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Sedimentology and stratigraphy of lower Cretaceous fluvial to shallow marine deposits on the central Atlantic passive margin: The Aaiun-Tarfaya Basin, Morocco

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A B S T R A C T

This paper presents the first integrated regional outcrop-based sedimentological study of the northern Aaiun-Tarfaya Basin located in Morocco (NW Africa). The Lower Cretaceous Tan-Tan Formation has been subdivided into six new members and placed within a sequence stratigraphic framework that includes two incomplete depositional sequences. Strong thickness variations of individual lithostratigraphic units from north to south suggest differential subsidence during sedimentation and/or the existence of major topography on the basal unconformity that the succession onlaps. The results provide valuable insights into the timing of local tectonics in the Western Anti-Atlas and the control on the evolution of the sedimentary system. Deposition of each of these six units is interpreted to be the result of a complex interplay between an overall eustatic sea-level rise during the early Cretaceous, sediment delivery controlled by tectonic movements in the Western Anti-Atlas and Reguibat Shield and periods of differential subsidence in the basin. The results document the style of evolution of a back-stepping wave-dominated system feeding into the Central Atlantic during the passive margin phase. The improved facies and depositional models together with improved understanding of the evolution of the delta have significant implication for exploring the deep-water equivalents offshore.

1. Introduction

Hydrocarbon exploration in the Aaiun-Tarfaya Basin (ATB) started in the late 1950's and early 1960's (Choubert et al., 1966; El Mostaine, 1991) with the acquisition of the first seismic lines and drilling of the first onshore wells. Km-scale thicknesses of Mesozoic sediments have been drilled offshore and sequences more than 10 km thick have been postulated in the deep offshore (von Rad and Einsele, 1980). A focus was placed on the lower Cretaceous wedge that was purportedly fed by a large fluvio-deltaic system (the "Tan-Tan delta"). In parallel with subsurface exploration, fieldwork on the Mesozoic and Cenozoic units onshore the northern part of the ATB started in 1959 by SOMIP (Société Maroco-Italienne de Pétrole). The Mesozoic and Cenozoic stratigraphy was first defined by Martinis and Visintin (1966) who named the Tan-Tan Formation. This formation was described as a 785 m thick interval of continental sandstones and subordinated muds, with minor marine incursions that become more frequent upwards. Precise dating of the Tan-Tan Formation was challenging due to the lack of age-diagnostic fossils in the continental sections and the limitation of long-ranging groups found in the marine intervals, although a pre-Albian age was widely-accepted.

The Tan-Tan Formation has been the most important reservoir target in the northern ATB. Sixteen offshore wells have been drilled to-date in the outer shelf and deep offshore, several with oil shows. Two further non-commercial discoveries have been made in Jurassic carbonates and one more in lower Cretaceous clastics (Fig. 1), all of which proves the existence of a working petroleum system, but the basin remains greatly underexplored compared with its conjugate counterpart in Nova Scotia.

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The expected deep water clastic reservoir outboard of the Tan-Tan delta has proven elusive and a better understanding of this system is needed. This new contribution establishes an updated outcrop-based litho-, bio- and sequence stratigraphic framework that can improve the existing understanding of the evolution of the so-called Tan-Tan delta system, and ultimately develop a depositional model.

2. Geological setting and methodological approach

The origin of the ATB (Fig. 1) is linked with the opening and evolution of the Central Atlantic during the Mesozoic. The break-up of Africa and North America along the Central Atlantic segment started during the Triassic (e.g., Labails et al., 2010). Rifting developed restricted basins that were filled with continental red clastics and later salt deposits on both sides of the nascent Atlantic (e.g., Davison, 2005). These evaporites were mobilised during the deposition of the Jurassic and Cretaceous series (Uranga et al., 2022). The first oceanic crust was formed in the Early Jurassic, marking the beginning of the drift stage (early/late Early Jurassic onset is debated; see Davison, 2005; Labails et al., 2010). Favourable conditions during the Jurassic triggered carbonate production and the development of extensive carbonate platforms along both conjugate margins (Hafid et al., 2006). The Cretaceous is characterized by the shut-off of carbonate production, with development of large clastic systems during the Early Cretaceous (e.g., Arantegui et al., 2019) followed by an overall transgressive system associated with rising sea-level, resulting in deposition of thick marine shales during the Late Cretaceous (e.g., Zühlke et al., 2004).

The current distribution of Cretaceous outcrops is the result of the Atlasian Orogeny, that whilst only having a mild effect south of the South Atlas Fault (Fig. 1), uplifted and exposed the basin margin. All Mesozoic outcrops along the Atlantic margin in the ATB were previously tentatively assigned to the Cretaceous. A re-interpretation of a number

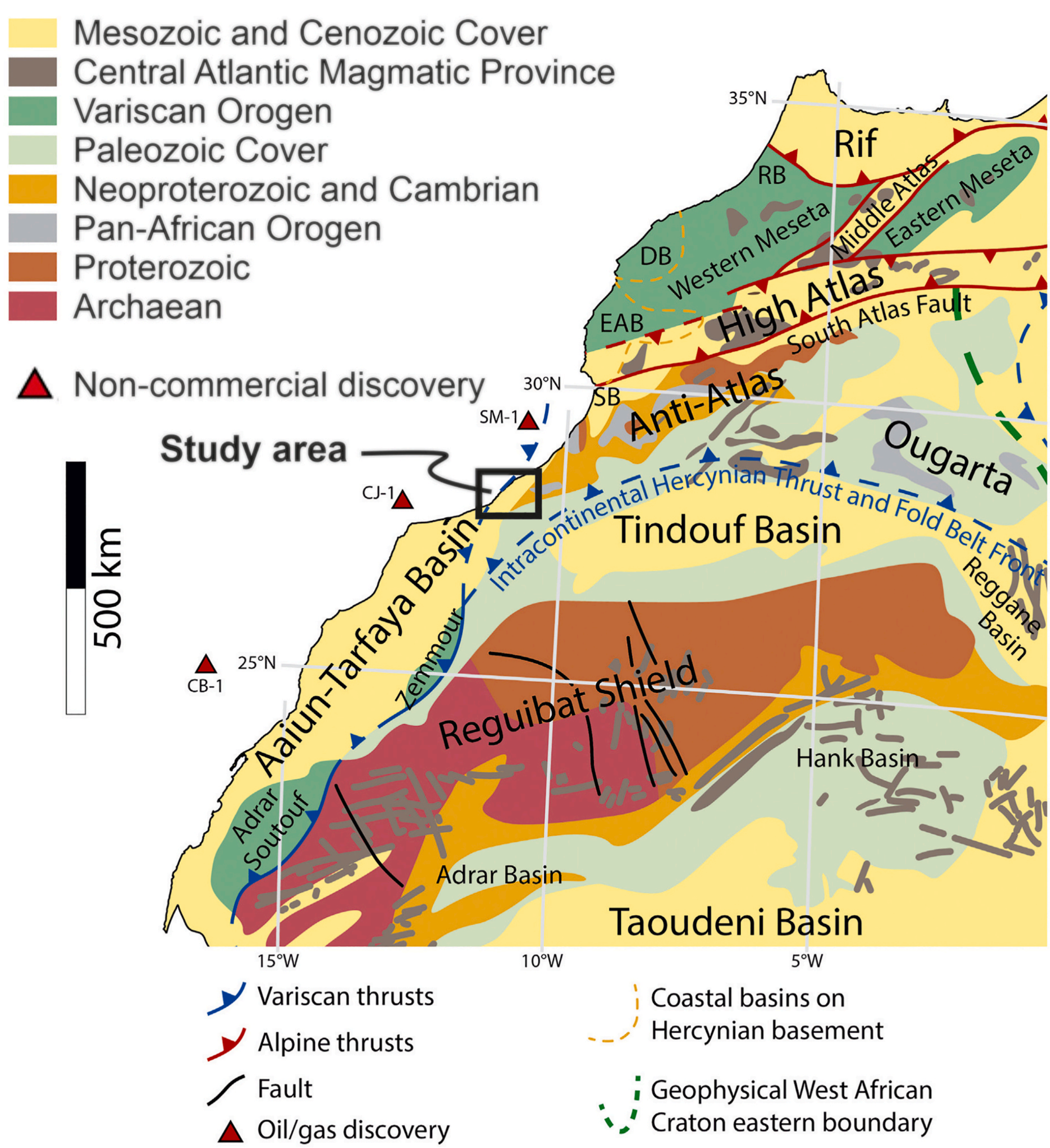

Fig. 1. Schematic map of structural elements of Morocco and northern West African Craton. (modified after Arantegui et al., 2019). The study area in Fig. 2 is highlighted.

of outcrops along the Atlantic side of the Ifni inlier has yielded an updated Bathonian or older age for part of the succession (Arantegui et al., 2019). Older sediments have also been recorded by commercial wells onshore and offshore and by the DSDP drilling programme.

The Cretaceous interval is very well exposed in the onshore ATB. Potential regional tilting (Wenke, 2014; Uranga et al., 2022 and references therein) to the west and lack of significant tectonism have resulted in gently dipping lower Cretaceous exposures along a NE-SW strip of the eastern part of the onshore ATB, along the western limit of the Anti-Atlas, Tindouf Basin and Reguibat Shield.

The Lower Cretaceous exposed in the ATB comprises the sandstone-dominated Tan-Tan Formation and the lower part of limestones and muds of the Aguidir Formation (Martinis and Visintin, 1966). Martinis and Visintin (1966) described the Tan-Tan Formation north of the locality of Tan-Tan, along the Oued Draa (Fig. 2), extending to the Atlantic river mouth, and following the coast SW up to Oued Chebeika. It was reported to attain a thickness of 785 m. The formation was reported to begin with a basal unit of red conglomerates approximately 50 m thick unconformably overlying the Palaeozoic of the Anti-Atlas. They describe the majority of the formation as made of monotonous units of cross-bedded sands with intercalations of clays and sandy marls. A unit, 65 m thick, of marls and limestones with bioclasts was further subdivided as the Membre Marnes du Draa (Dra Marls Member).

Most of the formation was interpreted as deposited in a continental environment, with episodes of marine sedimentation, mainly related with the Dra Marls Member. The fossil record is restricted to the marine units, where ammonites, bivalves and gastropods were recovered. The base of the Tan-Tan Formation is undated and rests unconformably on Paleozoic basement of the Anti-Atlas. The age for the top of this formation is constrained by Upper Aptian ammonites from the upper Tan-Tan Formation (Collignon, 1966, 1967) and by the overlying Albian-Maastrichtian Aguidir Formation (Martinis and Visintin, 1966).

The Aguidir Formation is exposed along the coastal basin from the river mouth of Oued Chebeika to the west (Martinis and Visintin, 1966), with a total reported thickness of 395 m. The age of the formation is reported as ranging from Albian to Maastrichtian (Martinis and Visintin, 1966). Although the formation is usually referred to as Aguidir Limestone Formation (Martinis and Visintin, 1966) the unit is mainly made of clays and marls. The limestone beds constitute the prominent units standing proud from the cliffs and hence the name. The unit has been interpreted to have been deposited in a shallow marine environment with poor water circulation.

The Aguidir Formation has been subdivided in three members, Oued Chebeika Clays (Argiles de l'Oued Chebeika), Derua Tuflit Limestones (Calcaires de Derua Tuflit) and Oued Haoui En Naam Marls (Marnes de l'Oued Haoui En Naam). The Oued Chebeika Member thickens westwards, and the top of the Member has a reported age of Cenomanian-Turonian.

The successions studied crop out along the Oued Draa and Oued Chebeika (Figs. 3 and 4), running approximately SE-NW, north and south of Tan-Tan. The study involved extensive regional mapping and sedimentary logging to describe facies in order to define the lithostratigraphic units. Key surfaces were physically walked-out. Fossils were also collected for biostratigraphic dating, based on ammonites and palynomorphs, and superposition related to newly dated underlying units.

3. Results

3.1. Sedimentary facies

Sixteen lithofacies (Table 1) and nine facies associations (Table 2) have been defined. Each facies association represents a distinct depositional environment. Examples of detailed sedimentary logs covering the main sedimentary features and depositional environments interpreted are illustrated in Fig. 4.

3.1.1. Alluvial fan FA

This association is present only at the lowermost part of the Oued Draa transect, preserved within a number of discontinuous exposures. It consists of fining upwards packages, up to 6 m thick, of red polygenic conglomerates (lithofacies A1 and A2) with thin interbeds of coarse sandstones (lithofacies C; Fig. 5A). Discrete sedimentary structures are not evident both in the conglomerates and the sandstones. The basal contacts of individual beds are sharp and erosive.

Fig. 2. Location map of the outcrops along the two transects presented in this work. More detailed satellite images and location of outcrops are shown in Fig. 3. Satellite image taken from GoogleEarthTM.

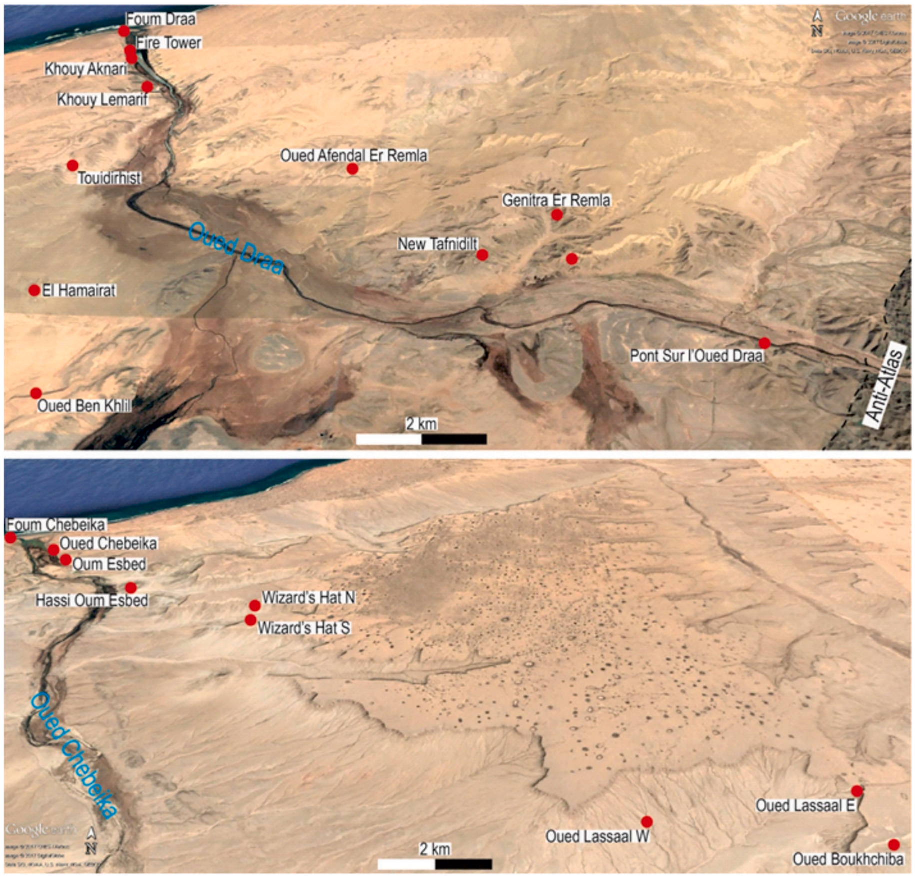

Fig. 3. Sections logged along Oued Draa transect (top) and Oued Chebeika transect (bottom) shown in off nadir angle satellite data from GoogleEarthTM.

Interpretation: The coarse grain size, erosive bases and absence of sedimentary structures suggest high-energy unconfined flows deposited quickly as gravel sheets within an alluvial fan (e.g. Miall, 2006).

3.1.2. Fluvial bar and channel fill

This association is represented by finning-upward packages up to 6 m thick of mainly cross-bedded sandstones (lithofacies B; Fig. 5B). Subordinate lithofacies include matrix-supported conglomerates (lithofacies A2), interbedded structureless sandstones (lithofacies C), and occasional beds with ripple tops (lithofacies H). Bases of the packages are erosive and sometimes channel-shaped. Lags of granules and pebbles are common either at the base of beds or cross-sets. Fossils and bioturbation are absent, except for occasional root traces. Palaeosols may develop in the coarse-grained sandstones as iron hardgrounds (lithofacies K). Occasional m-scale inclined bedding (accretion) surfaces of medium to fine-grained sandstones are present. Bioturbation and palaeosols developed at the top of the beds are common in fine-grained sediment. Relatively common gypsum veins at the bedding contacts and filling desiccation cracks.

Interpretation: Cross-bedding, coarse-grain size, fining-upwards trends and erosive surfaces, together with the absence of bioturbation and occasional palaeosols and root traces are typical of deposition in a continental setting. Sedimentary structures are generated by intermittent waning flows representing subaqueous dunes stacked to form bars (Miall, 2006). Channelized basal surfaces indicate channel-fills. The inclined bedding represents lateral accretion surfaces in a point bar environment or the in-filling of small ephemeral channels.

3.1.3. Fluvial floodplain

This association is mainly made of mottled silts to very fine-grained sandstones (lithofacies K, Fig. 5C) with occasional interbeds of cross-bedded, massive and rippled-laminated sandstones (lithofacies B, C and H). Packages are up to 2.5 m thick, do not show a clear grain size trend but they usually exhibit a striking red colour. Iron crusts, calcretes and gypsum nodules may be present.

Interpretation: The fine grain size of the sediment and occasional sandstone beds suggest deposition in a low-energy environment with intermittent higher energy flows. Development of palaesols and chemical precipitation of sulphates, carbonates and iron suggest high rates of evaporation and long times of subaerial exposure.

3.1.4. Peritidal bar and channel fill

This association is mainly made of fining-upwards packages of cross-bedded sandstones and subordinate normally-graded massive sandstones (lithofacies B and C) up to 7 m thick (Fig. 5D). Coarsening-upwards packages up to 2.5 m thick are also observed. This association exhibits an overall striking white to light grey colour in outcrop. Current and wave ripples are uncommon (lithofacies H and G). Palaesols red/green/yellow in colour may develop on thin interbeds of mottled silt to very fine-grained sandstones (lithofacies K). Sedimentary structures suggest approximately N-S bidirectional currents, but with N being the dominant sediment transport direction. Soft sedimentary deformation can be locally common. Bioturbation, mainly by vertical burrows is locally abundant in the fine-grained sandstones (lithofacies F). Rare bivalve bioclasts may be present at the top of coarsening-upwards packages.

Interpretation: The coarse grain size, cross-bedding and overall fining-upward grain size profile suggests subaqueous dunes filling channels or migrating bar forms. The presence of bioturbation and occasional bidirectional palaeoflows registered indicates tidal-influenced channel fills. Infrequent coarsening-upwards packages of cross-bedded sandstones crop out in the upper part of the thick peritidal successions

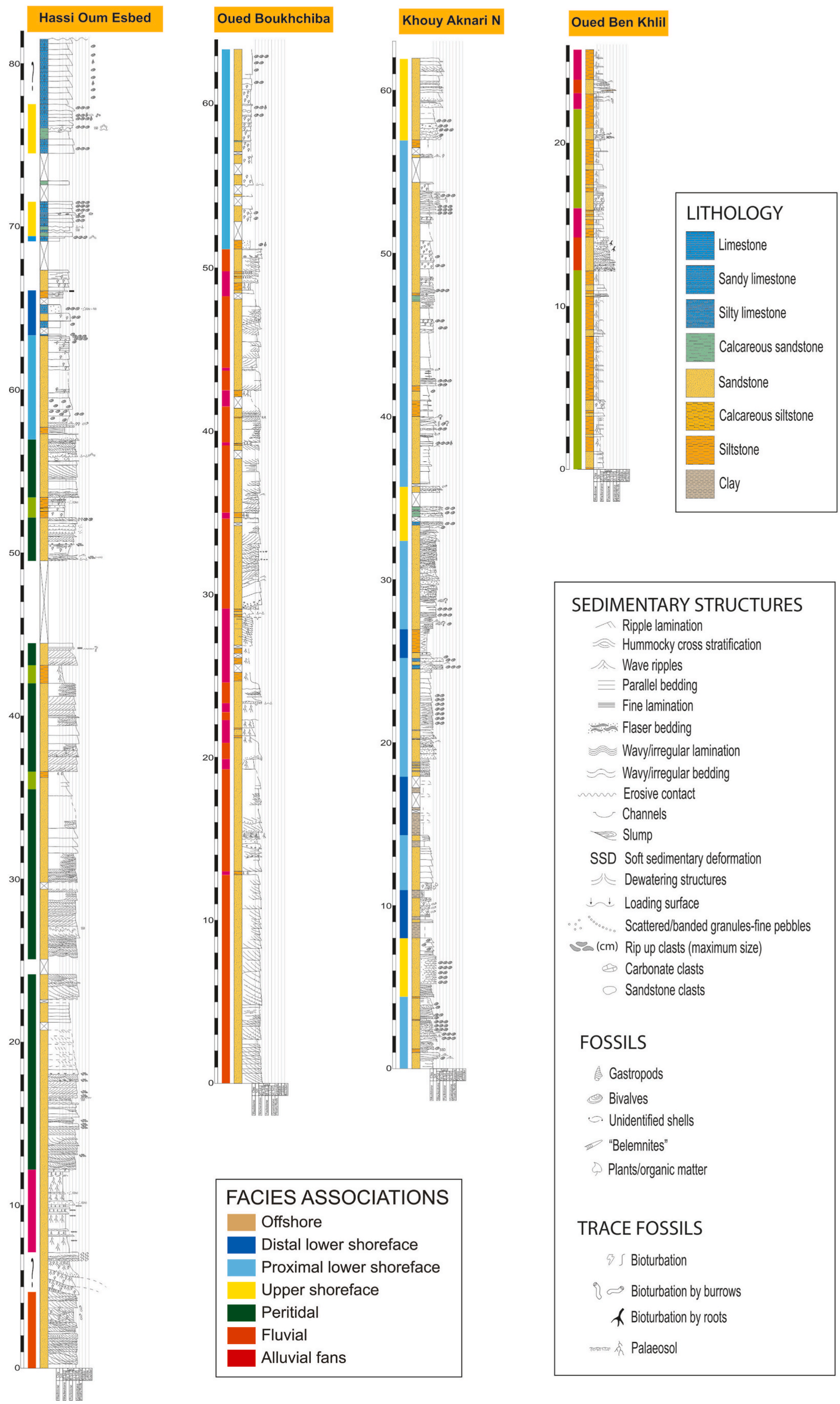

Fig. 4. Example of four graphic sedimentary logs showing main lithology, sedimentary structures, fossil content and interpreted depositional environments.

Table 1
Lithofacies recognised in the Tan-Tan Formation in the north Aaiun-Tarfaya Basin.

Name	Description	Interpretation
Conglomerate (A1)	10-110 cm-thick red conglomerates. Normally graded to massive lacking sedimentary structures. Bases are sharp undulating and erosive. Clast size ranges from pebble to cobble, poorly sorted, angular to subrounded and heterogeneous lithology.	Pseudoplastic debris flow forming sheets
Matrix-supported conglomerate (A2)	60 cm-thick matrix-supported conglomerates. Matrix is very coarse-grained sand. Clasts are pebble to cobble size, poorly sorted, subangular to subrounded and heterogeneous lithology.	Viscous plastic to pseudoplastic debris flow froming sheets
Cross-bedded sandstones (B)	15-210 cm-thick, normally graded, cross-bedded gravelly to fine-grained sandstone. Rare packstone to grainstone. Bases are sharp and usually erosive and can cut down the stratigraphy up to 200 cm, occasionally resembling channels. Sedimentary structures include planar, tangential and trough cross-bedding in sets from a few cm up to 2 m thick. Rare cross-sets can be over-steepened and deformed. Soft sediment deformation can be locally intense represented by load-casts, injected sands and contorted internal bedding. Pebble and granule lags are common, either at the base of beds and of individual foresets. Rip up mudclasts up to 15 cm may be present at the base of the bed. Rare horizontal bedding in very coarse-grained sandstones. Usually poorly sorted and relatively rounded. Clast mineralogy is mainly mono and pollycrystalline quartz and subordinated feldspars. Feldspar clasts can be locally common, euhedral and cm-scale. Locally, bivalves present to common. Occasionally, horizontal burrows can be abundant on the top surface and vertical burrows throughout. Unidentified bioturbation can be intense locally. Possible vertical root traces. Rare mottling and soil development.	Migration of 2D and 3D dunes by traction under unidirectional (wanning) flows Occasional plane-bed flow under super-critical flow
Parallel-bedded sandstones (C)	10-40 cm-thick massive to normally graded very coarse- to very fine-grained sandstones to calcareous sandstones. Beds are tabular with sharp undulating contacts, locally, erosive and load-casted. Occasional soft sedimentary deformation. Crude lamination is rare. Floating scattered quartz pebbles or mudclasts may be locally common. Sandstone clasts are rare but can reach 20 cm Common bivalves and minor gastropods are possible (either body fossils or dissolved moulds), sometimes accumulated at the base of individual beds. Red mottling is possible. Red cementation. Rare iron "hardgrounds" developed on top of beds. Occasional green beds.	Sediment-gravity flow deposits. Suspension fall-out. Destratification by intense bioturbation.
Laterally accreting Sandstones (D)	10-20 cm-thick normally graded very coarse- to very fine-grained grey/green to red sandstones displaying inclined bedding surfaces. Grey/green colour is usually at the bottom of beds. Pebbles and reworked clasts may be common at the base of beds. Desiccation cracks and probable rootlets may be present. Gypsum veins fill the desiccation cracks and sometimes follow bedding planes. Bioturbation can be intense in the upper part of beds. Current ripples may be present in the finer spectrum of grain size.	Lateral Accretion surfaces. Grey/red colour related with reduction/oxidation of periodic exposure.
Hummocky cross-stratified sandstones/limestones (E)	20-100 cm-thick coarse- to very fine-grained sandstones and calcareous sandstones. Main lithology can range up to recrystallized sandy packstone. Sedimentary structures include hummocky and low-angle cross-bedding/lamination. Infrequent sole marks at the base of beds. Symmetrical or combined-flow ripples capping beds are common. Scarce to abundant broken bivalves and unidentified bioclast fragments. Occasionally, floating quartz pebbles may be abundant. Bioturbation (*Diplocraterion paralellum*) can be locally intense.	High-energy oscillatory and combined flows during waning storm events.
Intensily bioturbated sandstones/calcareous sandstones (F)	10-110 cm-thick massive to normally graded medium- to very fine-grained sandstone to calcareous sandstone. Massive appearance and absence of sedimentary structures is likely due to intense bioturbation and weathering. Rare relicts of horizontal and ripple lamination. Occasional load casts. Minor floating granules/pebbles. Rarely, pebbles can be concentrated at the base of beds but do not form lags. Occasional lenses of slightly coarser sand. Some beds may have abundant bivalves and gastropods. Bioclast can be dissolved and recrystallized. Rare sideritised plant material, pyrite pseudomorphs and iron nodules. When fossils are absent the sand tends to be very clean. Individual beds can be better cemented and pervasive bioturbation by vertical burrows or Thalassinoides ichnofacies are identified.	Complete destratification by intense bioturbation. Possible sediment fall-out, migration of 2D/3D ripples and/or reworking by oscillatory currents.
Wave-rippled sandstones (G)	5-10 cm-thick fine-grained to very fine-grained sandstones with interlayered thin silt laminae. The main sedimentary structure is symmetrical ripple-lamination, with occasional flaser and lenticular bedding. Bioturbation can be moderate. Ichnogenera may include Thalassinoides.	Migration of ripples by oscillatory flows and periods of suspension settling.
Current-rippled laminated sandstones (H)	5-30 cm-thick asymmetrical ripple-laminated medium- to very fine-grained sandstones. Interbedded muds within the sands and scattered "isolated" ripple sets (lenticular and flaser bedding). Contorted discontinuous sandstone clasts might be possible. Plant fragments and bioturbation (Thalassinoides and Diplocraterion paralellum) may be locally common.	Migration of ripples by unidirectional currents under lower flow regime alternating with periods of suspension settling
Inversely-graded siltstones/sandstones (I)	20-40 cm-thick inversely graded siltstone to very fine-grained sandstone. Floating quartz granules and pebbles may range from abundant to absent. Mudclasts, cm-scale broken bivalves and bioturbation are possible. Thalassinoides possible. Mottling and/or palaeosol development possible.	Sandy debris flow deposit.
Pebble-bearing structureless siltstones/sandstones (J)	10-50 cm-thick structureless to normally graded, fine-grained sandstone to siltstone with floating quartz granules and pebbles and occasional reworked mud-	Dilute sediment gravity flow deposits.

(*continued on next page*)

Table 1 (*continued*)

Name	Description	Interpretation
	clasts and sandstone-clasts up to 10 cm Common bivalves and scarce gastropods and plant fragments may be present. Moderate bioturbation and/or palaeosol development may be possible.	
Mottled palaeosol (K)	20-120 cm-thick, usually red, mottled silt to very fine-grained sandstone. Colours may range from red/purple/mustard/green/grey. Red cementation may be possible, likely iron-related. Carbonate-cemented calcrete soils are frequent. Mottling and root traces occasionally developed in coarse sandstones. Occasional iron hardgrounds and gypsum concretions.	Soil formation with root development and chemical precipitation
Muds/calcareous muds (L)	Laminated to thinly bedded silts to clays with organic remains. Can be calcareous (marls). Minor small-scale shells (bivalves, gastropods, ammonites). Plant fragments can be abundant locally, including cm-scale leaves. Bioturbation can be intense locally.	Suspension settling
Mudstone-Wackestone (M)	10-40 cm-thick massive bioclastic-bearing micritic mudstone to wackestone. Rare faint undulating layering resembles HCS. Silt/sand content can range from absent to moderate. Bioclasts are mainly bivalves, and occasionally the content can increase upwards. Some bivalves are articulated. Oysters and other cm-scale bivalves can be locally abundant. Rare belemnites. Bioturbation can be intense.	Autoctonous fauna or short transport distance. Absence of sedimentary structures suggest quiet environment
Wackestone-packstone (N)	15-40 cm-thick beds of bioclastic-rich wackestones to packstones. Sharp undulating surfaces. Rare wave ripples on top surface. Bioclasts are mainly disarticulated bivalves and sometimes they can form lags. Gastropods can be locally common. Occasional nodules. Locally, abundant bivalves and intense bioturbation by Thalassinoides. Rare belemnites and serpulids.	Autoctonous fauna combined with current traction, migration of ripples and suspension settling
Grainstone (O)	10-65 cm-thick bioclastic-rich grainstones. Bivalves are the main bioclasts, but gastropods (nerinellids and scalarids) can be locally abundant. Sometimes coquinas. Shells can be completely recrystallized. Rare small-scale bulbous corals in the coquinas.	Reworking of bioclasts and washing out of fine-grained components by waves

(see m 50–57 at Hassi Oum Esbed outcrop in Fig. 4). Occasional abundant bioturbation at the base, bivalves at the top and the vertical relationship with other sedimentary facies suggest an interpretation of intertidal channelised bars (creeks and estuaries).

3.1.5. Peritidal flats

This association is mainly composed of mottled red (occasionally green and grey) muds (lithofacies K) with subordinated massive, cross-bedded, current and wave ripple-laminated and/or bioturbated sandstones (lithofacies C, B, H, G and F; Fig. 5E). Packages do not show a clear grain size trend or weak fining-upward trends, reaching up to 7 m in thickness. The red facies are generally muds to very fine-grained sandstones and can be bioturbated or have developed palaeosols. Tabular, laterally continuous, well cemented prominent white sandstones (lithofacies F) stand out over the red muddy background in some outcrops at the base of fining-upwards packages. These sandstones may show mud drapes on the cross laminae and are intensely bioturbated.

Interpretation: The cross-bedded, bioturbated and mud-draped sandstones were deposited in a relatively energetic environment probably in a shallow subtidal to intertidal environment. The red colour and development of palaesols suggests intermittent exposure, with low sedimentation rates in the intertidal to supratidal flats. An overall fining-upwards trend displaying the subtidal sandstones to the supratidal palaesols is characteristic of progradation in a peritidal environment. Thin sandstone levels interbedded within the muds represent storms or higher tides.

3.1.6. Upper shoreface

This association is mainly made of coarsening-upwards packages up to 5 m thick of cross-bedded, frequently bioclastic, and bioturbated sandstones (lithofacies B and F; Fig. 5F). Carbonate-dominated successions are represented mainly by bioclastic packstones and grainstones (lithofacies N and O). Subordinate lithofacies include current and wave ripple-laminated sandstones and muds/marls. Marine bioturbation by Thalassinoides can be locally pervasive in sandstones.

Interpretation: Sedimentary structures, fossil content and bioturbation suggest deposition in a subtidal marine environment under the action of unidirectional currents modulated by the oscillatory flow produced by wave action.

3.1.7. Proximal lower shoreface

This association is dominated by massive fine-grained yellow sandstones (lithofacies F). The massive appearance is probably due to weathering and complete destratification by intense bioturbation. Occasionally, less intense weathering allows identification of discrete bioturbation (Fig. 5G) or remnants of sedimentary structures (i.e., ripples). Subordinate lithofacies include hummocky cross-stratified, current and wave ripple-laminated and cross-bedded sandstones, micritic mudstones to wackestones with occasional bioclasts and muds (lithofacies E, H, G, B, M and L). Bioclastic grainstones or coquina beds (lithofacies O) can be present, spaced throughout the succession, some of them very prominent and laterally-extensive. A wide assortment of fossil groups may be found in an individual bed with bivalves (Trigoniids mainly; Fig. 5H) being the dominant group. Subordinated groups include gastropods, bulbous corals, and scarce brachiopods (Terebratulids).

Interpretation: The presence of hummocky cross-stratification overlain by wave-rippled tops is diagnostic of storms. Coquinas with cosmopolitan fossil assemblages are interpreted as shell lags, the result of storms reworking shallower sediments. The preservation of these two features indicates deposition below the fair-weather wave base, allowing preservation.

3.1.8. Distal lower shoreface

This association is usually made of interbedded fine-grained yellow sandstones and muds (lithofacies F and L) in coarsening-upwards packages up to 5 m thick. The amount of mud interbeds is higher than in the previous association. Subordinate lithofacies include occasional thin interbeds or lenses of massive, rippled-laminated, hummocky cross-laminated and wave ripple-laminated fine-to medium-grained sandstones (lithofacies C, H, E and G). Bioclasts can range locally from absent to common.

Interpretation. The higher proportion of muds indicates a more distal and deeper depositional setting. Preservation of HCS interbedded in muds puts it between the storm and the fair-weather wave base.

3.1.9. Offshore

This association is almost entirely made of clay-sized clastics and marls (lithofacies L). Thin interbeds of silts and fine-grained sandstones are infrequent (lithofacies H, B, G and C).

Interpretation: The fine grain of the sediment suggests mainly suspension settling in an offshore setting below the storm wave base. The scarce interbeds of coarser sediment represent small-scale turbidites probably related with storms affecting the shallower part of the shelf.

3.2. Biostratigraphy

Marine facies in the area are rich in bivalve faunas. Among the bivalves along Oued Draa, several specimens belong to the group of *Plicatula placunea* Lamarck, *Plicatula radiola* Lamarck and *Plicatula inflata* Sowerby. Those taxa are in need of a modern taxonomic revision but their known stratigraphic range is strictly restricted to the Aptian to Lower Albian (Kotetishvili et al., 2005). *Plicatula inflata* was reported from the Tan-Tan Formation at Cap Dra by Freneix (1972) and according to Collignon (1967, 1966), the associated ammonite fauna indicates a late Aptian age. It should also be noted that in the Essaouira Agadir Basin, *Plicatula placunea* and *Plicatula radiola* are very common in the Tamzergout and Lemgo formations (Ambroggi, 1963; Rey et al., 1986a, 1986b). It is now clearly established that these latter formations are of early Upper Aptian to early Albian age (Luber et al., 2017). In higher stratigraphic levels, at Oued Chebeika outcrop (Fig. 3) a specimen of *Cymatoceras albense* (Fig. 6A) was found, dating this part of the succession as late Albian. At the topmost section visited, at the Foum Chebeika outcrop, samples of black shales processed for palynological examination yielded dinoflagellates, spores and pollen of latest Albian to Cenomanian in age. Age diagnostic palynomorphs include the presence of at least two species of *Afropollis* (including *A. kahramanensis* described by (Schrank and Ibrahim, 1995) from the mid-late Cenomanian of Egypt and several rare specimens of elaterate pollen which are diagnostic of the Albian-Cenomanian Elaterates Province defined by (Herngreen et al., 1996). Stratigraphic ranges inferred from new specimens collected and from the literature are shown on the correlation panel in Fig. 8.

3.3. Lithostratigraphy

The stratigraphy covered during the present work belongs to the Tan-Tan Formation and the very lower part of the Aguidir Formation (Martinis and Visintin, 1966). From the descriptions and type section of Martinis and Visintin (1966) four main lithological intervals can be distinguished within the Tan-Tan Formation. Despite of this, only a 65-m-thick interval of interbedded marls and limestones was ranked as a Member (Membre des Marnes du Draa - Draa Marls Member; Martinis and Visintin, 1966). Previous interpretations of the main depositional environment for this succession suggest it was largely continental, interpersed with marine episodes, mainly towards the upper part, and better developed during deposition of the Draa Marls Member (the latter interpreted as neritic facies; Martinis and Visintin, 1966).

The acquisition of a vertical and lateral stratigraphic record for the Tan-Tan Formation in the study area is challenging, relying on two partial transects, in cliffs marking the margins of the valleys of the Oued Chebeika and Oued Draa. The strata have a low overall regional dip towards the W, and the vertical thickness of the exposed sections ranges

Table 2
Summary of the interpreted facies associations in the Tan-Tan Formation in the north Aaiun-Tarfaya Basin. In brackets subordinated lithofacies.

	Main depositional environment	Sub-environment	Lithofacies	Main features
FA1	Alluvial fans		A1, A2, (C)	Fining-upwards packages up to 6 m (not clear due to poor exposure)
FA2.1	Fluvial	Channel fills Bars	B, (C, H, K)	Cross-bedded fining-upwards packages up to 6 m Possible meter-scale inclined surfaces (HIS) Frequent lags of granules/pebbles Occasional roots and palaeosols developed in medium- to coarse-grained sandstones Rare desiccation cracks Occasional normally-graded beds are capped by ripples
FA2.2	Fluvial	Flood plain	K, (B, C, H)	Frequent palaeosol developed in silts to very fine-grained sandstones Interbedded sandstones (massive to small-scale cross-bedded to rippled) Thickness up to 2.5 m
FA3.1	Estuarine/peritidal	Channel fills Bars	B, C, (H, K, G, F)	Cross-bedded fining-upwards packages up to 7 m (overlying and underlying mud successions) Sedimentary structures suggest bidirectional flows with one predominant Frequent reworked mud clasts in the lower sandstone beds Common soft sediment deformation Occasional thin interbeds of mottled silt to very fine-grained sandstone Occasional vertical bioturbation by burrows Rare coarsening-upwards packages up to 2.5 m thick of very fine- to coarse-grained sandstones Occasional bivalves Characteristic white to light grey colour
FA3.2	Estuarine/peritidal	Peritidal flats	K, F, (C, B, H, G)	Packages of mottled red and green (sometimes grey) muds up to 7 m interbedded with tabular fine-grained sand bodies up to 1 m thick without a clear grain size trend Frequent palaeosols developed in muds with interbedded thin fine-grained sandstones Sandstones may be pervasively bioturbated (mainly vertical burrows), trough cross-laminated with mud drapes and well cemented with a striking white colour
FA4.1	Shoreface	Upper shoreface	B, C, F, N, O, (H, G, L)	Cross-bedded sandstones with interbedded bioclastic-bearing beds Bioclastic-rich packstones and grainstones Occasional intense biturbation by marine ichnotaxa
FA4.2	Shoreface	Proximal lower shoreface	F, G, E, M, (C, L, B, O)	HCS, low-angle cross-bedding and wave-rippled top beds can be locally abundant Locally common rippled-laminated fine-grained sandstones Occasional thin interbedded muds to fine-grained sandstones Mudstones-wackestones with occasional floating bioclasts in carbonate-dominated successions
FA4.3	Shoreface	Distal lower shoreface	F, L, (H, C, E, G)	Usually coarsening-upwards packages of interbedded muds and fine-grained sandstones up to 5 m thick Occasional thin interbeds to lenses of rippled-laminated fine- to medium-grained sandstones Bioclasts from absent to common Marls with thin interbeds of sandstones with current ripples or HCS usually capped by wave ripples
FA5	Offshore		L, (H, B, G, C)	Black clays Occasional interbeds of silts and fine-grained sandstones, including rippled top surfaces

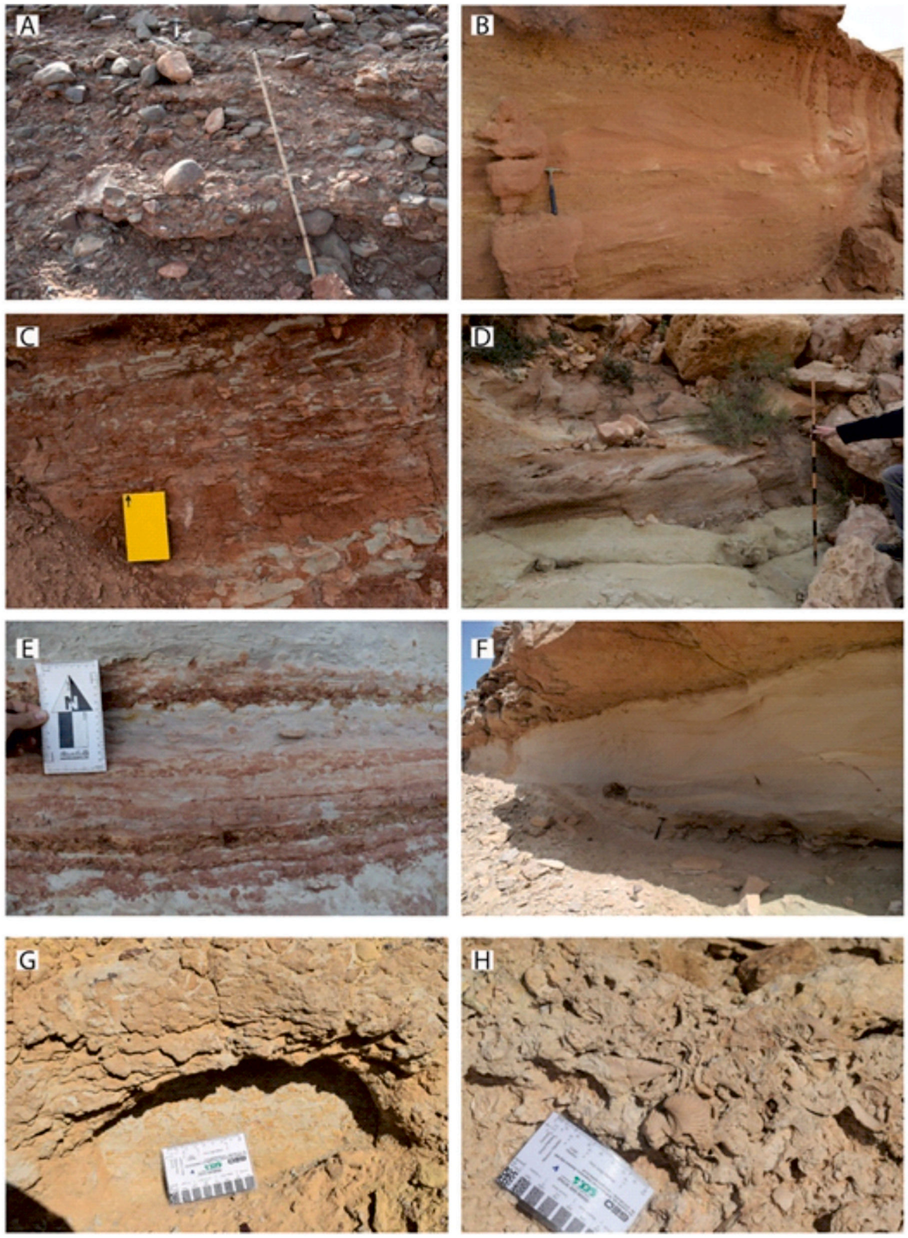

Fig. 5. Examples of facies associations in the field. A) Alluvial fan conglomerates at Pont Sur l'Oued Draa. Note poor sorting and absence of sedimentary structures. B) Fluvial cross-bedded sandstones and pebbly sandstones at Old Tafnidilt. C) Laminated mottled floodplain silts and fine-grained sandstones at Old Tafnidilt. D) Coarse-grained cross-bedded peritidal bar at Wizard's Hat south. Note the erosive base and reworking of sandstone clasts from the underlying unit. E) Intensely bioturbated and rippled alternation of fine-grained sandstones and silts at New Tafnidilt. Red levels are related with longer exposure and incipient palaeosols. F) Cross-bedded fine-to medium-grained upper shoreface sandstones. G) Intensely burrowed fine-grained sandstones interpreted as proximal lower shoreface at El Hamairat. H) Field photograph of a coquina along Oued Chebeika. Trigonids (center of image) are the most abundant group together with various unidentified bivalve groups.

from 26 to 84 m. Biostratigraphic constraint for the Tan-Tan Formation is not of a high enough resolution to afford a detailed correlation in many areas; however, age-diagnostic fossils, either from the literature or new data from this study have been used to improve the final correlation in the study area (Figs. 8 and 9). Some characteristic facies have, however, proved key for regional correlation: i) the continental alluvial fan conglomerates (FA1) display an intense red colour, and usually comprise fine-grained clastics with mottling and the development of palaeosols (FA3 and sometimes FA5); ii) a characteristic yellow colour was linked with marine deposits (FA6, 7 and 8); and iii) a very distinctive laterally continuous white sandstone unit (FA4), approximately 45 m thick, is exposed in the central part of Oued Chebeika transect. These white sandstones are also found along the Oued Draa, where it crops out in isolated exposures passing laterally to a more distal facies association, but it does not present a laterally extensive unit. Sequence stratigraphic concepts (e.g. identification of flooding surfaces) were also used for correlation purposes.

Applying a general approach to lithostratigraphy (e.g. Whittaker et al., 1991) the Tan-Tan Formation has been sub-divided into six members. These subdivisions integrate the previously proposed Draa Marls Member of Martinis and Visintin (1966). Our proposed erection of a lithostratigraphy is informal, and we use names that are largely descriptive (but we also propose names based on stratotype *in italics*). Within this framework we incorporate the previously recognised Draa Marls Member. The Members broadly represent the diachronous interfingering of marine "tongues" transgressing sharply from the west and

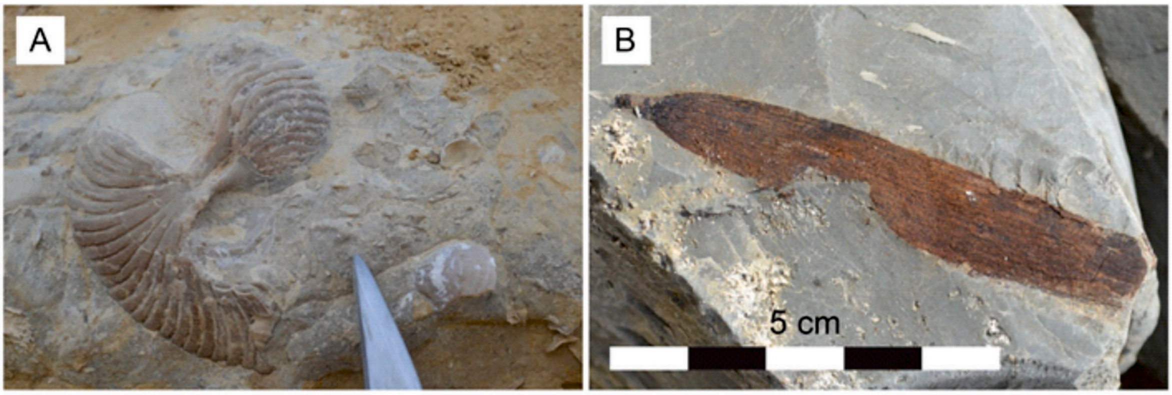

Fig. 6. Field photographs of fossils found along Oued Chebeika. A) Nautiloid (Cymatoceras albense) from Oued Chebeika outcrop. B) Unidentified plant leaf from Foum Chebeika outcrop.

north into continental facies which prograde towards the west and north. The datum for the correlation is the base of the Draa Marls Member (Fig. 8), marking the first occurrence of marine facies in the Tan-Tan Formation. This unit is present at both transects and it is traceable on satellite imagery at least as far south as the Smara region for more than 200 km to the south.

3.3.1. Red Conglomerates Member (RC) or the Pont Member, Tan-Tan Formation

This lithostratigraphic unit is exposed in the valley of the Oued Draa at its exit from the Anti-Atlas into the ATB (Fig. 7). It has an approximate thickness of 50 m. It is composed of red conglomerates with clasts up to cobble size (FA1) and no apparent sedimentary structures (Fig. 5A). Plant fossils are common, including a specimen of *Metapodocarpoxylon libanoticum*.

The conglomerates have a faulted lateral contact with the Anti-Atlas basement (Fig. 7; Hollard et al., 1985) and its base is not exposed. The conglomeratic facies crop out only in the proximity of Pont Sur l'Oued Draa, where the Oued Draa enters the ATB. Mapping in photo-imagery suggests a fan shape geometry to the unit, in part a combination of the regional tilting of the Mesozoic succession together with the erosion (Fig. 7). The present Oued Draa or an antecedent may have been active in its current location in the early Cretaceous, acting as the conduit for the alluvial conglomerates into the basin. The contact with the overlying Red Basal Sandstone Member is erosive (Fig. 7), but the significance of this surface (local incision, or regionally important erosion) is unclear.

3.3.2. Red Basal Sandstone Member (RBS) or Tafnidilt Member, Tan-Tan Formation

This lithostratigraphic unit makes up the lower 49 m of the section exposed at Oued Boukhchiba in the Oued Chebeika transect. It has a light reddish to whitish colour in outcrop. It is mainly composed of cross-bedded fluvial sandstones (FA2) with intercalated flood plain reddish silts and sands (FA3). The main palaeoflow direction is towards the NNE. It erosionally overlies the Red Conglomerates Member, and though this is not physically exposed in the area, probably onlaps the Palaeozoic which crops out approximately 750 m to the SE of Oued Boukhchiba. Along the Oued Draa it is probably >250 m thick and it is not clear

Fig. 7. Red conglomerates exposed at Oued Draa along the faulted contact between the Anti-Atlas and the Aaiun-Tarfaya Basin (see Pont Sur l'Oued Draa; Fig. 4). The red vertical arrows indicate an erosive contact between the conglomerates and the overlying fluvial sandstones.

whether it has a significant erosional contact with or be gradational upwards from the Red Conglomerates Member and/or onlap Paleozoic basement. In its upper in the central part of the Oued Draa valley, it also comprises more than 50 m of distinctly red and white peritidal sands and silts. Excellent exposures occur in the vicinity of Tafnidilt.

3.3.3. Draa Marls Member (Martinis and Visintin, 1966) or Draa Member, Tan-Tan Formation

This unit was originally defined along the Oued Draa. Despite the name originally assigned to this member, the unit is composed of heavily bioturbated fine-grained sandstones with interbedded bioclastic-rich sandstones/limestones (FA6, 7 and 8) and occasional clays to silts levels (FA9). It has a striking yellow colour and regional extent allowing mapping even in satellite imagery across the DLT Basin. It is exposed in the upper 14 m of the Oued Boukhchiba, Oued Lassaal east and the lower part of the Oued Lassaal west outcrops with a total thickness of ca. 30 m and around 50 m at Oued Draa transect. It sharply overlies the fluvial sandstones at Oued Chebeika transect and the fluvial to peritidal sandstones and silts at the Oued Draa transect belonging to the Red Basal Sandstone Member. In the valley of the Oued Draa it is thicker, and in its upper part correlative to the Red Upper Sandstone Member (described below), sandier, comprising peritidal channel-fills and flat facies. It therefore likely has a gradational lateral contact towards the south with the Red Basal Sandstone Member.

3.3.4. Red Upper Sandstone Member (RUS) or Oued Lassal Member, Tan-Tan Formation

The basal contact with the underlying member is poorly exposed. The best exposure is recorded in the upper part of the Oued Lassaal east outcrop. The first occurrence of pebble lags in cross-bedded sandstones, grain size increase and loss of marine fauna have been used to place the contact with the underlying Draa Marls Member. The unit has an estimated thickness of ~120 m in the valley of Oued Chebeika and its sedimentological features are characterized in the Oued Lassaal west outcrop. Facies are typified by cross-bedded sandstones and mottled silts and sands (FA2 and 3) recording a return to a continental setting similar to the Red Basal Sandstone Member. The main palaeoflow direction of this unit is towards the NW. This Member does not outcrop along the Oued Draa transect, and is instead there represented by laterally time-equivalent deposits of the Draa Marls Member.

3.3.5. White Sandstone Member (WS) or Oum Esbed Member, Tan-Tan Formation

This unit is not uniformly exposed across the study area. Along Oued Chebeika transect, this member is ca. 55 m thick, prominently white unit, and the contact with the underlying member is relatively sharp and well exposed at the base of the Hassi Oum Esbed outcrop, where the whole unit is exposed. Along Oued Draa transect this member is not as obvious, and is likely correlative to more open marine and shoreface strata exposed in the higher cliffs near the mouth of Oued Draa.

It is a sand-dominated interval with abundant cross-bedding, white to light grey in colour. Palaeocurrents are bi-directional and occasional intense bioturbation by invertebrates can be present even in coarse-grained sandstones. These features suggest interaction with a standing body of water and it has been interpreted as a tidal-influenced fluvial system (estuary) or tidal sand flats.

3.3.6. Yellow Upper Sandstone Member (YUS) or Foum Chebeika Member, Tan-Tan Formation

This yellow in colour unit is exposed at Wizard's Hat south and north, Hassi Oum Esbed, Oum Esbed and Oued Chebeika outcrops with an estimated thickness of ca. 65 m (Fig. 3). The contact with the underlying member is sharp and in some cases displays erosive scouring. The overall lithology and depositional settings represented are similar (FA6, 7 and 8) to the Draa Marls Member, although carbonates are more abundant. The fauna includes groups that were not observed in the Draa Marls Member, such as oysters, scarce domal corals and cephalopods (ammonoids, nautiloids and belemnoids) and occasional gastropod-monospecific beds. The erosive base unit is interpreted to be a ravinement surface. Along Oued Draa transect strata with similar affinities to these are tentatively ascribed to the Yellow Upper Sandstone M (Fig. 8).

3.3.7. Oued Chebeika Clay Member (Martinis and Visintin, 1966), or Oued Chebeika Member, Aguidir Formation

This unit is exposed around the mouth of Oued Chebeika. The contact with the underlying member is not well exposed. It is mainly made of dark grey clay-grade clastics and marls with interbedded fine-grained rippled- and hummocky cross-stratified sandstones (FA8 and 9). Plant fragments are common in the clay-sized clastics and marls (Fig. 6B), with scarce body fossils (gastropods, bivalves and cephalopods). This unit is eqivalent to the base of the Membre des Argiles de l'Oued Chebeika (Oued Chebeika Clay Member), which is the lowermost subdivision of the Aguidir Limestone Formation (Martinis and Visintin, 1966). No such time-equivalent strata are exposed in the Oued Draa transect, the stratigraphy being too low.

4. Discussion

4.1. Correlations and sequence stratigraphy

A sequence stratigraphic panel for both transects and a correlation between them is presented in Fig. 9. Both transects are oriented SE-NW. A sequence model with four systems tracts has been adopted for this study. To the classic model with lowstand, trasgressive and highstand (Posamentier and Vail, 1988; Vail, 1987; van Wagoner et al., 1988) the falling stage system tract (Plint and Nummedal, 2000) is incorporated.

Due to the absence of laterally-equivalent logged sections in continental sediments and the inherent difficulty of precisely identify flooding surfaces in continental successions, definition of parasequences have not been performed in the fluvial strata. Nevertheless, abrupt vertical changes in facies associations within continental environments have been interpreted as a possible effect of flooding events in distal areas.

(A part of) two depositional sequences have been interpreted based on correlations between the two transects. The Red Conglomerates Member is the lowermost unit exposed in the area, only exposed at the Oued Draa transect. Conglomerates belonging to the base of the Tan-Tan Formation have also been reported in the Cheb-1 and EA-1 onshore wells (Fig. 2). They are exposed next to a faulted contact on the margin of the basin with the Palaeozoic of the Anti-Atlas (Fig. 7), that is interpreted to have created the topography that developed the alluvial fan(s). Alluvial fans at the toe of the slopes of the Anti-Atlas have interpreted as a result of a sea-level lowstands. For example, lowstand wedge developed on the northwest African Altantic continental margin has been interpreted from seismic data, has been interpreted similarly and has been assigned a Berriasian (Wenke et al., 2011) or Valanginian (Todd and Mitchum, 1977) age. A sand-prone cycle in the turbidites of Fuerteventura has been dated as Berriasian, and interpreted as progradation of lower to middle deep sea fans (Arantegui et al., this volume). During the Berriasian, alluvial fans locally sourced from the Anti-Atlas developed during the sea-level lowstand. Possible incised valleys cut the exposed shelf as a result of bypass and erosion although such palaeovalleys were not recognised in this study, possibly due to non-exposure. At the same time deep water fans prograded at the platform margin reaching Fuerteventura. This moment represents the maximum progradation of the shoreline, represented in this study area by a sequence boundary (SB1; Fig. 9). We are, however, circumspect about assigning a Berriasian age to the base of this succession.

The Red Conglomerates Member is overlain by fluvial sandstones and silts belonging to the Red Basal Sandstone Member. Although the contact is not exposed, Palaeozoic rocks of the Anti-Atlas are exposed close to the base of the Oued Boukhchiba outcrop, and it is assumed the Red Conglomerates and Basal Red Sandstone members onlap the SB1 in

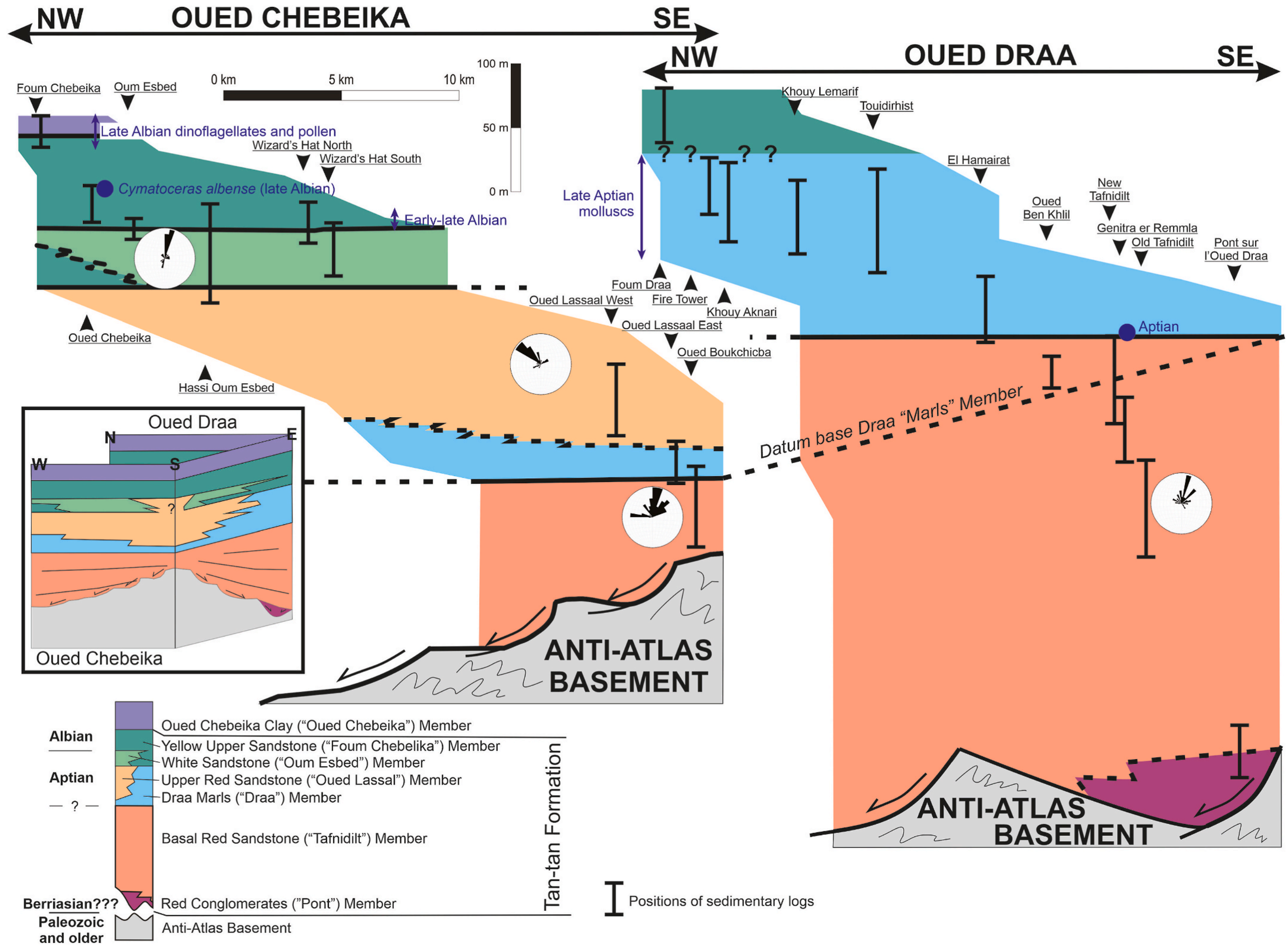

Fig. 8. Correlation panels of the two transects along the Oued Draa (right) and Oued Chebeika (left) showing proposed lithostratigraphic subdivisions, position of sections logged, and dating from the existing literature and new specimens collected. Both transects are parallel and oriented NW-SE. Inset, possible 3D correlation between the two transect.

this area (Fig. 9). Recorded palaeocurrents in the fluvial successions at Oued Boukhchiba and Old Tafnidilt outcrops yield a consistent transport direction towards the NNE. The upper ca. 60 m of this member at the Oued Draa transect represent deposition in a transitional setting interpreted as interfingering distal flood plain and tidal flats (FA3 and 5; Fig. 9). These peritidal sections have a striking red colour punctuated by dm-thick prominent white sandstone beds. These beds represent the base of mappable (numbered) parasequences that can be correlated between the logs taken at Genitra er Remla, New Tafnidilt and Oued Ben Khlil (Fig. 9). The parasequences have the typical fining-upwards profile, characteristic of peritidal progradation (Daidu et al., 2013). Occasional fining-upwards packages of cross-bedded sandstones less than 4 m thick punctuate this silt-dominated interval, and are interpreted as tidal creeks. Six parasequences (P1-P6) are identified in this upper interval, and are definitive about the transgressive nature of the upper part of the Basal Red Sandstone Member (TST1; Fig. 9). The succession between the Palaeozoic basement and these upper marginal marine facies are tentatively assigned to the lowstand systems tract (LST1; Fig. 9), but there is a marked lack of exposure of this succession.

The base of P7 marks a sharp transition to marine sandstones, silts and carbonates belonging to the Draa Marls Member. The strata recording the deepest water occur at the base of the second parasequence in the marine section (P8) along both the Oued Chebeika and Oued Draa sections, and include distal lower shoreface facies. In this interval, marine strata occur apparently across the basin. The maximum flooding surface of Sequence 1 (MFS1; Fig. 9) is therefore placed here. Along the Oued Chebeika, facies shoal rapidly to red fluvial sandstones of the Upper Red Sandstones Member within P8. One significant difference of these by comparison with the Basal Red Sandstones Member is that they palaeoflow towards the NW, as opposed to NNE for the lower interval. Along the Oued Draa the marine facies shallow less abruptly into interstratified packages of marine and sand rich peritidal facies and channel-fills with marine affinities (assigned to the Draa Marls Member; P9-P15; Fig. 9). The Red Upper Sandstone Member is absent in this area, P9 to P13 exhibit a SE to NW transition from a more proximal sand-dominated peritidal setting to upper shoreface and proximal lower shoreface sandstones and subordinate mudstones, and siltstones. The base of P13 and P14 represent flooding events of possibly higher magnitude and the facies recorded entirely represent the lower shoreface. Overall, there may be some higher-frequency autogenic or allogenic cyclicity within P8-P15, but they broadly stack to form a weakly progradational unit, which is therefore assigned to the highstand systems tract of Sequence 1 (HST1; Fig. 9).

The base of the next sequence (Sequence 2) is placed at the base of the White Sandstone Member along Oued Chebeika (SB2+TS2; Fig. 9). The White Sandstone Member is not impossibly a valley-fill given the estuarine nature of the deposits, which sit sharply over fluvial and channel-fill deposits of the underlying Upper Red Sandstone Member.

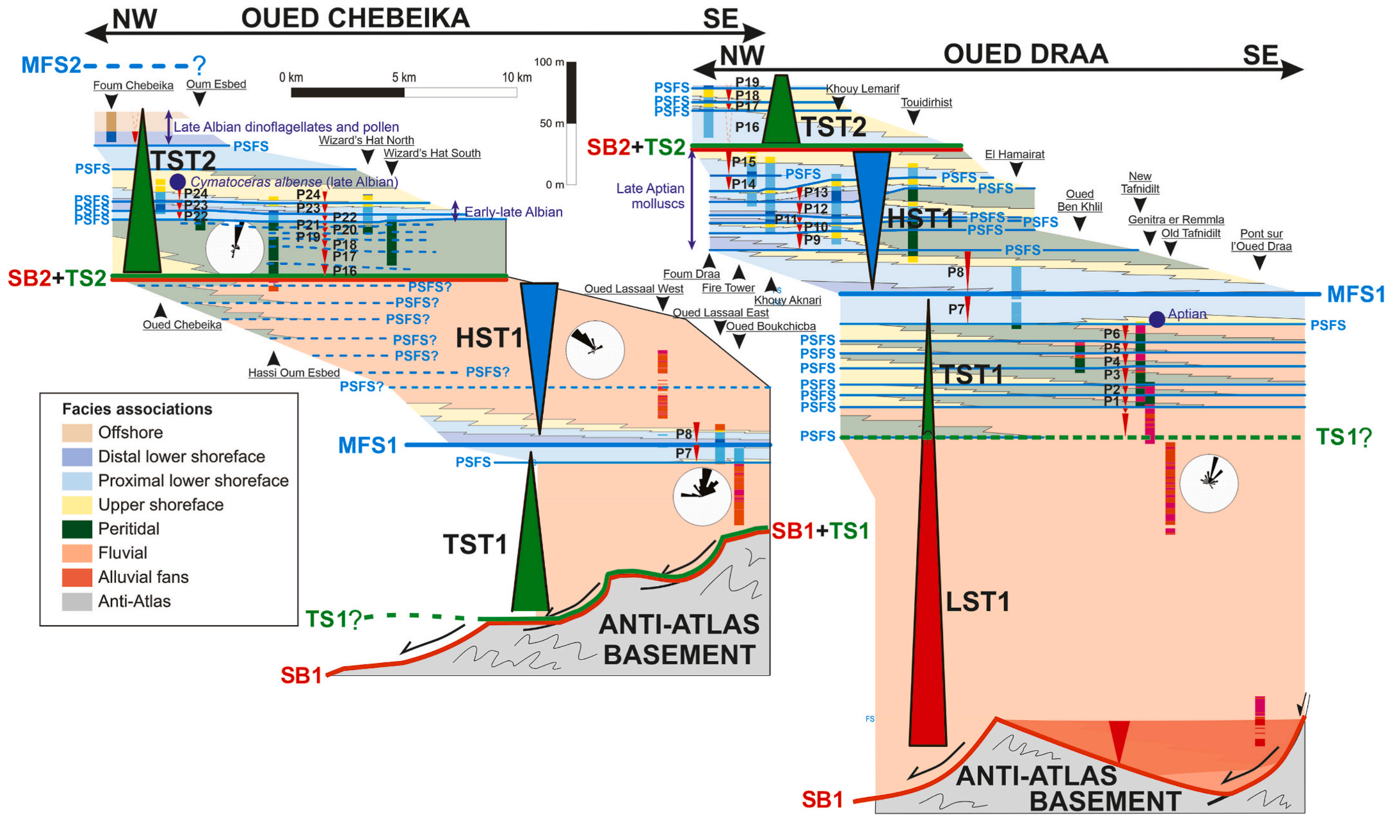

Fig. 9. Correlation panels of the two transects along the Oued Draa (right) and Oued Chebeika (left) showing facies associations and position of sections logged. Dating from the existing literature and new specimens collected is also shown. PSFS: parasequence flooding surface (base); P: parasequence; SB: sequence boundary; TS: transgressive surface; MFS: maximum flooding surface; SB + TS: amalgamated sequence boundary and transgressive surface.

Six parasequences (P16-P21; Fig. 9) have been identified in the White Sandstone Member, recorded across four outcrops. Only at the Hassi Oum Esbed outcrop (Fig. 4) is the member completely exposed. Most of the parasequences exhibit a fining-upwards profile typical of progradation (Daidu et al., 2013) from peritidal to fluvial channel fill and abandonment. Palaeocurrent measurements show an asymmetric bidirectional flow NNE-SSW, which supports the peritidal or estuarine interpretation. The base of parasequences P16 to P19 are marked by a sharp increase in grain size, erosive surfaces and occasionally abundant mud clasts. Parasequences P20 and P21 show a coarsening-upwards grain size trend that has been interpreted to be developed by tidal bars (Olariu et al., 2012). Given clear marine influence from the base of the White Sandstone Member, the basal surface is both a sequence boundary and a transgressive surface (SB + TS2; Fig. 9). Equivalent strata long the Oued Draa transect are assigned to the Yellow Upper Sandstone Member, and are represented by four parasequence (P16-19; above which there is loss of section), of unconfined distal to upper shoreface deposits. The existence of an erosional surface at the base of P16 here is not necessary, but a coupled sequence boundary-transgressive surface is placed at the base of this succession.

Along the Oued Chebeika, the White Sandstone Member is capped by lower shoreface deposits that mark the base of the Yellow Upper Sandstones Member at this location. Three parasequences (P22-P24) have been identified in the lower part, comprising shoreface sediments (FA6, 7 and 8) that overall describe a progradational stacking pattern. P22 starts with a very prominent, erosive based, fining-upwards 3 m thick unit that is readily correlated across outcrops. This package has a variable thickness, decreasing towards the NW. In proximal settings (such as the Wizard's Hat north outcrop) this marker unit starts with a basal matrix-supported conglomerate with quartz pebbles and mud clasts up to 10 cm, resting on an erosive contact. It is overlain by medium-to coarse-grained hummocky cross-stratified sandstones, which in turn are overlain by fine-to medium-grained sandstones with wave ripples. The upper part contains shelly lags and interbedded sandstones capped by bioclastic sandy grainstones. Based on the vertical evolution of lithofacies this unit has been interpreted as a tempestite or ravinement lag.

The lower part of the Foum Chebeika outcrop is made of clays, marls and interbedded hummocky cross-laminated and wave-rippled fine-grained sandstones. Due to missing section between the Oued Chebeika and Foum Chebeika outcrops, the uppermost parasequence has not been numbered in Fig. 9. Some patchy outcrops contain fine-grained sandstones and numerous bioclastic-rich levels, including abundant oysters. These are assigned to the Oued Chebeika Clay Member. Based on the average parasequence thickness in the area, two or three parasequences are expected, but this interval is patchy and not very well exposed and will need further investigation to construct a composite log through the missing interval. Overall, although P16-21 and P22-24 represent two distinct parasequence sets, the net stacking pattern from P16 into the Oued Chebeika Clay Member is transgressive, and the entirety of the White Sandstone Member, Yellow Upper Sandstone Member and basal part of the Oued Chebeika Clay Member are ascribed to the transgressive systems tract of Sequence 2 (TST2; Fig. 9).

4.2. Sediment provenance

The provenance of the lower Cretaceous siliciclastics of the Tan-Tan Formation has been located at the Precambrian Reguibat Shield and Palaeozoic Mauritanides (Ali et al., 2014a, 2014b) based on geochemical and radiogenic isotope analyses. Nevertheless, the sampling for those studies was not representative for the entire formation and concentrated only at the Oued Boukhchiba outcrop.

Analysis of the sedimentology and palaeocurrents throughout the entire Tan-Tan Formation has confirmed a provenance from the West African Craton, south of the study area, but has evidenced also the Anti-

Atlas played a role as a source of sediments. The varied lithologic composition of clasts (i.e., quartzites, rhyolites) in the Red Conglomerates Member is characteristic from the Palaeozoic terrains of the Anti-Atlas. Despite suggested subsidence or relative stability of the western Anti-Atlas during most of the Early Cretaceous (Gouiza et al., 2017a), the presence of alluvial fans suggest local uplift pulses of the Palaeozoic basement due to increased subsidence of the basin accommodated locally by normal faulting.

The dominant NNE sediment transport direction in the Red Basal Sandstone Member along both transects, supports the WAC sediment provenance from Ali et al. (2014a, 2014b). A major cooling event in the western Reguibat Shield during Barremian and possibly early Aptian (Gouiza et al., 2017b) may be the main responsible for deposition of the this member.

A net change in palaeocurrents towards the NW is recorded in the Upper Red Sandstone Member. A combination of autocyclic processes and reconfiguration of the drainage area due to local tectonics of the western Anti-Atlas is a plausible explanation. Nevertheless, the significant thickness of clastics recorded during this interval and the consistency of the palaeocurrents throughout it, favours an allocyclic, long-term tectonic control.

During deposition of the White Sandstones Member, although dominated by the tidal influence, palaeocurrents returned to the previous NNE (and SSW) direction. Volumes of sediment eroded in and transported from the Reguibat Shield are interpreted to have decreased dramatically (Charton et al., 2021), illustrated with a clear contribution is mainly coming from the Anti-Atlas.

4.3. Tectonostratigraphic evolution of the early Cretaceous section

The distribution and vertical evolution of facies associations suggests that the Tan-Tan Formation in the study area was deposited under fluctuating sediment supply, changing source areas and variable subsidence, linked with tectonics in the Anti-Atlas and Reguibat Shield (Gouiza et al., 2017a, 2017b) and an overall relative sea-level rise during most of the early Cretaceous (Haq et al., 1987; Snedden and Liu, 2010). The combined interplay of these processes resulted in a depositional system with possible deltaic affinities and marked by distinct progradation events, at the scale of parasequences and certain parasequence sets, but was subsequently dismantled by wave and tide action during transgression associated with relative increase in accommodation. A strong basin subsidence is needed paired with the eustatic sea-level rise in order to accommodate more than 500 m of sedimentary sequence exposed in a proximal location of the basin. The effect of tectonic pulses inland is interpreted to have modulated the overall trend switching exhuming areas and rerouting sediment (Charton et al., 2021).

The lowermost unit of the Tan-Tan Formation in the study area is the Red Conglomerates Member. This unit is on the flank of the Anti-Atlas and in the Oued Draa area can be related with a faulted contact that was probably responsible for creating the topography necessary for the deposition of the alluvial fans. Red conglomerates were also found at the base of lower Cretaceous continental successions in the proximal onshore well EA-1. Deposition of these facies was related to topographic highs in the Anti-Atlas created by tectonic uplift and faulting, together with a relative sea-level fall (e.g., Sehrt et al., 2017). The available exposures integrated with well data allow a reconstruction of the palaeogeography onshore. In this interpretation the coastal plain and inner shelf would be areas of mainly bypass and possibly incision. A thin shallow marine succession is deposited close to the edge of the Jurassic carbonate platform (Wenke et al., 2011). Submarine canyons and associated slope fans develop at the front of the slope.

The main Tan-Tan "delta" is interpreted to have prograded out mainly during the lowstand that formed the basal unconformity (Fig. 9). The main source of sediment during this period of time was probably from the Reguibat Shield. The Red Conglomerate Member and lower part of the Basal Red Sandstone members may hace been confined to and onlapped incised valleys, or residual, probably inactive normal-faul bounded grabens developed into the Paleozoic basement. The sediment was routed to a narrow coastal plain down-dip of the present study area, or directly fed shelf-edge "fan" deltas. During the first transgressive systems tract (TST1; Fig. 9), the system back-stepped, and coastal facies developed in the upper part of the Basal Red Sandstone Member (e.g. PS1-6; Fig. 9) implying a coastline characterised, in this area at least, by peritidal flats and channels passing towards a broad shelf wave-dominated shelf rather than by a "delta". Total transgression occurred in the area (possibly in the Aptian; MFS1), and it is possible that the westernmost part of the Anti-Atlas was covered by this event. These marine strata are represented by the Draa Marls Member.

Following this major transgression, a major episode of shoreline progradation occurred (HST1) and significant volumes of sediment delivered to the shelf. In the area of the Oued Chebeika transect, continental conditions were rapidly re-established (Red Upper Sandstone Member), but marine or marine-influenced conditions were maintained in the area of the Oued Draa to the north (persistence of the Draa Marls Member). Discharge patterns suggest sediment was eroded from an uplifted Western Anti-Atlas and possibly the Reguibat Shield, as illustrated by Charton et al. (2021). Overall, at this time, the progradational parasequences in the Oued Draa area continue to show peritidal channel and flat systems passing through the upper to lower shoreface deposits. The absence of lagoonal deposits in any part of the system, then, suggest the coastline was characterised by the development of a strandplain system; fluvial distributaries were individually too small to overcome the effects of wave and tidal reworking in the face of the open Atlantic. We favour a regime in which the coastline was relatively straight, and characterised by many (tidally-influenced) distributaries, debouching collectively large enough volumes of sediment to result in shoreline progradation, but that the main process of sedimentation at the terrestrial/marine interface was reworking of the sediment by wave processes.

Following shoreline progradation (HST1; Fig. 9), strata along Oued Chebeika suggest the Upper Red Sandstone may have been exhumed and eroded (SB2; Fig. 9), before being transgressed by estuarine strata (White Sandstone Member). Alternatively, no erosion occurred at the base of the White Sandstone Member, and the top of the Upper Red Sandstone represents the acme of regression, before the beginning of the next transgressive event (i.e. a "Type 2 Sequence Boundary"). Irrespective of erosion or not, this surface marks a significantly lesser-magnitude regression that SB1 at the base of Sequence 1. This is supported by the markedly less continental strata that overlie the surface compared to SB1 at Oued Chebeika and in particular at Oued Draa. The estuaries of the White Sandstone Member deconfined northward into a shoreface setting at Oued Draa, again implying a coastal geomorphology characterised by the embayment of marine conditions landward, rather than the formation of projecting, lobate delta-systems. No characteristic mouth bar facies were recognised in this study. Ultimately, the estuaries in the Oued Chebeika area were transgressed by shoreface conditions (Upper Yellow Sandstone Member) culminating in the deposition of open shelf strata of the Oued Chebeika Clay Member (Aguidir Formation).

Overall, Sequence 1 shows stronger evidence for erosion at its base, and contains significantly more proximal strata than Sequence 2, including the magnitude of its maximum flooding surface. Taken together, the stacking of the two sequences reflects a longer-term transgression of the basin.

5. Conclusions

An outcrop-based study of the Tan-Tan Formation, and lowermost Aguidir Formation of the northern Aaiun-Tarfaya Basin has been performed for the first time since it was originally described in the late 1960s. Several sections have been logged along two sub-parallel transects, following the main two rivers in the area (i.e., Oued Draa and

Oued Chebeika). Correlation shows that lateral equivalent lithounits represent more distal depositional environments at Oued Draa (north) than at Oued Chebeika (south).

An outcrop-based sequence stratigraphic framework has been established with two part-depositional sequences, and can be used to correlate with the distal offshore. Available new biostratigraphic data have been fed into this framework in order to better constrain the main episodes in the evolution of the Tan-Tan system. Accumulation of sediment in the basin was controlled by the interplay between basin subsidence, vertical movements in the basement and eustacy. An updated and more refined lithostratigraphic subdivision in six members is proposed, incorporating the members originally defined by Martinis and Visintin in 1966.

i) Red Conglomerates Member. Composed of red conglomerates derived from the Western Anti-Atlas and deposited as alluvial fans as result of differential subsidence of the basement and the basin accommodated by normal faults. These facies are also identified in wells drilled onshore farther south of the study area. Correlation with seismic interpreted offshore and sedimentary trends in the distal turbidites of Fuerteventura suggest a possible Berriasian age for deposition of this member. It represents the falling stage systems tract (FSST) and it is capped by a sequence boundary (SB1).
ii) Red Basal Sandstone Member. Crossbedded sandstones and silts deposited as fluvial bars, channels and flood plain deposits. The upper part at Oued Draa transect is represented by peritidal sandstones and muds correlated with fluvial facies at Oued Chebeika. The sediment provenance area for this unit is located to the south, at the Reguibat Shield and Mauritanides. Strong differential subsidence, and/or relict topography from north to south has resulted in more than 250 m of sediments in the north and less than 80 m in the south. Its lower boundary is the SB1 at Oued Draa and, an amalgamated sequence boundary and transgressive surface at Oued Chebeika (SB1 + TS1). A Valanginian to Barremian age is possible for this member.
iii) Draa Marls Member. It is composed of marine sandstones, silts and limestones with variable fossil content. The age inferred from new faunas and literature is Aptian. This unit represents an important flooding event in the area, well recorded by marine facies along both transects. A maximum flooding surface within this unit marks the limit between the TST and the overlying HST of Sequence 1. It is time-equivalent to the Upper Red Sandstone Member in its upper part.
iv) Red Upper Sandstone Member. This comprises similar sedimentary facies to the Red Basal Sandstone Member, and is confined to the south (along Oued Chebeika transect). It was deposited during the Aptian and it may be replated to an exhumation pulse uplifted the Western Anti-Atlas to the SE. The Anti-Atlas sediment source is supported by a consistent change in palaeocurrents.
v) White Sandstone Member. This comprises peritidal, estuarine crossbedded sandstones and minor silts and is confined to Oued Chebeika. It may be Albian in age, and is time equivalent to the Yellow Upper Sandstone Member to the northat Oued Draa. It represents the base of Sequence 2.
vi) Yellow Upper Sandstone Member. Marine, predominantly shoreface clastics and carbonates of late Albian age only exposed along Oued Chebeika. It is the upper member of the Tan-Tan Formation.
vii) Oued Chebeika Clay Member. It belongs to the overlying Aguidir Formation and made of black clays and marls deposited in an offshore, shelfal environment during latest Albian to Cenomanian.

CRediT authorship contribution statement

Angel Arantegui: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Rhodri Jerrett:** Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **J. Lovell-Kennedy:** Methodology. **Luc Bulot:** Data curation, Formal analysis, Supervision, Writing – original draft. **Remi Charton:** Writing – review & editing. **Jonathan Redfern:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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