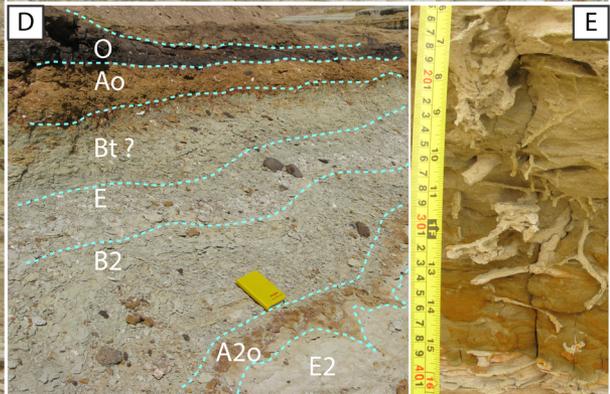
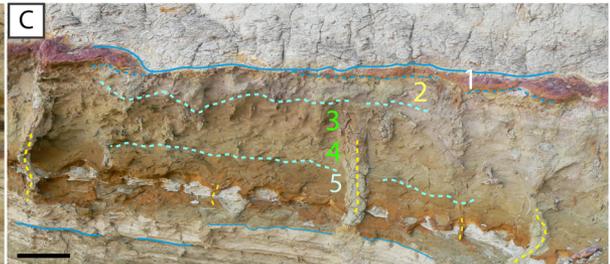


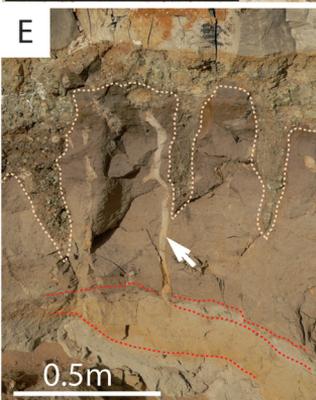
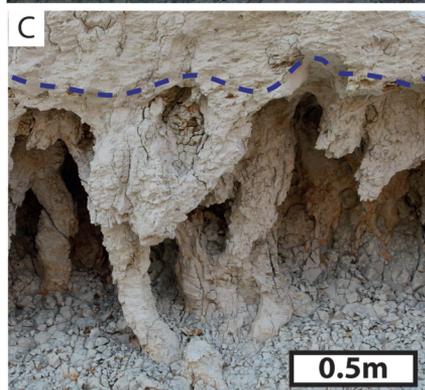
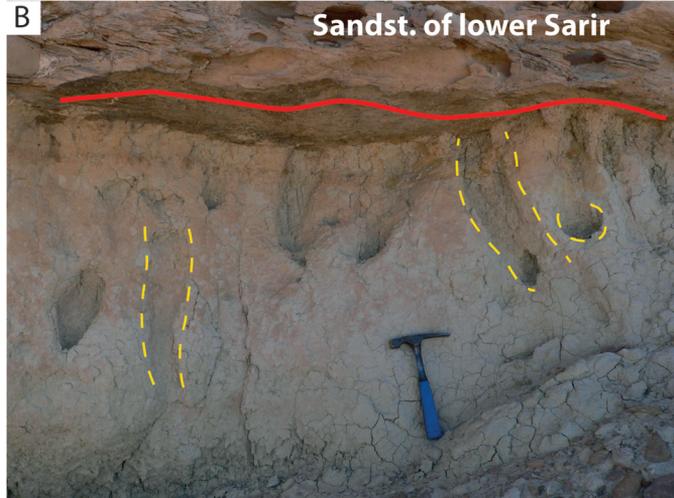
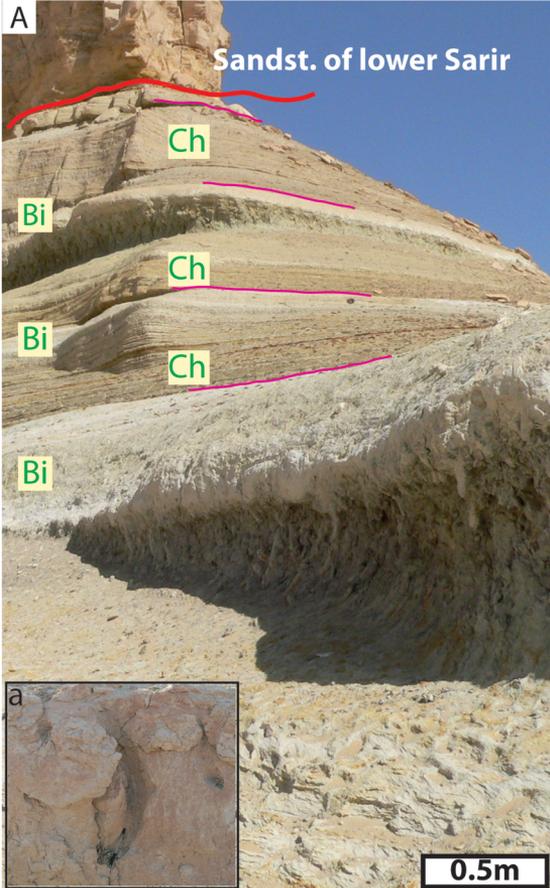
- paleosol horizons
- Cross-bedded sandstones
- Claystones
- Siltstones
- Fe/Mn concretions
- Concretions of carbonate
- Mud clasts
- Microconglomerates
- Oyster banks
- Units boundary
- Crayfish fossil burrows
- Fossil termite nests
- Fossil roots
- Petrified trees and trunks
- Fossil turtle burrows
- leaf imprints
- Mudcracks
- Terrestrial fossil bones
- Fossil fish
- Cross-laminations

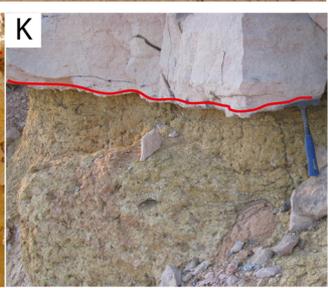
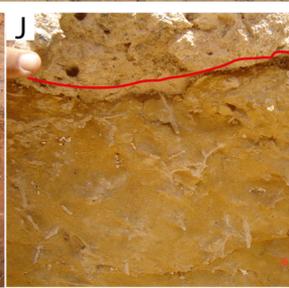
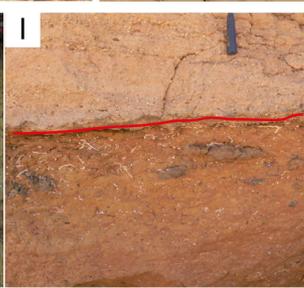
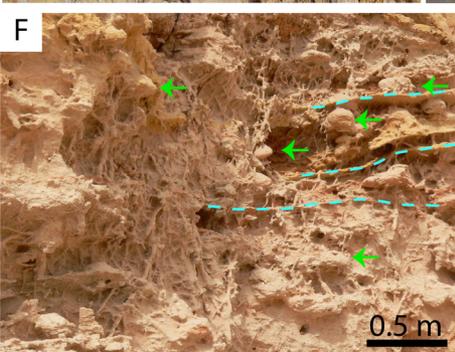


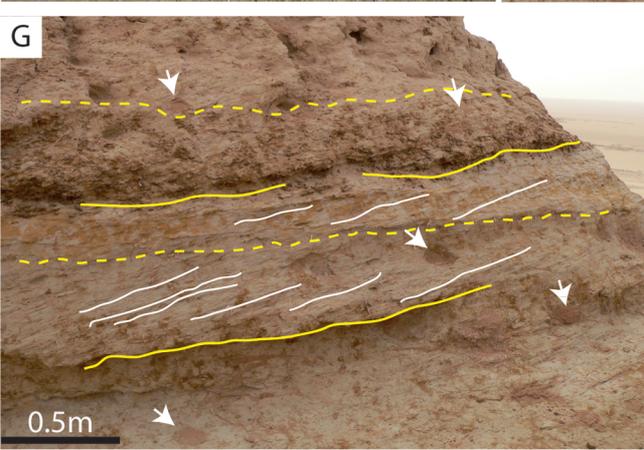
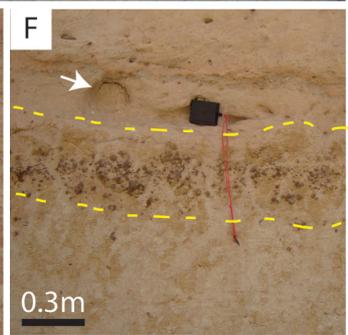
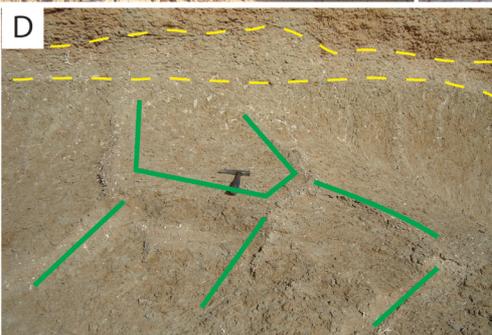
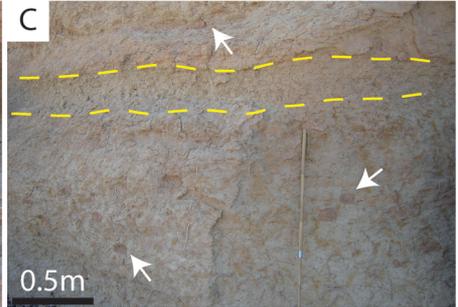
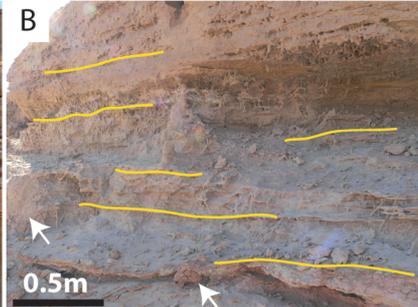
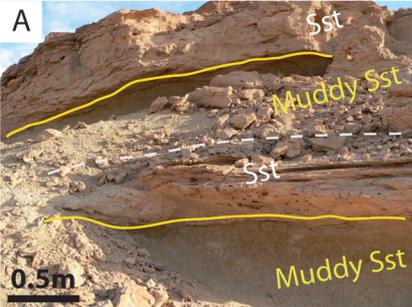


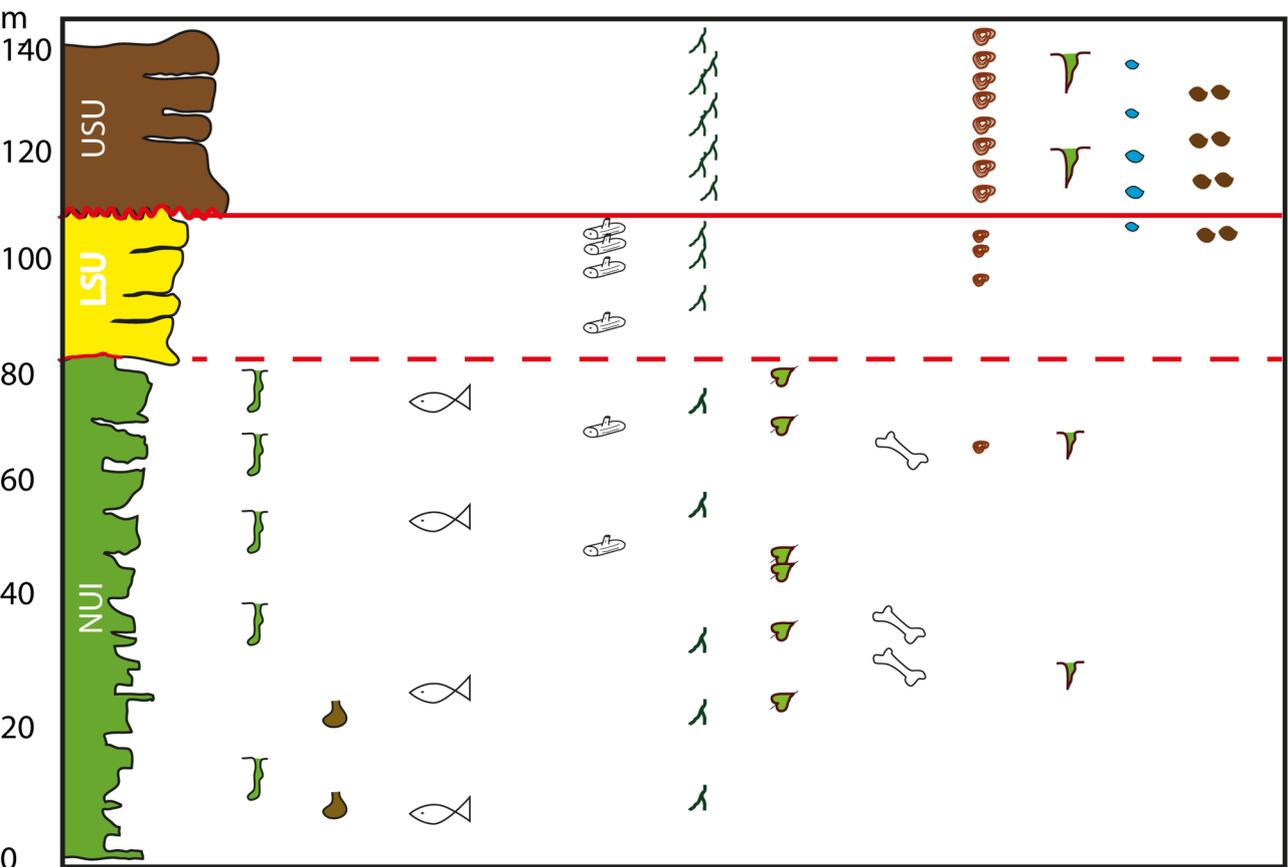












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| | Crayfish fossil burrows | | Fossil roots | | Mudcracks |
| | Fossil turtle burrows | | leaf imprints | | Carbonate nodule |
| | Fossil fish | | Terrestrial fossil bones | | Fe/Mn nodules |
| | Petrified trunks | | Fossil termite nests | | Unconformity |