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Sedimentary Facies and Depositional Environment of Oligo-Miocene of the Southern Shore of the Strait of Gibraltar (Rif, Morocco)

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ABSTRACT

This paper highlights a detailed sedimentological investigation of the deposits of Oligo-Miocene age on the southern shore of the Strait of Gibraltar commonly called flyschs Numidian, micaceous-sandstone flysch of Beni Ider and merinid flysch. This study has allowed us to demonstrate the existence of different facies and environments linked to the different processes that prevail in the Maghrebian basin under the simultaneous control of sedimentary input, eustatism and the tectonic process. Our study is based on the observation and the detailed stratonomic analysis of the different facies encountered in the Oligo-Miocene age series of flyschs from the southern shore of the Strait of Gibraltar. For the first time, this analysis shows that the Numidian successions studied, except that of Oued Lihoud, were deposited in deltaic environments (deltaic cone) at the level of the North African margin (Rif chain). These are prodelta deposits where slides, slumps or turbidites of predominantly fluvial delta fronts, regular waves and storm waves, fluvial and estuarine channels and tidal plains are sometimes intercalated. The micaceous-sandstone flyschs are due to gravitational sedimentation at the level of the submarine plain of the Maghreb basin. We have identified different categories of deposits: low, medium and high density turbidites, pulsation turbidites, homogenites, debris-flows and contourites. The Merinid flyschs are also due to mixed gravity sedimentation from a lithological point of view between the Numidian sandstones and the micaceous-sandstoneof Beni Ider. These deposits have therefore occupied an intermediate position between the southern and northern margins of the Maghrebian basin. In addition to the gravity facies, the deposits show high-density megaturbidites. This study also allowed the identification a major eustatic decline that was recorded during the Oligocene, the cold climate of the Oligocene and distensive (north) and compressive (south) tectonic movements depending on the position in the basin.

Keywords: Oligo-Miocene, deltaic deposits, turbidites, storm deposits, Merinids, Numidian, eustatic, Rif.

INTRODUCTION

The Oligo-Miocene formations on the southern shore of the Strait of Gibraltar (western Rif) belong to the alpine orogeny of the western Mediterranean zone. These flyschs were deposited palaeogeographically in the Maghrebian basin (Bouillin, 1986; Guerrera, 2019), which was located at the southern limit of the Alboran microplate and at the northern margin of the African plate, and was subject to major climatic, eustatic and tectonic events. The Eocene-Oligocene transition saw a major cooling that evolved into glaciation during the Neogene and Quaternary periods (Frakes, 1979). This cooling persisted until the Aquitanian-Burdigalian (Oligocene), leading to a eustatic drop of around 200 m recorded between -35 Ma and -30 Ma (Vail et al., 1987). This decline became more pronounced during the Lower Miocene at around -21 Ma as a result of increased glacial influences (Haq et al., 1987).

The tectonic evolution of the Maghreb basin is linked to the movements of the African and European tectonic plates, and to the Alboran microplate (Hoyez, 1989; Salhi, 1994; Michard et al, 2004; Chalouane et al, 2008; Vitale et al, 2015). During the Eocene, the first compressive events were felt in the flysch nappes, with conglomeratic deposits and numerous synsedimentary faults (Salhi, 1994; Ouldchalha et al., 1995). The Oligocene-Miocene transition underwent widespread compression, which led to the closure of the basin and the ejection of the Maghrebian flysch towards the outside of the chain. As a result, the internal domain overlapped the flysch nappes and the latter were carried to the external domain (Chalouan et al. 2008; Vitale et al, 2015). This clamping causes the suture between AlKaPeCa (Michard et al., 2002) and the North African margin, with crustal thickening of up to 30–32 km and suture metamorphism (Favre, 1995; Seber et al., 1996; Calvert et al., 2000; Gurria and Mezcua, 2000; Bokelman and Maufroy, 2007).

In the Rif mountain range, most of the research carried out on the Oligo-Miocene flysch, to reconstruct its geodynamic history, has focused on structural, lithos-stratigraphic and bio-stratigraphic studies, but little has been studied from a sedimentological point of view (Chiochini et al., 1980; Hoyez, 1989), essentially recognising gravity facies such as medium- and high-density turbidites. Subsequent studies have recognised other depositional environments such as deltas and platforms (Salhi, 1994; Ouldchalha et al., 1995; Hammoumi et al., 1995).

Geographical and geological context

The Oligo-Miocene flyschs studied belong to the Numidian nappe, the Béni Ider micaceous-sandstone flyschs of the Mauretanian nappe and the mixed flyschs (micaceous-sandstone and Numidian) of the Merinides nappe. In the Rif, the Numidian outcrops mainly between Tangiers and Chefchaounène, to the north of the possible extension of the Jebha fault. The allochtony of the Numidian was first highlighted in Morocco and Algeria by Durand (Delga and Mattauer 1959c). The "Numidian flysch" occurs in the form of rafts or disjointed masses in suprastructure over terrains of varying age and nature, belonging either to the Cretaceous and Tertiary flyschs, or to the Tangier unit. Stratigraphic (Sikora et al., 1979) and sedimentological (Salhi et al, 1990) have shown that the marls of the internal Tangier unit, in the Tangier mountains, correspond to the substratum of the Numidian sandstones, which have been the subject of several studies that agree on their depositional environment: gravity sedimentation on a slope under the effect of turbidity currents (Chiochini et al., 1980; Guerrera, 1981-1982; Hoyez, 1989; El Khanchoufi and Beaudoin, 1989–1993). However, they have been the subject of controversy as to the origin of the lithological material of which they are composed, as well as their paleogeography and their relationship with the other units of the chain.

According to (Lancelot et al. 1977), the source of the material is southern, corresponding to the Tunisian sandstones (Wezel, 1968, 1970) or the Nubian sandstones in Sudan (Guerrera, 1981-1982; Chiochini et al., 1980; Hoyez 1988), or northern (Beaudoin et al., 1989). Currently, the majority of authors agree that the Numidian material comes from the south from the West African craton (Zaghloul et al, 2005; Azdimousa and al, 2019; Belayouni et al, 2023).

Palaeogeographically, the sedimentation basin would be in an internal (ultra) position, north of the chain (Durand-Delga and Mattauer, 1960; Andrieux et al., 1962), currently abandoned theory; or in an external (citra or infra) southern position (Durand-Delga et al., 1962; Durand-Delga, 1980–1988; Guerrera, 1981–1982; Hoyez, 1989). Their emplacement is the result of shearing tectonics in the form of thrust sheets (Durand-Delga et al., 1962; Didon et al., 1973; Hoyez, 1989; Chalouan et al, 2008); or they are stratigraphically continuous in the outer areas of the Rif (Leblanc et al., 1982) and in the Tangiers unit (Hoyez, 1989). The Numidian successions studied here belong geographically to the Lhaouta Ben Médiar, Jbel Zinat, Tangier Mountain, Dhar Zhirou and Ziaténe-Elbranes massifs (Fig. 1).

The Al Hajra section (Lhaouta Ben Médiar massif in the Sidi Habib region) has been dated to the Lower Oligocene in its base series (Didon and al., 1973 and 1984; Hoyez, 1989) and to the Maestrichtian in the limestone blocks of the base levels of the sub-Numidian argillites (Hoyez, 1989).

The Dhar Zhirou section (Dhar Zhirou massif) has been dated to the Oligocene (Hoyez, 1989) by foraminifera (determined by Bizon) and nannoplankton (determined by Feinberg). The Zinat section (Jbel Zinat) has been dated to the Lower-Middle to Upper Oligocene in its basic series (Feinberg et al., 1981; Hoyez, 1989). The Ziatène-Elbranes section (Tangier Mountain) has been dated to the Upper Oligocene in its basic series (Didon et al., 1973 and 1984; Chiochini and al., 1980; Hoyez, 1989) and to the Eocene (Sikora et al., 1979). The Oued Lihoud section (Tangier Mountain) is attributed to the Terminal Oligocene-Aquitanian on the basis of the similarity of

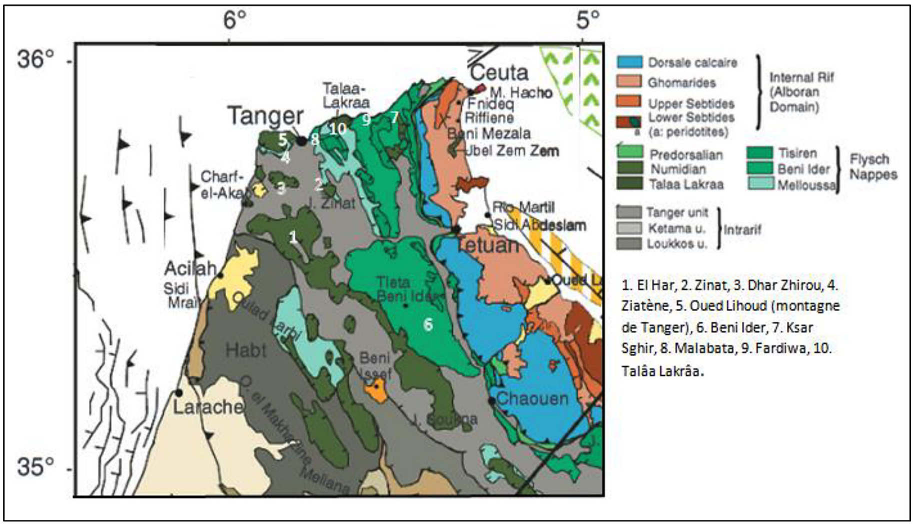

Fig. 1. Location of the Oligo-Miocene sections studied on the Tangiers geological map (Chalouan et al., 2008)

the facies of its basic series with those of the sub-Numidian clays dated in other regions.

The micaceous-sandstone flysch of Béni Ider belongs to the Mauretanien nappe and represents the stratigraphic continuity of the Tisirène flysch (Durand-Delga and Mattauer, 1959, 1960, 1962; Didon et al., 1973). This flysch outcrops from the southern piedmont of Jbel Tisirène to the Strait of Gibraltar, where it rests in a thrust sheet on the Melloussa nappe and the Tangier unit.

In the Beni Ider stratigraphic series, the oldest known levels are clear granoclassified calcarenites in slabs with silicification and clear siliceous levels, and polychromatic marls dated to the Cenomanian (Hoyez, 1989). These formations are surmounted by red and green marls or clays of Senonian age in which a few metric slabs of fine white or greenish azoic limestone are interspersed. They are then topped by bioclastic or sandstone limestone slabs with algae and Microcodium from the Paleocene. The Lower and Middle Eocene are composed of Nummulite calciturbidites and conglomerates. The Middle-Upper Eocene is characterised by the presence, in places, of centimetric to decimetric calcarenites with large Nummulites. These alternations are between 25 m and 50 m thick, gradually giving way upwards to upper clays around 100 m thick.

The Béni Ider series is crowned by a powerful micaceous-sandstone flysch up to 2,000 m thick, characterised by turbiditic successions of Upper Oligocene to Lower Burdigalian age (Guerrera, 1981-1982; Salhi, 1994; Zaghloul et al., 2002; de Capoa et al. 2007; Vitale et al, 2015). Sedimentologically, these flyschs form turbiditic sandstone successions alternating with pelites and marls deposited on a deep submarine plain. In proximal positions (in relation to the input sources), this flysch may begin with conglomerates rich in detritus from the metamorphic basement and its sedimentary cover, associated with clasts and pebbles from plutonic and volcanic rocks. In the most distant areas of sedimentation, there is a gradual transition from the terms of the first interval to the micaceous-sandstone flysch of Béni Ider. This transition is marked by a change in colour from red to brownish.

The successions studied in the micaceous-sandstone flysch of Béni Ider are: the Ksar-Sghir section which outcrops to the east of the village of Ksar-Sghir, the Malabata section which outcrops at the level of the Malabata point, the Tlata de Béni Ider section which outcrops near the village of the same name and which gave it its name and the Fardiwa section which outcrops to the west of the village of Ferdiwa and just to the east of Oued aliane (Fig. 1).

Didon and Hoyez (1978) defined the Merinide flysch as a series of mixed numidian and interstratified micaceous-sandstone facies of Tertiary age in the western Rif. A typical Merinid series outcrops at Talâa-Lakrâa (east of Cap Malabata and west of Ksar-Sghir), where the Numidian and micaceous-sandstone deposits show comparable facies. The continuity of the base of this series with deposits of Upper Cretaceous-Eocene age is apparent at a few points (Hoyez, 1989; Belayouni, 2023). The Talâa-Lakrâa section outcrops at Ain Bou Mâaza to the east of Sidi Kankouch (Fig. 1).

Lithostratigraphy of the section was carried out by Hoyez (1989), who highlighted two groups:
- A pelitic term with thin sandstone strata of Upper Oligocene-Upper Aquitanian age,
- A sandstone term with Numidian and micaceous-sandstone facies of Upper Aquitanian age.

METHODOLOGY

This study is based on observation and a detailed stratonomic analysis of the different lithofacies encountered in the Oligo-Miocene age series of the flyschs of the southern shore of the Strait of Gibraltar.

The first step consists of traveling to the field to choose the most representative outcrops of the different formations. We then proceed to the faithful description of the lithofacies in the most precise manner possible from the base to the top of the series. The analysis of the strata is done by deducing the arrangement of the different elements (grains, pebbles, etc.) which form the sedimentary figures inside these strata (ripples current, convolutes bedding, laminae, etc.). The formation of the latter corresponds to a hydrodynamics, a water depth, a slope, a biological activity (ichnofacies) and/or a well-determined tectonic activity. The succession of figures within the same stratum can be considered as a lithofacies (elementary sequence). These lithofacies are reported on graph paper in the form of a lithological log (Reineck and Singh, 1686; Reading, 1996). The description of these strata, according to their thickness, is of the millimetric to plurimetric order. Each time there is a change in the lithofacies (color, grain size, etc.), one or more samples are collected for possible testing in the laboratory.

A lithofacies alone cannot be interpreted in terms of depositional environment. It must be associated with other overlying and underlying lithofacies and the succession of these lithfacies (elementary sequences) gives a higher order sequence. This can give a clear idea of its depositional environment based on the theory of actualism, that is to say, the observation of facies in current environments which can be compared to those encountered in the ancient series to interpret them in terms of depositional environments. A sequence is an ordered lithological succession that is limited by discontinuities. Within the sequence the different terms are genetically linked. It is necessary to highlight the different sedimentary discontinuities, highlight the most important ones and define the sequences that they separate. Also, each time there is a change in genetically linked facies, there is a change in environment hence a break, we therefore delimit the sequences by these breaks (Reineck and Singh, 1686; Reading, 1996). The succession of these higher order sequences which are interpreted in terms of depositional environment or part of this environment, which corresponds to a certain depth of the water slice; can help determine the evolution of sea level over time (Reineck and Singh, 1686; Reading, 1996). Also this study is associated with a petrological study using a polarized light microscope and a mineralogical study in order to determine the different minerals constituting the lithofacies, with the aim of going back to the source which supplied the sedimentation basin. Also these two associated studies can tell us the climate that reigned during the time of deposition.

RESULTS AND DISCUSSION

Facies and sedimentary environments

A detailed stratonometric analysis of the Oligo-Miocene successions revealed different types of facies relating to different environments such as the slope (deep sea fan), the platform, the delta and the littoral.

Slope lithofacies

Lithofacies LF1 – corresponds to bars 4 m thick, consisting of a microconglomerate as a matrix and centimetre to metre-sized figured elements, some of which correspond to fragments of strata showing terms from the Bouma sequence (1962), sometimes deformed, and clay lenses (Fig. 2). These bars may show reverse granoclassing and intense synsedimentary deformation. These bars gradually change towards the top to a fine lithology such as clay. This facies can be interpreted as a debris flow "facies A1″ of Mutti and Ricci Lucci (1975), which reworks consolidated sediments, initially deposited by turbidity currents, in unconsolidated gravity sediments. This type of deposition can be linked to sudden drops in sea level or to tectonic movements that cause the margin to be re-sedimented. The gradual transition to fine sedimentation marks the gradual reduction in the power of the current.

Lithofacies LF2 – this is a chaotic unit, ten to one hectometre thick, with a dominant clay matrix and very poorly classified figured elements of centimetre to multi-metre size (Fig. 3). These elements are generally rounded, with green and white sandstone-carbonate. They are generally affected by intense synsedimentary deformation. When they are not deformed, they show associations of proximal platform sedimentary figures dominated by normal waves and storm waves. This lithofacies corresponds to Muttu and Ricci Lucci's (1975) "facies A1" and is associated with muddy flow.

Lithofacies LF3 – this lithofacies corresponds to a hectometre-thick chaotic level consisting of a deformed clay matrix and figured elements of variable decimetric to plurimetric size affected by intense synsedimentary deformation (Fig 4.). At the base, the elements correspond to high-density megaturbidites, and at the top to fragments of Bouma (medium density) and Stow (low density) sequences. This lithofacies corresponds to a megaslump affecting unconsolidated gravity deposits. It can be compared to the "facies F2″ of Pickering and al (1986). It is linked either to sudden drops in sea level or to tectonic movements, or to both events simultaneously, leading to resedimentation of the margin.

Lithofacies LF4 – this facies corresponds to a chaotic level, varying in thickness from 10 to 70 m, with a clay matrix and boulders of varied lithological nature, poorly classified (centimetre to multi-decametre size), sometimes affected by intense synsedimentary deformation. It also contains clastic veins (sills and dykes). This is a megaslump that reworks consolidated and unconsolidated sediments; it is linked either to sudden drops in sea level, or to tectonic movements, or both, which lead to re-sedimentation of the margin.

Lithofacies LF5 – this lithofacies consists of metric to multi-metre thick, lenticular banks with a highly erosive base and load figures, groove casts and flute casts of centimetre to decimetre size, as well as traces of pebbles and soft pebbles. The beds are of varied lithological nature:
- Massive granular sandstone without bedding,
- Microconglomerate with gullied internal surfaces delimiting clusters that differ either in the gravel/matrix ratio (dominant matrix or jointed elements), or in the type of granoclassing (normal or inverse).
- Conglomerate with jointed elements (centimetre to decimetre size) that are very rounded, gradually changing to a microconglomerate towards the top.

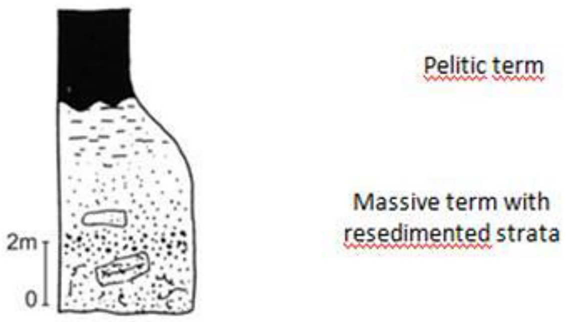

Fig. 2. Lithofacies LF1

Fig. 3. Lithofacies LF2

Fig. 4. Lithofacies LF3

These sedimentary bodies are often affected by synsedimentary folding and deformation at different scales. The deformation may affect the whole bed or just its basal part, which frays and mixes with the underlying deposits. Clastic veins are also common at the base of strata. These strata correspond to the filling of deep submarine cone channels, and their emplacement is linked to granular and debris flows (Middleton and Hampton, 1973). Synsedimentary deformation is linked to syn-depositional and post-depositional events that are induced by tectonics and/or eustatism. Clastic veins are linked to sand injections by hydraulic fracturing at the time of deposition (El Khanchoufi and Beaudoin, 1993).

Lithofacies LF6 – corresponds to elementary sequences of multi-metre thickness (8 to

10 m) which show a progressive transition from a coarse carbonate sandstone term or a carbonate microconglomerate term to a multi-metre (60 cm to 5 m), marly or marly-silty term (Fig. 5). These sequences all have a flat basal boundary with dragged object and scour figures. They are differentiated only by associations of sedimentary structures on the sandy level.

- Sequence type 1 (Fig. 5), shows a term of coarse carbonate sandstone or a carbonate microconglomerate 3 to 4 m thick, massive or with frustrated flat laminae that appear at different levels. It may also show soft pebbles and/or pelitic lenses.
- Sequence type 2 (Fig. 6), shows from base to top, a coarse granoclase sandstone and a bedded term of flat or slightly undulating parallel laminae (metric scale) with water escape figures "diches & pillards structures".
- Sequence type 3 (Fig. 7), is made up of several terms: (i) a granoclassified term, (ii) one with a flat parallel laminae term, (iii) a term with overlapping unidirectional current ripples of type A and B, (iv) a term with a bedding of slightly undulating parallel laminae, (v) a "convolute bedding" term and vi- a relatively fine term with a bedding of parallel laminae.
- Sequence type 4 (Fig. 8), corresponds to a carbonate microconglomeratic bed with a "supported" matrix that shows a succession of normal and reverse granoclassifications and is affected at its base by intense synsedimentary deformation. It may contain soft pebbles.
- Sequence type 5 (Fig. 9), is formed at the base by sequence type 3 and at the top by a 50cm thick term with unidirectional type A current ripple bedding.

Due to their plurimetric thickness, their extent over several kilometres and the absence of gully and channelisation structures, these sequences are considered to be "megaturbidites" (Mutti et al., 1984). The abundance of water escape figures, the granoclassification and the gradual transition from a coarse to a pelitic term, show that these bars originate from a single brutal energetic current, with a high sediment load, which becomes less and less competent as it moves from the proximal parts to the distal one of the basin. The reverse granoclassification can be explained by the "traction carpet" phenomenon (Lowe, 1982) or by energetic jumps.

These sequences can be compared with the present-day megaturbidites described in the eastern Mediterranean (Heick, 1984), the tsunamites of the Mediterranean abyssal plain (Kastens and Cita, 1984) and the Herodotus abyssal plain (Cita and al., 1984), and the ancient megaturbidites (Skipper and Batta Charrjef, 1978;

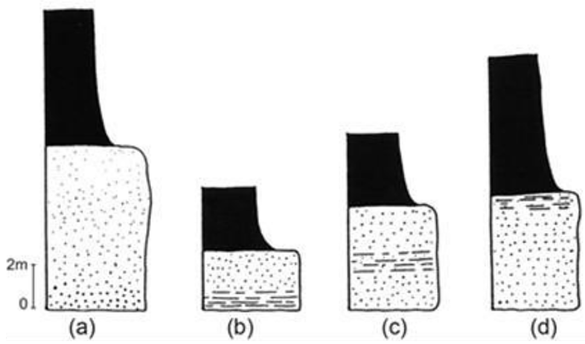

Fig. 5. Lithofacies LF6 (sequence type 1)

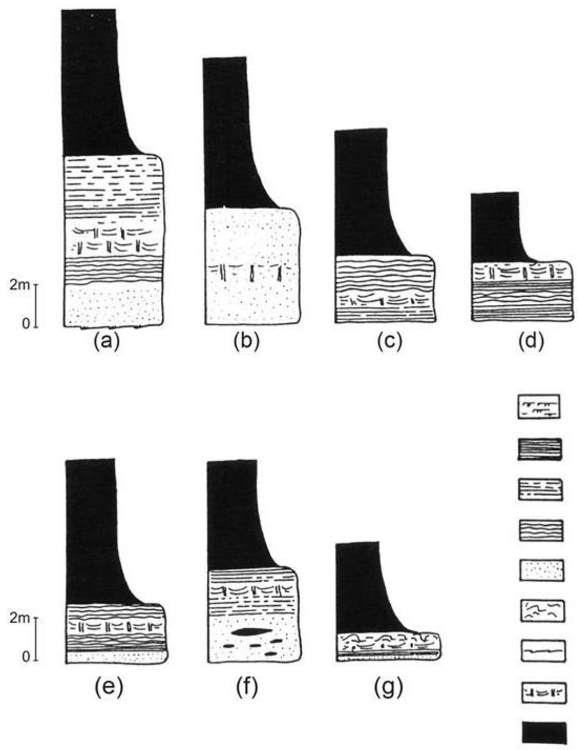

Fig. 6. Lithofacies LF6 (sequence type 2)

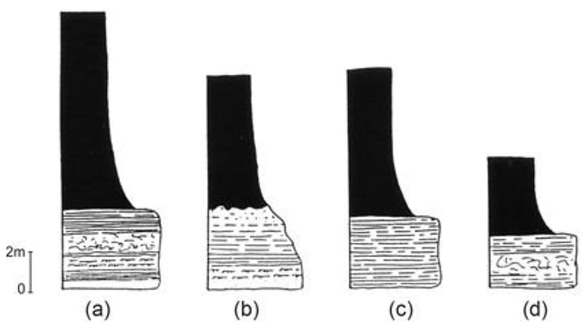

Fig. 7. Lithofacies LF6 *(*sequence type 3)

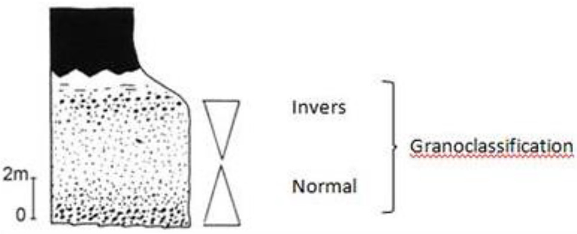

Fig. 8. Lithofacies LF6 (sequence type 4)

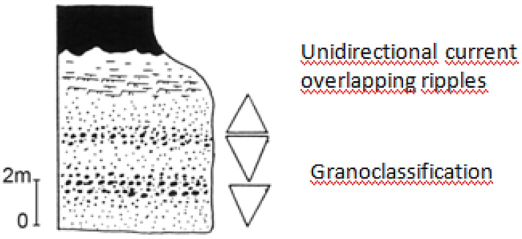

Fig. 9. Lithofacies LF6 (sequence type 5)

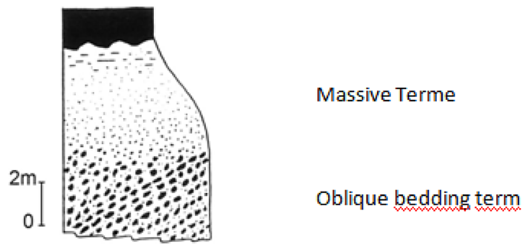

Fig. 10. Lithofacies LF6 (sequence type 5)

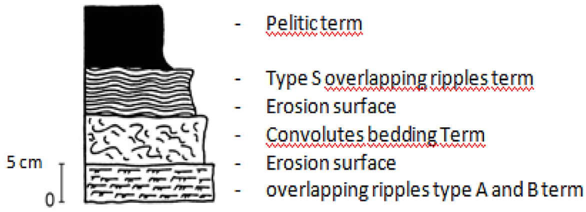

Fig. 11. Lithofacies LF7

Ricci Lucci, 1975; Ricci Lucci, 1984; Pickering and Hiscott, 1985; Baghli, 1989). The sheet like shape of the homogenites indicates sedimentation on a submarine plain relatively far from the slope in relation to jerky tectonic movements, sudden drops in sea level or both at the same time.

Lithofacies LF7 – this facies corresponds to an elementary sequence of centimetric to decimetric thickness with plane-parallel boundaries, consisting of several terms separated by erosion surfaces:

- A term with a bed of overlapping type A and B rippeles,
- A convolute bedding term,
- An S-type overlapping ripple bedding term,
- A low density turbidite or pelitic term.

This succession can be truncated at different levels: Tad, Tac, Tbd, Tabc. It is interpreted as a pulsating turbidite (Baghli and al., 1989) induced by a turbid puff (Ravenne and Beghin, 1983; Laval, 1988; Laval and al., 1988). Pulsating turbidites are linked to a varied transport mode (traction-suspension) with an energy surge that results in the formation of an erosion surface. These are either single flows with velocity fluctuations or sediment inputs (Normark and Dickson, 1976) or multiple flows (Pickering and Hiscott, 1985). The "convolute bedding" results from a deformation of the traction or traction-suspension ripples during the abrupt transition between these two types of transport (Baghli and al., 1989). The "d" term corresponds to a low-density distal turbidite or pelitic term that reflects the deposition of passive suspensions that form after the passage of a turbid puff (Fig. 11).

Lithofacies LF8 – this lithofacies corresponds to a granodecreasing elementary sequence with several terms, centimetric to decimetric in thickness with flat, parallel boundaries. The terms from bottom to top are:

- A granoclastic sandstone term whose basal surface is erosive with scouring figures,
- A sandstone term with parallel laminae,
- A sandstone term with a bedding of overlapping ripples of types A and B which sometimes change to "convolutes bedding",
- A siltstone term with parallel laminae,
- A pelitic term.

This succession can be truncated at different levels in sequences such as Tac, Tcd, Tce, Tab, Tbc and Tabc. This lithofacies corresponds to the Bouma (1962) sequence, which is induced by a medium-density turbidity current. It develops at channel levees, in the interlobes and distal parts of a deep sea fan (Mutti and Ricci Lucci, 1975; Mutti, 1977) (Fig. 12).

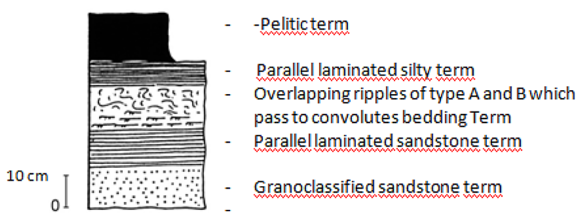

Fig. 12. Lithofacies LF8

Lithofacies LF9 – this facies corresponds to a silty-clay bed, generally centimetric in thickness, rarely decimetric, with flat, parallel boundaries. It corresponds to an elementary sequence made up of several terms, from bottom to top:

- A clay term with lenticular and irregular laminae of silt,
- A clay term with regular and parallel silt,
- A clayey term with frustuous silt laminae,
- A finely graded clay term.

This sequence is interpreted as a low-density turbidite (Piper, 1978; Stow and Shunmugan, 1980; Stow and Piper, 1984). This sequence is considered to be a single unit of granodecreasing deposition (Stow and Bowen, 1980). The basic terms reflect the existence of a traction current that deposits coarse silts and as its competence decreases and its load dilutes, it deposits laminae and fine lenses of silt and clays (Stow and Bowen, 1978-1980; Hess and Choug, 1980). Low-density turbidites are deposited in channel levees and in the most distal parts of a deep sea fan (Stow and Piper, 1984) (Fig. 13).

Lithofacies LF10 – consists of a decimetre-thick pelitic interstratum and a millimetre- to centimetre-thick silt-carbonate stratum, with no internal structures and parallel basal and summit boundaries. This lithofacies is interpreted as a hemipelagic submarine plain deposit. It is interpreted in this way according to its characteristics (grain size, absence of internal current structures and erosion surfaces) and its association with the other facies.

Deltaic lithofacies

Lithofacies LF11 – this lithofacies is made up of very bioturbated interbanks of a pelitic nature and of decimetric to metric thickness, and banks of centimetric thickness (Fig. 14). Three types of bed have been distinguished on the basis of their lithology and their association of sedimentary figures and structures:

- Centimetre to decimetre thick bank of ferruginous siltstone, massive and highly bioturbated;
- Two-term sequence: a millimetre- to centimetre-thick silt-carbonate or silty stratum, a term with overlapping unidirectional current ripples of type A and B or massive, which changes to a term with a bedding of flat parallel laminae or a term with "convolutes bedding"; the basal surface may contain some bioturbation figures and figures of scouring and dragged objects;
- A millimetric stratum with no internal structure and a clear base and top rich in bioturbation figures.

This lithofacies corresponds to sedimentation in a calm environment. It is interpreted as a prodelta deposit on the basis of its association with other deltaic facies.

Lithofacies LF12 – this lithofacies is made up of a pelitic interstratum of decimetric or metric thickness and a silty stratum of centimetric thickness which may be bioturbated (Fig 15). Several types of strata are distinguished according to the sedimentary figures and structures they contain:

- Strata with a bed of unidirectional current ripples and a bed of asymmetrical wave ripples of type 1 or type 7 of De Raaf and al (1977) or symmetrical ripples,
- Strata with overlapping unidirectional current ripples, symmetrical wave ripples and "convolutes bedding",
- Unidirectional parallel laminae "sheet like" stratum;
- Strata with lingoid ripple bedding,
- Strata entirely affected by "convolutes bedding",
- Strata with asymmetrical ripple bedding of type 3 of (De Raaf et al., 1977) or with symmetrical wave ripple bedding.

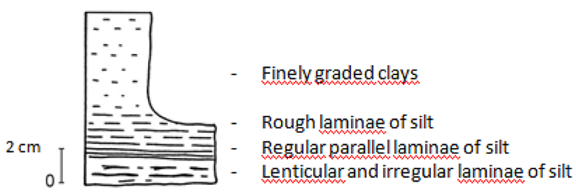

Fig. 13. Lithofacies LF9

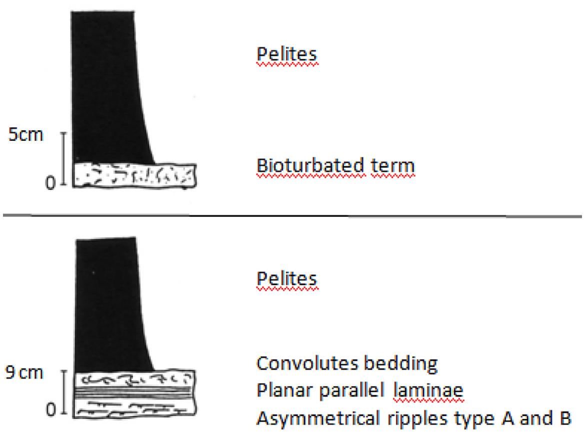

Fig. 14. Lithofacies LF11

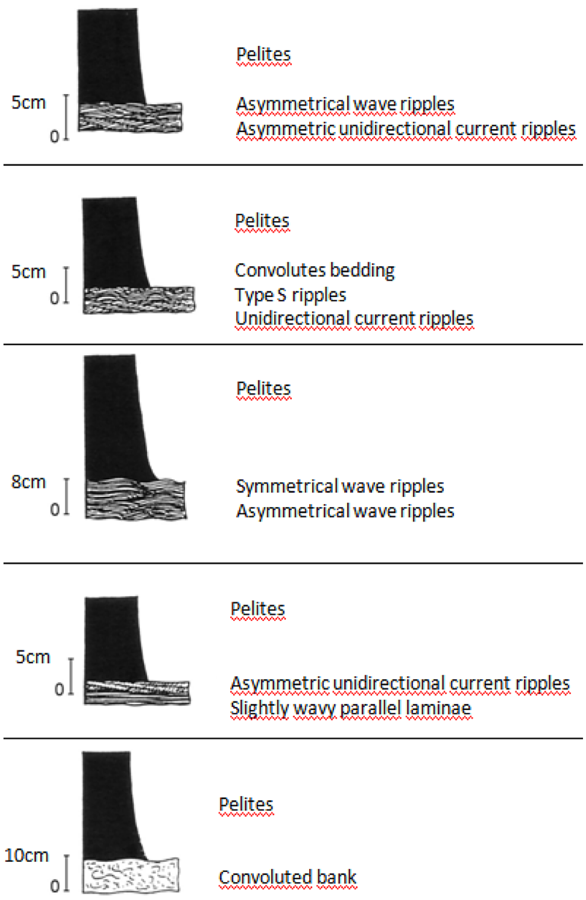

Fig. 15. Lithofacies LF12

This lithofacies results in sedimentation in a delta front dominated by waves and unidirectional (fluvial) currents.

Lithofacies LF13 – this is a sandstone bar made up of multi-metre-thick banks, amalgamated with clean, erosive top and bottom surfaces, and whose bedding is expressed by low-angle oblique bedding and tangential oblique bedding. This lithofacies corresponds to a mouth bar deposit (Postma, 1990) (Fig. 16).

Lithofacies LF14 – this facies consists of coarse granular sandstone bars with a metrically undulating top surface and a gullying basal surface (Fig. 17). Its internal structure shows interfering ripples and crescent ripples. At its base the bar shows massive levels, levels with frustrated flat or slightly undulating parallel laminae and sometimes "convolutes bedding". The bar may also contain soft pebbles. These bars are interpreted as channel deposits reworked by littoral dynamics.

Lithofacies LF15 – two types of bed separated by pelitic joints can be identified in this lithofacies. The first type is a multi-metre thick sandstone bed that varies laterally and is sometimes lenticular in shape (Fig. 18). Its top surface is intensely bioturbated, with occasional longitudinal ripple ridges that in places become lingoid ripples. Its basal surface is erosive. It is made up of massive levels and levels with flat or undulating parallel laminae, which are often frustrated. It also has dish &pillards structures and synsedimentary deformations of varying importance. The second type is microconglomeratic with pebbles (dominant matrix), of decimetric to plurimetric length with a lenticular shape, a gullying basal surface and decimetric thickness. This lithofacies is interpreted as a deposit of tidal flat channels and lateral bars (Eliot, 1986).

Lithofacies LF16 – this lithofacies corresponds to a metric to plurimetric lenticular bed, with a gullying erosive base, showing several terms from bottom to top:

- A granoclastic microconglomeratic or conglomeratic term;
- A sandstone term with an arched or flat oblique bedding;
- A plane-bedded sandstone term;

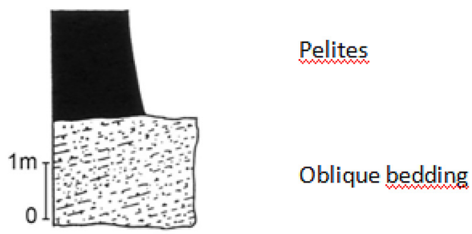

Fig. 16. Lithofacies LF13

Fig. 17. Lithofacies LF14

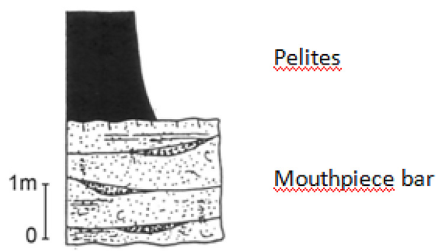

Fig. 18. Lithofacies LF15

- A silt-clay term which may show desiccation cracks and lingoid ripples. It also contains fossils (bivalve shells).

This lithofacies is interpreted as a fluvial channel deposit on a deltaic plain by association with other facies (Fig. 19).

Lithofacies LF17 – this lithofacies is made up of alternating pelitic interbanks of decimetric to metric thickness, and banks of ferruginous siltites whose summit surface shows numerous bioturbation figures and ferruginous and algal encrustations (Fig. 20). The beds are in the form of: (i) centimetre-thick silty lenses with oblique bedding of unidirectional current ripples, (ii) centimetre or millimetre layers with flat parallel basal and summit boundaries with a massive structure or a fine rough parallel bedding, and (iii) centimetre or millimetre layers with centimetre-scale undulating boundaries and bedding of type A and B unidirectional current ripples or wave ripples in some cases. This type of deposit reflects sedimentation on a deltaic plain dominated by rivers, with siltstone lenses caused by wind-induced waves. The other types of bed are interpreted as flood deposits (Eliot, 1986).

Lithofacies LF18 – this lithofacies corresponds to an alternation of metric-thick pelitic interbanks and millimetre-thick gypsum sheets. This facies reflects sedimentation in an environment with very low water levels on a tidal deltaic plain.

Lithofacies LF 19 – this lithofacies is made up of decimetre-thick interbanks and centimetre-thick siltstone beds that show several types of sedimentary structure: a very open, sigmoidal "S"-shaped oblique bedding, an oblique bedding with clay doublets separated by a millimetre-thick sandy lamina (flood/ebb cycle); or packets of laminae whose thickness varies cyclically (spring/neap cycle). In some cases, the summit surface may show stromatolitic algal crusts, ferruginous crusts and traces of bioturbation. The sedimentary structures recognised are linked to tidal dynamics (Visser, 1980; Allen and Homewood, 1984). This lithofacies reflects sedimentation in the lateral bars of tidal flats and the tidal bars of estuarine channels.

Platform lithofacies dominated by storms

Lithofacies LF20 – this lithofacies is made up of decimetre-thick pelitic interbanks and centimetre-thick silt or silt-carbonate beds with a bedding of overlapping co-genetic phase ripples ("S" type) with polygonal crests (Fig. 21). This bedding reflects the dynamics of storm waves (Guillocheau, 1983; Brenchley, 1985).

Lithofacies LF21 – this lithofacies corresponds to an alternation of pelites and ovoid silt-carbonate sedimentary bodies, aligned according to the stratification plane, which have a clear contact with the host rock and which have a plane or slightly undulating parallel bedding. They are assimilated to the miches resulting from the filling of gullies and/or erosion furrows by storm deposits in the offshore (Guillocheau, 1983; Hammoumi, 1988) (Fig. 22).

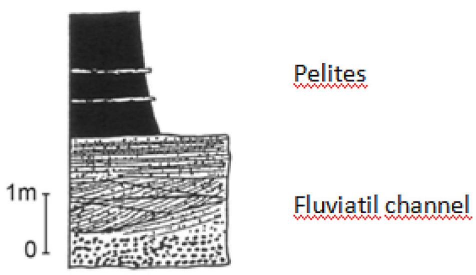

Fig. 19. Lithofacies LF16

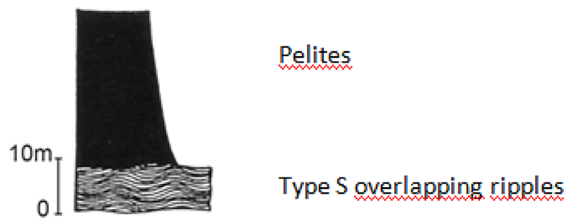

Fig. 21. Lithofacies LF20

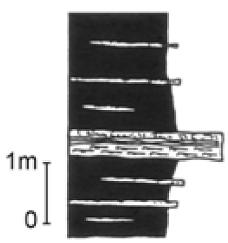

Fig. 20. Lithofacies LF17

Fig. 22. Lithofacies LF21

Lithofacies LF22 – this lithofacies is made up of bioturbated pelitic interbanks of centimetre thickness and siltstone and sandstone beds of centimetre to decimetre thickness. The banks have erosive, undulating basal and summit boundaries and are formed by the amalgamation of centimetre-thick strata of siltstone and sandstone with a bedding of S, A and B type ripples. The ripples are relatively pronounced and spatially correspond to unorganised three-dimensional ripples with symmetrical crests (post-vortex ripples, Southard in Harms and al., 1982). This lithofacies reflects sedimentation in a shoreface of energetic storm waves.

Changes in lithofacies along the series studied

The study of facies evolution along the successions studied revealed, for the first time in the Rif chain, fan delta progradation sequences and proximal slope gravity series in the Numidian deposits, as well as distal slope and submarine plain environments in the Beni Ider micaceous-sandstone flysch and Merinid flysch. Fluvio-deltaic deposits have been recognized in the Numidian of central Tunisia (Yaich and al, 2000).

Fan delta environments dominated by the action of permanent waves, storm waves, tides and unidirectional currents have been recognised in the successions of the Lhar (Fig. 23), Zinat (Fig. 24), Dhar Zhirou (Fig. 25) and Ziatène/El Branes (Fig. 26) massifs. These are deep-water delta fans (Postma, 1970) of the "delta slope" type. The facies associations identified made it possible to recognise the typical sequences that relate to the different physiographic units of a deltaic apparatus.

- Slope deposits identified: boulder clays were recognised in the Ziatène/El Branes and Oued Lihoud sections, medium density turbidites in the Zinat section and hemipelagic deposits in the Dhar Zhirou section;
- The prodelta sequences recognised in all the successions;
- Delta front sequences with channel deposits, mouth bars and in some cases fluvial channels. The upper part of these deposits is sometimes reworked by littoral currents. These have been identified in the Zinat, Dhar Zhirou and Ziatène sections;
- Offshore sequences resulting from the reworking of delta front deposits by normal waves and storm waves at Dhar Zhirou;
- Tidal deltaic plain sequences with tidal channels and lateral bars, and gypsum deposits have been recognised at Ziatène/El Branes and El Har.

The proximal slope environment has been recognised in the Oued Lihoud succession (Tangier Mountain) (Fig. 27). It comprises megaslumps

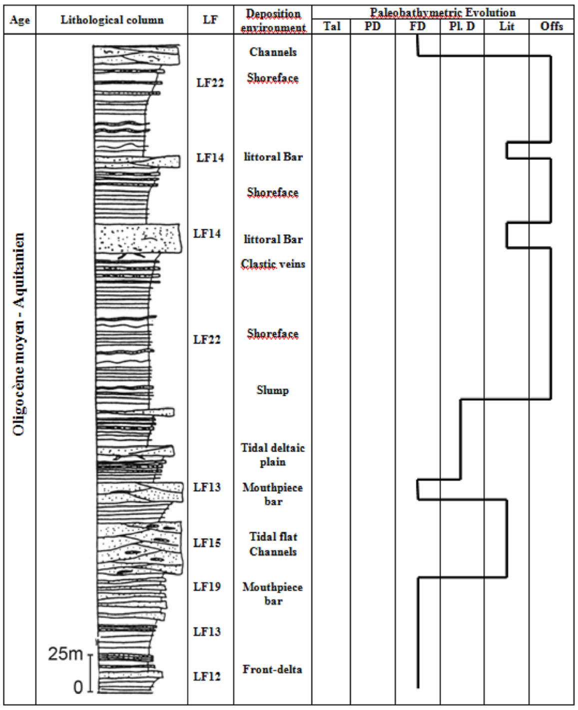

Fig. 23. Succession of Lhar: summary of the results

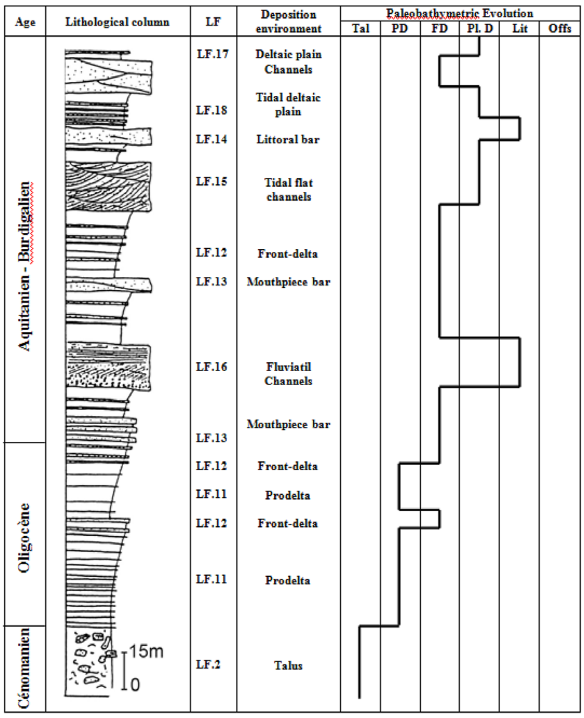

Fig. 24. Succession of Zinat: summary of the results

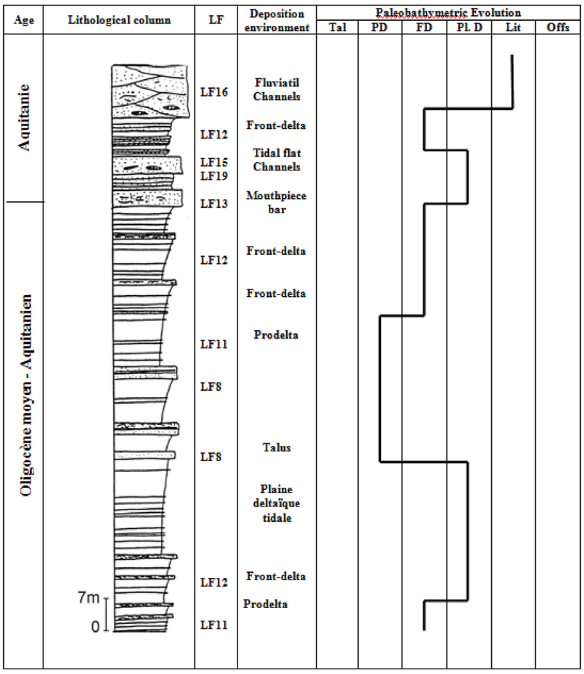

Fig. 25. Succession of Dhar Zhirou: summary of the results

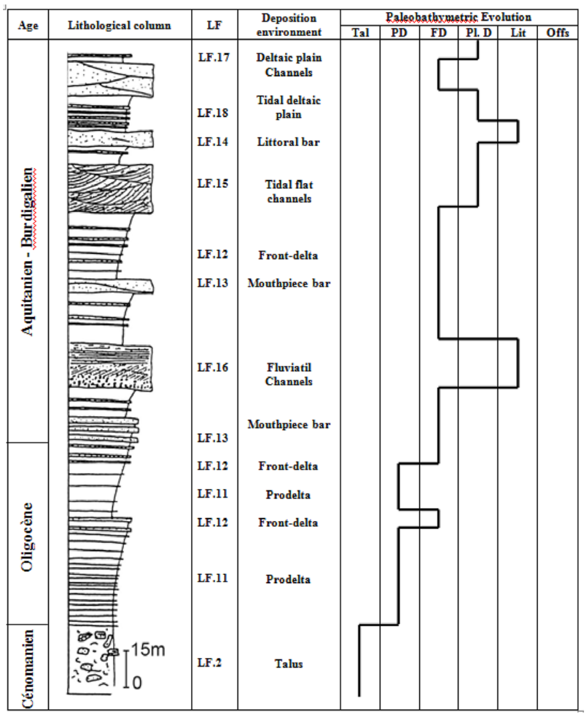

Fig. 26. Succession of Ziatène/El Branes: summary of the results

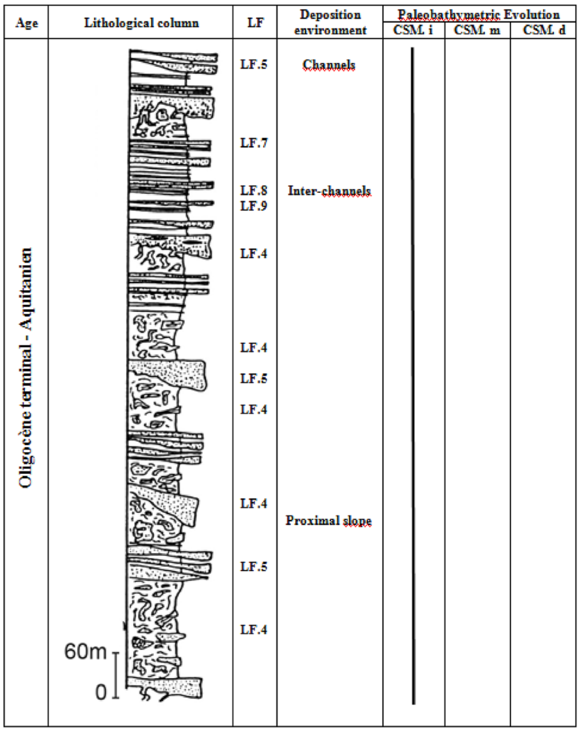

Fig. 27. Succession of Oued Lihoud: summary of the results

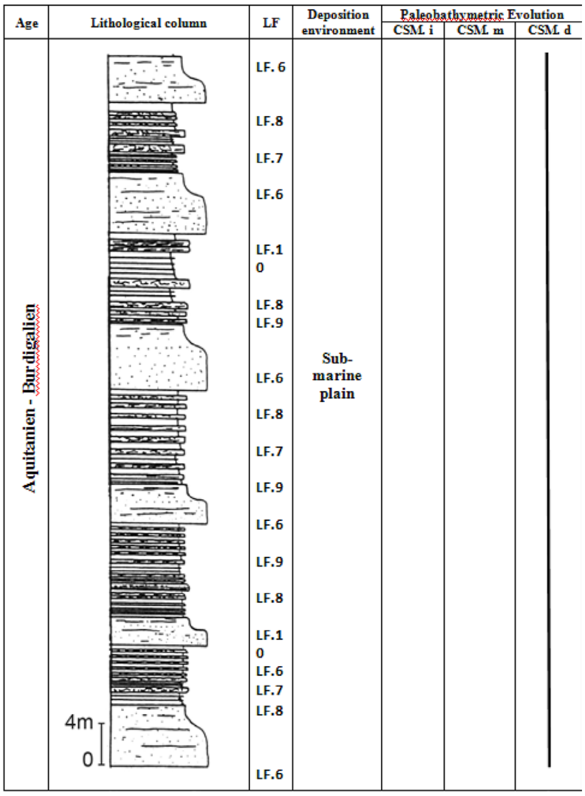

Fig. 28. Succession of Tlata de Béni Ider: summary of the results

and deposits of channels and channel lifts that are sometimes included in landslides. It also appears to the north-west of Dhar Zhirou where the prodelta deposits contain slumped Numidian sandstone blocks of variable size (hectometres).

Distal slope and submarine plain environments have been identified in the Tlata de Béni Ider (Fig. 28), Ksar Sghir (Fig. 29), Malabata (Fig.

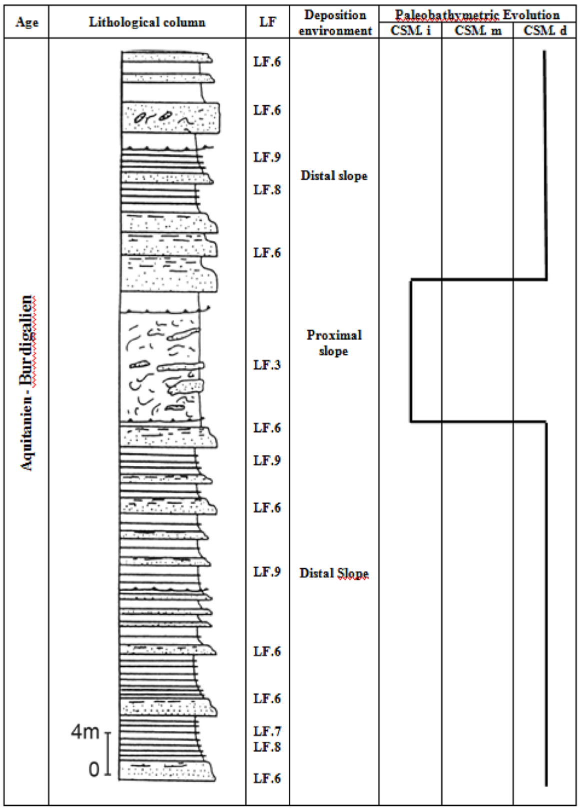

Fig. 29. Succession of Ksar Sghir: summary of the results

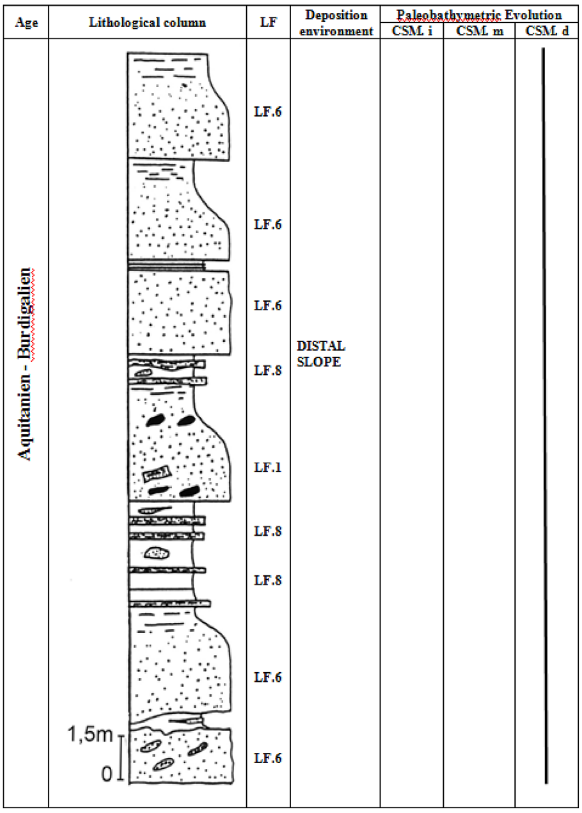

Fig. 30. Succession of Malabata: summary of the results

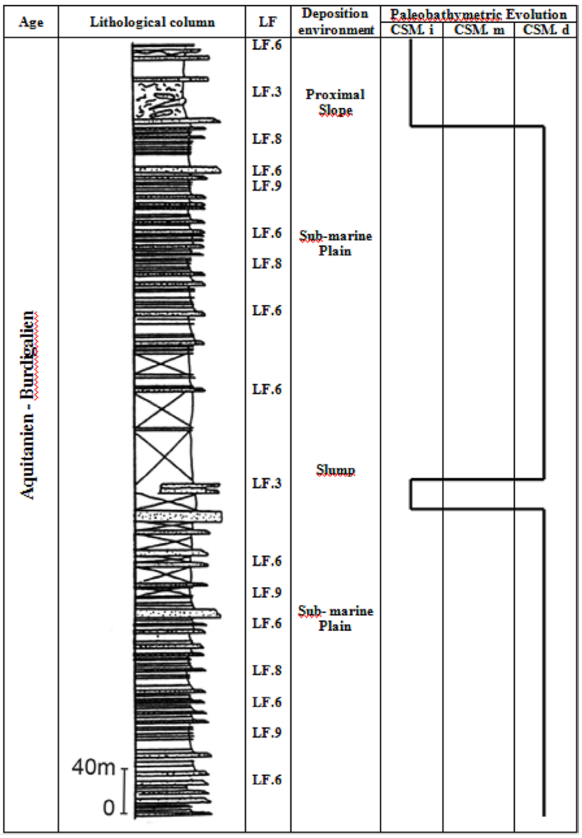

Fig. 31. Succession of Fardiwa: summary of the results

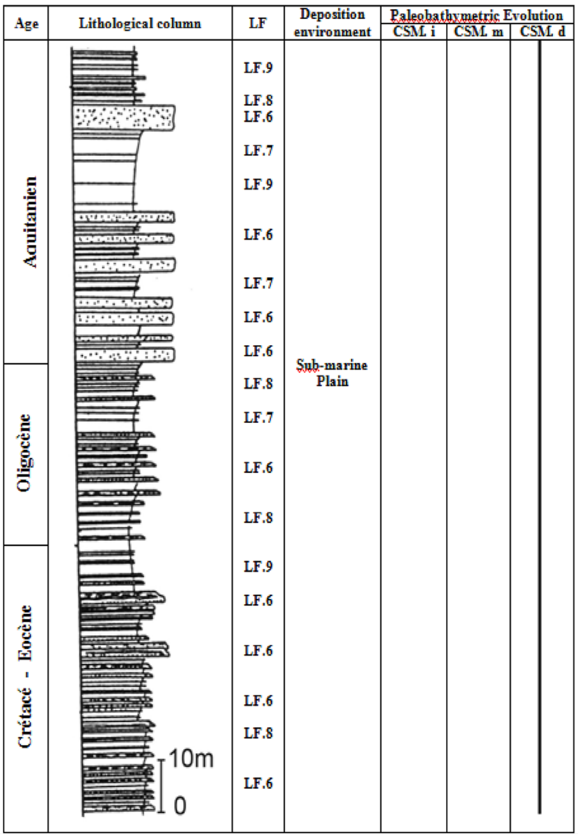

Fig. 32. Succession of Talâa Lakrâa: summary of the results

30), Fardiwa (Fig. 31) and Talâa Lakrâa (Fig. 32) sections. They were controlled by low, medium and high density turbidity currents, pulsations, contour currents and catastrophic spreading such as seismoturbidites and homogenites. These environments are associated with Mutti's (1985) type 1 "channel detached lobe" deep sea fan. In this system, sediments are deposited in unchannelled sedimentary bodies. At the top, there are erosional surfaces and chaotic deposits. The type 1 system reflects a period of low sea level and is typical of the elongated basins of active chains.

Sediments and sources of supply

The Numidian "flyschs"

Petrological studies of the Numidian series have identified several petrofacies belonging to three types of sediment: silicoclastic sediments, carbonate sediments and mixed sediments.

a) Silicoclastic sediments. These are quartzarenites, quartzwackes (according to Pettijohn, 1973), granular arenites and ferruginous siltites. They are made up of: quartz of volcanic and sedimentary origin, very poorly classified (100 µm to 5 mm), of variable shape (rounded to angular) often intensely fractured, rare plagioclases of sub-rounded shape and small size (60 µm), muscovite, rare fragments of sub-rounded volcanic rocks, glauconite pelloids, rolled zircon, opaque minerals and a binding phase with a clay matrix, or a siliceous cement and an iron cement.
b) Carbonate sediments. They are represented by biomicrosparites and micrites in Folk's classification (1968). Biomicrosparites are essentially made up of a sparite cement as well as fragments of organisms (foraminifera, gastropods, lamellibranchs), spores and glauconia; whereas micrites are made up of a micritic mud that can be recrystallised into dolomite and calcite at fissure level.
c) Mixed sediments correspond to "micritic sandstones", "silty micrites″, "micritic siltstones″, "sandy bioclast limestones″ and "bioclastic muddy allochem limestones″ in Mount's classification (1985), which differ only in the size and percentage of constituents.

The silicoclastic phase is made up of quartz of volcanic, metamorphic and sedimentary origins of medium size (30 µm to 250 mm) and angular to subrounded shape, plagioclases (3%) of small size and subrounded shape, rare muscovites, rolled and small zircon, opaque minerals and a very low percentage of glauconia (less than 1%). The carbonate phase is made up of debris from unidentifiable bioclasts, foraminifera (orbitolines) that are sometimes micritized, gastropods, lamellibranchs, sponge spicules and spores, as well as a microsparite cement or micritic matrix.

Micaceous-sandstones flysch

A petrological study of the micaceous-sandstone flysch series has identified several petrofacies that belong to mixed slicoclastic-carbonate sediments; they correspond to "micritic micaceous sandstones″, "lithic micritic sandstones″, "micaceous silty micrites″ or "micaceous micritc silts″.

The silicoclastic phase consists of poorly classified volcanic and metamorphic quartz (30 µm to 250 mm) of variable acicular, angular to rounded shape; feldspars (up to 10% of the rock) which are microclines and plagioclases, angular to rounded in shape ; fragments of volcanic (microgritty and microlithic), metamorphic (micaschists and metaquartzites) and carbonate sedimentary rocks (up to 30%), which are angular to rounded. This phase also contains micas (up to 15% of the rock) which are muscovite, biotite and chlorite; opaque minerals, small rolled zircons, peloids, glauconite and a clay matrix. The carbonate phase is made up of micritic rock fragments known as bioclasts, which can make up 50% of the rock. These bioclasts correspond to globigerine foraminifera, lamellibranchs and unidentifiable shell test debris. The binding phase corresponds to a micritic mud and/or microsparite cement.

Interpretation of results

The sediments of the Oligo-Miocene age series are derived from four sources:

- A distant silicoclastic source whose products are characterised by a high degree of textural and mineralogical maturity. This distant source is thought to have originated in Africa (Chalouane and al., 2008; Azdimousa and al, 2019), as is also attested by the association of clay minerals such as kaolinite, chlorite and illite, with kaolinite predominating. In fact, this association reflects a supply from a more or less flat source subject to chemical alteration that favours the development of soils and the formation of alteration products (chlorite and kaolinite). This source is thought to correspond to the Nubian sandstones in Sudan (Hoyez, 1989; Guerrera and al., 1981-82; Chiochini and al., 1980). It fed the Numidian series and some levels of the Fardiwa and Talâa Lakrâa successions.

- A silicoclastic source with a metamorphic, volcanic and sedimentary component, close to the sedimentation basin and subject to rapid erosion processes. It corresponds to the internal betico-rific domain that formed the southern margin of the Alboran microplate (Guerrera and al., 1981–1982; Hoyez, 1989; Salhi, 1994; Chalouan and al., 2008; Guerrera and al, 2019), as attested by the recognised clay mineralogical assemblages such as illite, smectite, kaolinite and chlorite, with illite predominating (over 50%). This source fed the successions of the sandstone-mica series of Béni Ider, part of the Talâa lakrâa succession and the basic terms of the Zinat section.
- An extrabassinal carbonate source close to the sedimentation basin, located in the southern margin of the Alboran microplate at the level of a carbonate platform (northern margin of the basin) which corresponds to the limestone ridge (Salhi, 1994; Chalouan and al, 2006; El Kadiri and al 2006; De Capoa and al. 2007; Chalouan and al, 2008). This source also fed the micaceous-sandstone series of Béni Ider, the Talâa lakrâa succession and the basic terms of the Zinat section.
- An intrabasinal carbonate source, linked to pelagic organisms, which fed fine micritic mud to all the Oligo-Miocene successions and the platform deposits of the Tangier unit for the base series of the Dhar Zhirou and Ziatène sections.

Synthesis of results

Oligo-Miocene palaeogeography

The facies identified in the Ziatène, Dhar Zhirou, El Har and Zinat Numidian series show that their deposits developed in the proximal part of the basin in delta slope-type fan deltas, while the Oued Lihoud succession, further north, was deposited in a more distal environment (talus). Petrological and mineralogical studies have shown that these successions were fed from the African continent. In addition, the palaeocurrent measurements carried out as part of this study generally show flows from south to north, from south-south-east to north-north-west and from south-south-west to north-north-east. All these results confirm the southern origin of the Numidian sediments. They are supported by the results obtained by Hoyez (1989), which show a decrease in the granulometric size of the quartz from south to north, the identity of the thermoluminescence of the East African Numidian quartz and the Precambrian age of the zircons (from the West African craton).

The Numidian series are associated with the southern margin of the Maghreb basin, and their current spatial distribution more or less reflects their original layout. In fact, they occupy the highest structural position, are relatively less affected by Alpine tectonics and generally dip slightly (measurements carried out as part of this study), unlike the other series of the same age, which generally dip steeply (generally vertically) and are always detached from their bedrock. On the other hand, the contacts observed between the Numidian and Tangier units are either normal sedimentary contacts or local tectonic contacts. The angular unconformity that sometimes occurs between the Numidian and the Tangier unit is linked to ante-Oligocene and post-Upper Cretaceous tectonic phases (Michard and al., 1991; Salhi, 1994).

The micaceous-sanstones flysch series were deposited in a Mutti (1985) type I deep sea fan environment, close to the northern margin of the basin. Paleocurrent measurements show different orientations, but with a relative dominance of north-south flow. However, due to the complex tectonic history affecting these series and the imprecision of stratigraphic dating, it is difficult to propose a precise palaeogeography of the northern margin (Chalouan and al., 2008). Nevertheless, the Talâa Lakrâa series must be located in an intermediate position in the centre of the basin (Belayouni and al. 2023) with the Fardiwa series, as these two successions were fed by both the southern and northern margins.

Geodynamic, climatic and eustatic evolution during the Oligo-Miocene

The sedimentary series of Oligo-Miocene age on the southern shore of the Strait of Gibraltar were deposited in the "Maghrebian basin" (Bouillin, 1986; De Capoa and al. 2007), and recorded several geological events that took place on both the African and European margins (AlKaPeCa) (Bouillin and al., 1986; Michard and al,. 2002–2004; Chalouan and al., 2008).

The Numidian series developed in the southern margin, which corresponds to the platform of the Tangier unit, and their deposition is linked to eustatic, tectonic and climatic events:

- A major eustatic decline was recorded during the Oligocene (Vail and al,. 1987). This has been identified in sediments corresponding to platform edge and proximal slope processes;
- The cold climate of the Oligocene (Frakes, 1979) could be the cause of a rhexistasis favourable to the dismantling of soils and the entrainment of a detrital fraction (Hoyez, 1989);
- Distensive movements (Skakni, 2020) have created slopes that have guided the drainage system; the basic series at Dhar Zhirou and Ziatène is affected by synsedimentary faults. Tectonic activity continued throughout the period of sedimentation, producing significant subsidence, leading to landslides and synsedimentary faults in all the Numidian series. The clastic veins found in the Oued Lihoud and El Har sections are thought to be linked to this tectonic activity;
- The installation of a system of fluvial networks, which cut into the Tangier unit via valleys, enables Numidian material to be transported to the edge of the platform. Sediments trapped in the fan-deltas can be taken up and resedimented on the proximal slope (as in the Oued Lihoud section) following subsidence of the margin. They can also be resedimented on the submarine plain, towards the centre of the basin, where they are intercalated with the sediments from the northern margin and form mixed series such as Talâa Lakrâa and Fardiwa during periods of low sea level.
- The micaceous-sandstone flysch was deposited close to the northern margin of the basin, which corresponds to the internal Rifian: domain Alboran microplate (De Capoa and al. 2007). Their sedimentation is linked to several tectonic and eustatic events:
- The oligo-miocene eustatic decline is recorded at the level of the northern margin by the development of Mutti (1985) type I deep sea fans;
- Compressional tectonics (Skakni, 2020) induced the elevation of relief and accelerated erosion processes;
- Overriding tectonics leading to the scaling of the sedimentation basin, which is at the origin of megaturbidites and splitting of series such as the Fardiwa series and the Talâa Lakrâa series.

CONCLUSIONS

In summary, the Numidian series were deposited in fan-deltas of the 'delta slope' type, and further north, in a more distal environment (slope). The petrological and mineralogical study showed that these successions were supplied from the African continent. Because they occupy the highest structural position, they are less affected by Alpine tectonics. In general, the Numidian filed on the Tangier unit, which is its normal bedrock. On the other hand, the other series of the same age show strong dips and are always detached from their bedrock. The sandstone-micaceous flysch series were deposited in a submarine fan environment near the northern margin of the basin. The Talâa Lakrâa series occupies an intermediate position in the center of the basin with the Fardiwa series, because these two successions were fed by both the southern margin and the northern margin.

The Numidian series of Oligo-Miocene age from the southern shore of the Strait of Gibraltar are linked to several events; eustatic, tectonic and climatic; a significant eustatic decline induced the installation of a system of fluvial networks allowing the transport of Numidian material towards the edge of the platform; the cold climate and distensive movements allowed the creation of slopes which guided the drainage system. Tectonic activity continues throughout the sedimentation period, materialized by synsedimentary faults.

For the sandstone-micaceous series were deposited near the northern margin of the basin which corresponds to the internal Riffian domain. Their sedimentation is linked to several tectonic and eustatic events; the Oligo-Miocene eustatic decline is recorded at the northern margin by the development of the submarine fan, a compressive and overlapping tectonic inducing the elevation of the reliefs and accelerating the erosion processes given the significant thickness of the sandstone flysch micaceous and scaling of the sedimentation basin.

Acknowledgements

We dedicate this work to the late Ali Bahmad, geological engineer at the Société Nationale des Etudes Du Détroit (SNED), may God rest his soul. A humble person full of knowledge, he always showed us friendship and care; rest in peace, we will always have you in our hearts.

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